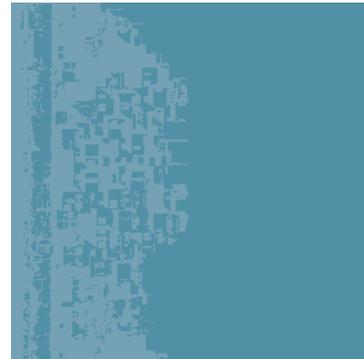


# SYSTEM STRUCTURES IN ARCHITECTURE

- CONSTITUENT ELEMENTS OF A CONTEMPORARY INDUSTRIALISED ARCHITECTURE



KASPER SÁNCHEZ VIBÆK  
PHD-THESIS

CINARK - CENTRE FOR INDUSTRIALISED ARCHITECTURE  
THE ROYAL DANISH ACADEMY OF FINE ARTS  
SCHOOLS OF ARCHITECTURE, DESIGN AND CONSERVATION  
SCHOOL OF ARCHITECTURE  
OCTOBER 2011



KASPER SÁNCHEZ VIBÆK

SYSTEM STRUCTURES IN ARCHITECTURE  
- CONSTITUENT ELEMENTS OF A CONTEMPORARY INDUSTRIALISED ARCHITECTURE

PHD-THESIS  
ELABORATED AT CINARK - CENTRE FOR INDUSTRIALISED ARCHITECTURE

© 2011 KASPER SÁNCHEZ VIBÆK AND

THE ROYAL DANISH ACADEMY OF FINE ARTS  
SCHOOLS OF ARCHITECTURE, DESIGN AND CONSERVATION  
SCHOOL OF ARCHITECTURE

ISBN: 978-87-7830-275-5

PUBLISHED BY:  
THE ROYAL DANISH ACADEMY OF FINE ARTS  
SCHOOLS OF ARCHITECTURE, DESIGN AND CONSERVATION  
SCHOOL OF ARCHITECTURE  
PHILIP DE LANGES ALLE 10  
DK-1435 COPENHAGEN K

PRINT:  
SANGILL GRAFISK PRODUKTION

GRAPHIC DESIGN:  
MALENE HENSSEL

# TABLE OF CONTENTS

## PART I – FRAME

I.1	PREFACE	006
I.2	ACKNOWLEDGEMENTS	009
I.3	INTRODUCTION TO THE PROBLEM AREA	011
I.4	DEFINITION OF SCOPE	018
I.5	METHOD AND SCIENTIFIC APPROACH	023

## PART II – SYSTEM

II.1	SYSTEMS IN ARCHITECTURAL THEORY	042
II.2	CLASSIFICATION SYSTEMS IN CONSTRUCTION	065
II.3	INDUSTRIAL PRODUCTION THEORY	077
II.4	GENERAL SYSTEMS THEORY	099
II.5	SYSTEMS TERMINOLOGY FOR ARCHITECTURE AND CONSTRUCTION	122

## PART III – PRODUCT

III.1	COMMODITISATION IN ARCHITECTURAL CONSTRUCTION	140
III.2	CUSTOMISABLE ARCHITECTURAL SUBSYSTEMS	152
III.3	DEVELOPMENT AND CLASSIFICATION OF INTEGRATED PRODUCT DELIVERIES	171

## PART IV – MODEL

IV.1	MODEL PRESENTATION	196
IV.2	SYSTEM STRUCTURE ANALYSES	209
IV.3	KIERANTIMBERLAKE	212
IV.4	SCANDI BYG	244
IV.5	NCC	261
IV.6	ARUP ASSOCIATES	279

## PART V – REFLECTION

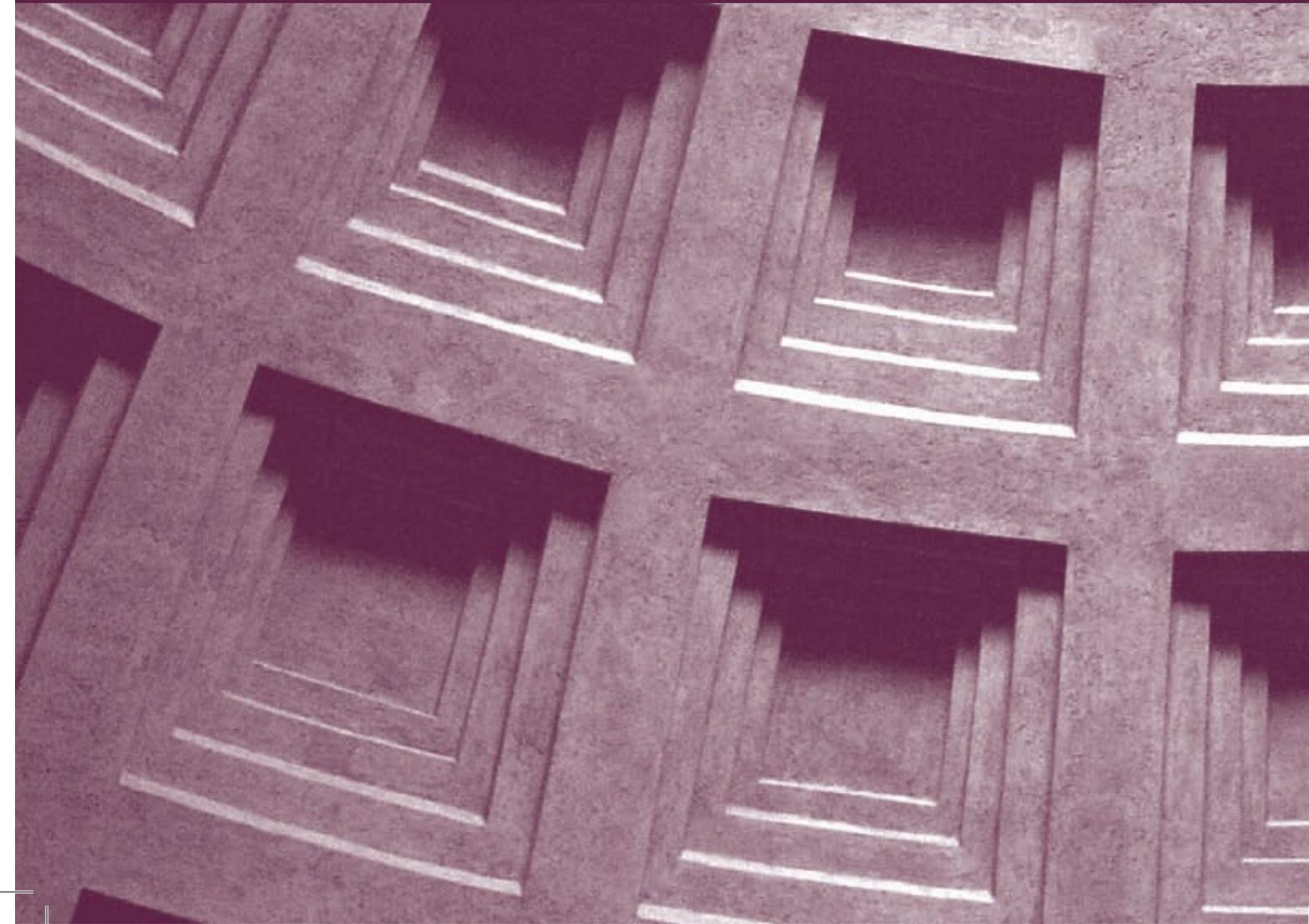
V.1	FINDINGS	300
V.2	METHODOLOGICAL EXPERIENCE	323
V.3	CONCLUSIONS IN SHORT	338

## PART VI – APPENDIX

VI.1	ILLUSTRATION CREDITS	348
VI.2	BIBLIOGRAPHY & REFERENCES	351
VI.3	KEYWORD INDEX	354

- ONLY ON CD:

VI.4	PROJECT FRAME DESCRIPTION	
VI.5	ARTICLES , PAPERS, AND ABSTRACTS	
VI.6	DATA MATERIAL, CASES	
VI.7	COURSE MATERIAL	
VI.8	OTHER PRESENTATIONS	
VI.9	CURRICULUM VITAE	



# PART I

# FRAME

- I.1 PREFACE
- I.2 ACKNOWLEDGEMENTS
- I.3 INTRODUCTION TO THE PROBLEM AREA
- I.4 DEFINITION OF SCOPE
- I.5 METHOD AND SCIENTIFIC APPROACH

- 1 [http://www.karch.dk/cinark\\_uk/table/Profile](http://www.karch.dk/cinark_uk/table/Profile) accessed on September 3, 2011
- 2 <http://www.realdania.dk/English.aspx> accessed on September 3, 2011

## I.1 PREFACE

### ORGANISATIONAL LOCATION, FINANCING AND GENESIS

The present thesis is the result of 30 months of study and research conducted at CINARK – Centre of Industrialised Architecture from 2009-2011. Organisationally located under the Institute of Architectural Technology at The Royal Danish Academy of Fine Arts, School of Architecture (RASA), CINARK *‘develops, accumulates and co-ordinates research and education activities concerning the production of industrialised architecture from a sustainable point of view.’*<sup>1</sup> Through several earlier and ongoing research projects – a considerable part of them conducted as PhD-projects – CINARK has since 2004 developed knowledge around the processes as well as the products – or physical results – of architecture and architectural creation exposed to modern industrialised means of production.

The PhD-project has been made possible through cofinancing between the RASA and Realdania – a major private Danish *‘strategic foundation created with the objective of initiating and supporting projects that improve the built environment.’*<sup>2</sup> The Realdania cofinancing was given on the basis of a grant application without other conditions than proper documentation of progress according to a project specific research plan approved by the RASA and the provision of the related standard half-year evaluations. The stipulated length of 30 months – slightly shorter than a normal PhD-project – has its origin in an earlier project by another candidate that was abandoned. Due to earlier research work and experience within the field, the candidate of present project was considered qualified to complete the project within the available amount of time.

The incentive to engage in present project is rooted in the candidate’s earlier research work at CINARK that started in 2004 with a project concerned with the goals and strategies in the process of architectural design. A subsequent project from 2006 was more focussed on the outcome of these strategies and processes and dealt with industrialised structural building systems. Finally an international collaboration between CINARK, Chalmers University of Technology in Sweden and Paris-Belleville Ecole Nationale Supérieure d’Architecture in France from 2007 looked into user requirements and mass customization

in industrial building systems.<sup>3</sup> All projects have had a special focus on the consequences of the industrialised means of production and construction for the architectural quality of our built environment. Architectural quality is a holistic concept than can not easily be reduced or atomised into clear, quantifiable sub parameters characterising an industrialised logic. It is this tension between the constituent parts and the whole that continuously has driven my interest towards present examination of systems and systems thinking in architecture. While the main part of the research has been conducted at CINARK, supplementary supervising was also received during a six month stay as visiting scholar at University of Pennsylvania, Department of Architecture.

3 See (Jensen & Beim 2006, Beim, Vibæk & Jørgensen 2007, and Beim, Nielsen & Vibæk 2010)

## STRUCTURE OF THE THESIS – A READER’S GUIDE

Apart from disseminating some kind of final result or findings, the ambition has also been to express some of the processes and the different steps that led to these results and findings. This is sought reflected in the format of the thesis in the sense that it is structured around a number of parts that express a development from a theoretical exploration over a practical to the proposal and application of an analytical model. Several papers and articles have been published during the course of the project. These have in several cases served as the basis for chapters or parts of these in the final thesis but have however been considerably restructured for the purpose in order to get a coherent result and avoid too much repetition. All related abstracts, papers and articles produced during the project are enclosed in the appendix that however mainly is located on a CD in order to keep the format and the focus on the main thesis.

The thesis is divided into five main parts and an appendix. Each main part comprises several sections gathered around a common main theme such as framework, theoretical exploration, practical exploration, model and case studies, and final discussion and methodological reflection.

Part I is called FRAME. This part describes the overall framework for the research i.e. how the project was made possible, what the thematic and organisational background is and how the scope and research problem is defined. A last section of this part describes the methodological approach and tries to relate this approach to a general discussion of scientific approach and knowledge production.

Part II is called SYSTEM. This part is the theoretical exploration of the thesis. Here different theoretical paths of systems thinking are examined with reference to the research problem defined in part I. A first section is a historical view on systematic thought in architectural theory. A second section deals with different applied classification systems and taxonomies in construction as opposed to architectural creation. Next follows two sections on other kinds of systems theory outside the field architectural construction such as industrial production theory and general systems theory. A final section seeks to define central concepts as they are used in this thesis.

Part III – PRODUCT is an exploration of the practical reality within architectural construction and its current level of industrialisation and systemic elements. *Commoditisation* is proposed as a useful concept in this context. Subsequently a section deals with the emergence of system products within the field of construction seen as combinations of matter, process, and thought. A final section deals with the specific development of integrated products in construction and seeks to establish an initial product catalogue.

PART IV called MODEL is the presentation of a model as the primary outcome of the thesis. The elaborated model represents an analytical structure or a supportive tool applicable to contemporary and/or future architectural construction. A first section presents the model its current state. Subsequently the model is applied as an analytical tool to a series of cases (case studies).

Part V – REFLECTION is a discussion of the most important findings from the case analyses and the general applicability of the proposed model. Subsequently follows an after the fact methodological critique and reflection on the methods applied, the experience gained and the lessons learned throughout the process of the current PhD-research. A last section draws up the main conclusions in a short form related to the main problem and hypotheses and points out further development perspectives and future research needs.

The last part VI is an APPENDIX containing e.g. illustration credits, bibliography and references, and a keyword index for the thesis. Furthermore, supplementary documentation and material produced during the course of the project is located on an indexed CD to be found inside the cover of the thesis.

## I.2 ACKNOWLEDGMENTS

This work would not have been possible without the support and contributions from many persons to whom I feel deeply in debt.

Nobody mentioned, nobody forgotten, but with the excuses to those I might not have mentioned here, I would however like to thank the School of Architecture and Realdania for making the work financially possible and for providing the institutional framework e.g. around the research school and research administration represented by persons like Henrik Oxvig, Lise Steiness and Jacob Kristoffer Hansen. This framework has on the practical side constituted an efficient and flexible basis and has saved me much time to concentrate on the academic content.

Special thanks to my two principal and invaluable supervisors during the project, Anne Beim and Jesper Nielsen. While Anne as former head of CINARK and now professor of architectural technology at our institute mainly helped me through the first half with her well-founded research experience and broad knowledge within the field, Jesper, as present head of CINARK, has with his more practically founded experience and close connection to the industry strongly qualified the more technical aspects and mainly supervised during the second half of the project course.

With good experience from earlier research projects, I have also this time had the luck to have and would like to thank my advisory group that apart from my principal supervisors also included Architect and Associate Professor Per Kortegaard from the Aarhus School of Architecture and Engineer and Professor Lars Hvam from DTU Management Engineering. The advisory group has approximately every six months used their time to give valuable input on the status of the project.

I would also like to thank the midway presentation panel, Professor Olga Popovic Larsen, Professor Carsten Juel-Christiansen both from the School of Architecture, and Project Manager Lenny Clausen from Realdania. Equally thanks to David Leatherbarrow and Bill Braham from University of Pennsylvania for receiving me as visiting scholar during the spring of 2010.

A huge number of people have assisted me in different ways during the four case studies and will be mentioned there. However special thanks to Stephen Kieran, James Timberlake, Billie Faircloth and Carin Whitney at Kieran-Timberlake for making my four month stay in the office a very positive and rewarding experience with enormous benefits for the project and the thesis.

Equally thanks to the final assessment committee Professor Simon Austin, School of Civil and Building Engineering, Loughborough University, Associate Professor, Prorector Charlotte Bundgaard, Aarhus School of Architecture, and Associate Professor, Director of Centre for Sports and Architecture, Rene Kural from the School of Architecture. Apart from the valuable feedback in the preliminary recommendation, the committee provided me with the excellent occasion to qualify the final work before the defence as a revision of the dissertation.

Finally but not the least, I would like to thank my beloved family – Reyes, Fiona and Pablo – for their invaluable moral support and encouragement as well as their patience towards my at times unreasonable mental absence at home.

## I.3 INTRODUCTION TO THE PROBLEM AREA

- Handling complexity in architecture and construction

“Design today has reached the stage where sheer inventiveness can no longer sustain it. To make adequate forms, one must be able to explore the relations between circumstances more fully than is done at present, so that the decision as to just where to apply precious and limited inventive power can be made”

(Chermayeff & Alexander 1965:161)

### *Industrialised Architecture*

Organisationally located at CINARK, Centre for Industrialised Architecture, this thesis takes its starting point and naturally continues the line of earlier research within the field of *industrialised architecture* – a term that CINARK among others have contributed to the definition of. Industrialised architecture does not in itself point towards a specific architectural expression or the appearance of a specific (new) architectural style. Neither can one talk about a distinctly identifiable building typology; it is not about industrial architecture!<sup>4</sup> While industrialised architecture as field of research still has the architectural result as object of research, it quickly also involves the *organisation* and *production processes*, their industrialisation, and the perspectives and consequences for the architectural result of this industrialisation. Architecture is generally about creating the best possible physical surroundings for human life, and decisive for the final result of all creation is not only the material but also the tools and the related techniques. Organisation and production processes are equally important when it comes to the definition of the architectural solution space given for each architectural project.<sup>5</sup> Rather than dealing with a specific result, industrialised architecture is a particular way to construct or assemble buildings – a way to *think* about architecture and construction – that however has significance for this result: the finished work or building.

To deal with industrialised architecture as field of research here should not be seen as a direct promotion of organisation, processes and results falling within this category as being something particularly conducive for the architectural result. Rather, it should be seen as a critical discussion of and taking a stance on

- 4 In Danish, (Center for) *Industrial Architecture* is used in the meaning of *industrialised* as a parallel to *industrial design*. Consequently, *industrial architecture* is normally termed *industry architecture* in Danish.
- 5 For a discussion of *architectural solution space* – the set of all possible solutions for a given set conditions or parameters – seen in an architectural context see e.g. (Vibæk 2007).

- 6 A discussion of fundamental differences between industrial and architectural design can be found under *Commoditisation of architectural construction*, III.1
- 7 This paragraph is partly taken from (Beim, Nielsen og Vibæk 2010:77f)
- 8 Wealth of *nations* is not necessarily coincident with general wealth of the individual citizens
- 9 The British sociologist Anthony Giddens use the notion of expert systems to explain how people in their everyday life draw on large amounts of embedded knowledge when e.g. taking the bus or using the telephone. (Kaspersen 2005:439 and Giddens 1990)

a range of tangible tendencies that is observed concerning the way we presently build. This, on the one hand in relation to architects and other consultants that are contributing to the project basis of building projects as well as on the other hand in relation to stakeholders involved in the practical realisation of building projects. The latter group of stakeholders is increasingly becoming a mix of industrial manufacturers producing parts in offsite factory environments and the more traditional builders as contractors and their subcontractors that process and adapt building materials and components directly on the building site. Countless times construction has been compared with the product industry and its mass produced standard goods for large markets. Although much within the construction sector can be regarded as production there are reasons to believe that construction seen as *architecture* has – and probably always will comprise – elements that cannot be produced as finished goods in a true industrial sense. This is partly due to the fact that architecture is fundamentally bound to time, place and culture in a different way by constituting the framework of rather than the tools for human action and development.<sup>6</sup> An important question here becomes: How does this industrialisation of *construction* look?

#### *Division of labour and the modularisation of construction*<sup>7</sup>

Although in some primitive form it has always existed in human communities, the division of labour is one of the most significant characteristics of modern society. In 1776 the British economist Adam Smith describes the division of labour as one of the most efficient ways to improve the productivity performance of companies hence increasing the wealth of nations.<sup>8</sup> His best known example is a pin manufacturing company. After splitting up the process of making pins in different subtasks – thus specialising the workers – productivity raised by factor 240 (Smith 1776). Since the time of Smith, a pronounced division of labour has spread to all areas of society that partly due to this fact have become increasingly complex. Construction and architecture is not an exception.

Industrialisation within construction starts later than the general industrialisation of society. Up until the massive industrialisation of building processes and products in the 1960's, the division between the crafts and professions on the one hand and the modularisation of architectural construction on the other was always identical. The building crafts could be seen as independent modules – or systems of coherent expert knowledge - with clearly defined interfaces to adjacent modules.<sup>9</sup> Construction specifications, i.e. drawings, had a substantial set of conventions, allowing a few instructions (as e.g. lines and signs) to

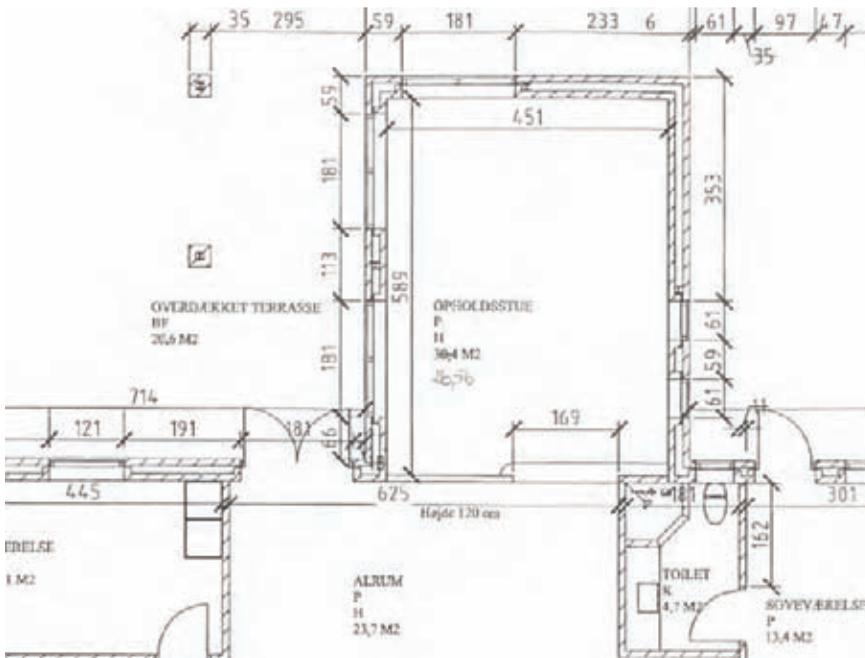


FIGURE I.1.1  
CONSTRUCTION SPECIFICATIONS AS  
CONVENTIONAL PLAN DRAWINGS  
INCLUDE LARGE AMOUNTS OF EMBED-  
DED KNOWLEDGE

be clearly comprehended due to a large amount of implicit – or *embedded* – knowledge. The dimensions of the windows on the plan of a masonry building, for instance, is known to refer to the window sills, not to the sides of the actual carpentry. The carpenter knows that he has to subtract the size of the joint (for which he has responsibility). It is thus not necessary for the architect as a ‘specifier’ to design this specific interface, only to define where it is. If the architect wants to control the appearance of the detail, he can supply a drawing. If he does not, the craftsman’s default solution will be used, still with a high-quality result, as this detail will seem coherent in the particular building. The *complexity* of the design task is reduced by making use of this embedded knowledge of the implicit building tradition applied by the craftsman.

Today, the crafts and construction skills have almost disappeared from the construction industry in their traditional form due to increased technical and economical demands in architecture. Large standardised quantities, extreme precision on the technical side and a need for increased productivity with less manpower on the economic side, dissolve the essentials of the traditional manually based workshop production and on-site adaptation. At the same time, the explosion in the number of choices within the building material industry has made it impossible for anyone to cope with all possible combinations in a traditional non-explicit (tacit) manner. Although the fundamental architectural challenge is relatively unchanged and still generally is about creating the best possible physical surroundings for human life (in all aspects), the premises for solving this task as specific buildings has changed considerably – building has become much more complex both as object (material) and design task (process). Simultaneously, the possibility for the architect of drawing on coherent knowledge from the crafts has been reduced. It is not that expert knowledge in construction has decreased – quite the contrary – but this knowledge no longer relates to and is no longer automatically embedded into a coherent way of building. Local vernacular architectures are expressions of such traditionally coherent knowledge systems with the crafts as subsystems. However, although

- 10 BMS = Building Management System is a computer based control system that controls and monitors the building's mechanical and electrical equipment ([http://en.wikipedia.org/wiki/Building\\_management\\_system](http://en.wikipedia.org/wiki/Building_management_system)) accessed on August 8, 2011
- 11 For a similar assertion, see e.g. (Bachman 2003:6)

the crafts still exist to some extent, they no longer cover construction as a whole. More and new areas of specialisation have emerged as crystallisations or fusions of earlier trades as e.g. foundation work, flooring, ventilation, alarm, and BMS systems etc.<sup>10</sup> A next question then becomes: How can this increased complexity and knowledge fragmentation in construction be handled in order to facilitate a focus on the architectural core instead of getting lost in technical and economical details that however still needs consideration and control?

#### *Architecture as (industrialised) production*

In this context, the present thesis claims that the architect has a special integrative role among and in relation to the stakeholders involved in construction.<sup>11</sup> *Etymologically* speaking architect means *master builder* or *supreme carpenter* (Becker-Christensen ed., 2001) and the architectural profession deals (to a great extent) with the conception and the creation of physical wholes. It is the task of the architect to bring the different knowledge systems and their physical outcome or products together in order to create these wholes – or coherent systems – that become more than the sum of their constituent elements: They become architectural works. However, it seems that the architect's tools for creating this integration or synthesis has not evolved parallel to the described development and specialisation within the construction sector in general and the building component industry in particular. The architect is trained with and still widely works from a 'craft based' approach that through use of a range of materials transforms an architectural concept into a true physical form. The modules or *systems* used for architectural thinking, it is argued here, still predominantly correspond to the traditional crafts rather than to the specialised and partly industrialised building industry that is supposed to produce them. That this is *also* the case for the processes of most of the traditional contracting companies does not necessarily reduce the problem in relation to the handling of complexity. There is apparently a growing gap between how on the one hand architecture is conceived and, on the other hand, how it is or can be produced. Just the mere expression of architecture as *production* probably 'grates on the ear' of many architects.

If however, we assume that industrialisation is a *condition* – not just an option – that architects and other stakeholders in construction have to respond to but simultaneously also stress that that architecturally speaking industrialisation is a *means* not a goal in itself, then perhaps the discussion is less controversial and can become more fruitful. This way the discussion of industrialisation of

construction and industrialised architecture can be diverted from a dialectic perspective of pros and cons towards a focus on potentials and perspectives of a conscious and critically well-balanced application of industrial logic in construction and architecture. Industry and industrialised production methods draw on strict methodologies and systems in order to reduce or handle complexity. While these methodologies and systems earlier inherently meant standardisation of the product, modern information technology has gradually facilitated the standardisation of even complex *processes* that on the contrary can lead to huge variety when it comes to the resulting products. This phenomenon is often termed *mass customisation* with direct reference to and as alternative to traditional mass production. The term *new industrialisation* covers, as pointed out in earlier CINARK-research, a current parallel tendency within the Danish construction sector with reference to and as alternative to the first wave of industrialisation in construction in the 1960's (Beim, Vibæk og Jørgensen 2007:25 and Jørgensen 2007).<sup>12</sup> While the first industrialisation wave in construction was heavily standardised in its architectural expression and almost became an architectural style in itself, the new industrialisation of construction and architecture points towards a systematisation of project specific and context sensitive solutions. This leads to the question: How can architecture and construction be seen - and possibly conceived - as a system of processes and/or products that better match the means of production that currently produces our built environment while *simultaneously* taking into account architecture's specific attachment to time, place and cultural context? – and: What (kind of) knowledge can possibly be transferred to a general system level thus reducing the complexity to be handled within each building project seen as a single and context specific design task?

#### ***Product architecture and integrated product deliveries***

Within the product industry when designing e.g. cars, computers, washing machines or bags, the notion of product architecture is used to describe, analyse, and optimise how production and product in the most adequate way can be divided into a number of constituent elements of processes and/or physical modules. Product architecture is not about architecture in the sense that architectural designers usually apply it but simply refers to organisational and product structural issues. The product architecture defines how different subsystems form part of a complete supply chain and production line, and how these subsystems are assembled in the final product without this structure necessarily being perceivable to the end user. Through the product architecture,

- 12 The Danish Technological Institute has lately initiated a network of companies and research institutions co-ordinated by a so-called *Centre for New Industrialisation (CNI)*. <http://www.cni.teknologisk.dk/> accessed on July 15, 2011

a system level is established that sustain the whole while simultaneously splitting up this whole into meaningful elements that subsequently as more or less interdependent entities can be treated (designed and produced) separately – as processes and/or physical elements that perhaps even are performed by different independent suppliers. The product architecture as a design and production tool reduces the complexity of the design task without necessarily reducing the complexity of the product itself. This is particularly the case, when subsystems or elements of the product architecture are based on standardised solutions or well-known principles and/or processes.

In contemporary architecture and construction there is no self-evident product structure as it earlier was provided by the crafts – although in a non-conscious manner. The coherence between how architecture is conceived and how it can be produced has, as mentioned, been broken due to both technical as well as economical causes. A way to view ‘the product architecture of construction’ could become a useful tool – not just in construction phases but equally during the earlier architectural design phases. Precision, strict methodology and control can also be used in a creative manner! In the first case, such a tool (as analytical) could increase the understanding of how buildings are and can be put together from different industrial scenarios understood as a combination of production (prefabrication) and on-site construction. In the long run, the tool could potentially also be developed into a design supportive tool that, apart from reducing the complexity of the architectural design process, could increase incentives for true product development of architectural subsystems in the form of more and new types of integrated product deliveries. Earlier research at CINARK, described in the publication *Three Ways of Assembling a House*, points out the emergence of such integrated product deliveries as a product level between traditional onsite construction and the turnkey solutions of the conventional offsite building manufacturers (Beim, Nielsen & Vibæk 2010). The present thesis seeks to go one step further both concerning development and clarification of concepts as well as regarding the tool development. Inspired by the industry, it seeks to examine how different systems approaches can be used to bridge the gap between conception and realisation in the most appropriate way. The underlying research thus deals with a question of commoditisation of construction. This is not the same as a commoditisation of buildings as products or of architecture itself. As pointed out, this commoditisation can take place (and already does so) on a subsystem level in the form of integrated product deliveries that are used as elements of a building. I will

return to a formal definition of systems and integrated product deliveries as central notions of this thesis.

13 See VI.4 Project grant description (in Danish) in Part VI – 'Appendix' on enclosed CD

## I.4 DEFINITION OF SCOPE

This section describes the scope of the present PhD research project within and as a condensation of the problem area sketched in the previous section. With point of departure in the originally given project frame, the section clarifies the main topic and the sub themes to be treated in the thesis.<sup>13</sup> Through the description of three main work packages it outlines the overall procedural approach throughout the project. Finally it touches more specifically upon the principal outcome of the research – a model, its *non-scopes*, and how it can be seen as a contribution in a wider research context and as a response to the tendencies and problems sketched in the problem area section.

Present PhD-research has the overall purpose of examining what role system design, systems thinking and building concepts play in relation to modern industrialised construction with a focus on how this world of ideas is expressed in architecture.

***Main question:***

**How can systems thinking help bridging the apparent gap between architectural ideation and its subsequent realisation as process and result in contemporary industrialised construction while simultaneously handling the increased complexity of specialisation and technical development?**

***Goal:***

To propose an analytical structure (interpreted as a tool or a model) for clarifying the potential of industrialised construction as positively enabling rather than limiting the architectural solution space.

***Work packages:***

The project, the main question and the goal is operationalised into three main 'work packages' that overlap in time and outcome:

- a) a theoretical study
- b) an empirical study
- c) model generation

## a) Theoretical study:

Through literature surveys and selected in-depth studies the following topics are examined:

- Selected parts of architectural theory and its features of classification (into constituent elements), dogmatic thinking, ideology, and value systems. How has architectural theory with point of departure in architecture, understood as a dependant art, dealt with the balance between a systematic approach and free artistic expression?
- Selected part of classification systems in construction as they have been used among a wider range of stakeholders involved in the execution of building projects.
- Selected parts of industrial production theory in particular focussing on concepts like supply-chain, product architecture, modularisation, platforms and product family and whether these have or can have counterparts in architectural design and construction.
- Selected parts of (general) systems theory shedding light on its overall purpose and general elements and how this can be related to architectural design. A special focus is put on concepts like parts vs. whole, system delimitation/interface, (inter)dependencies and complexity.
- Theory/philosophy of science about the use of *abduction* as an alternative or supplementary paradigm for research and knowledge production within the field of architectural research and other similar disciplines.

Findings from the theoretical exploration are primarily located in Part II – ‘Systems’ that establishes the conceptual basis for the subsequent parts.

## b) Empirical study:

Through a market scanning of current building products available and a series of case studies of recently finished building projects (one primary and a number of secondary cases) it is examined:

- What kinds of integrated product deliveries do already exist on the market and how can they be classified?
- What is actually systematised within the creation of a building project and how does this influence or connect to the architectural solutions and

the final result? In other words: How can a building and/or its process of coming into being be conceptualised in terms of systems while drawing on inspiration from the theoretical study (above)

Findings from the empirical exploration and study is located in the parts III and IV

c) Model generation:

With point of departure in the theoretical and empirical material collected 'a)' and 'b)' a model is generated to regard each building (work of architecture) and the process of erecting it as a complex system - a node of subsystems brought together in a given context at a certain point of time with a specific purpose. Through *abductive* reasoning ideally the model combines studied elements of architectural theory, systems theory, and production theory with the empirical findings of market scanning and case studies into one single model proposal – a hypothesis of a generally applicable model. Subsequently the model is iteratively tested for explanative power and refined through exposure to the empirical case material and the evaluation of the *analytical discussions* it is able to generate. Due to the qualitative research approach, the case *analysis* and the case related *discussions* cannot be separated in a meaningful way. Analysis of qualitative data is inherently also interpretation

The elaborated model represents the *analytical structure for clarifying the potential of industrialised construction* as defined as the primary goal of the present research (above). The model is used for generating theoretical scenarios as well as for analysing empirical evidence. These exercises will contribute to the qualification of the model and its possible explanative power and application within both architectural research and practice

**Non-scope**

The model is not – at first – meant to become a software tool. This consideration has to do with both economy and time frame of the project, but more important is that the core of the initial model development must be the *content* and its *explanative power* rather than its technical functionality and performance. Focus on the two latter aspects would move a lot of effort (work) into programming which needs to be preceded by a proper understanding of what should actually be programmed. What need the model is supposed to cover

and in what way comes first. This does however pose certain limits to the complexity and the contained data layers of the model in order to make it manually applicable. The vision is that it is a *visual* tool that apart from being relatively easy to code moreover through its graphical qualities is able to communicate various levels of information in an easily perceivable way. The primary target group for the model is the architect – working in practice, education and/or research. In its preliminary version being primarily applied analytically to *existing* cases it serves as generally enhancing the understanding of the field (of industrialised architecture) thus being mainly educational. In later more developed versions it is envisioned to become more proactively applicable for early phases of architectural design. Other potential users of the model are other building consultants, contractors as well as manufacturers of building products and building concepts of more or less integrated nature.

The model is in its present state not meant to become a production planning tool and (intentionally) lacks aspects like time and economy. Again this is in the first place to keep coding parameters and the visual result of a coding relatively simple. Although later, possibly software based, versions could include such (and more aspects) it is so far an open question whether these *should* actually be integrated. A risk could be that too many and too specific parameters reduce the flexibility of the model and thus possibly its applicability to early architectural design phases where many aspects (should?) remain on an abstract level in order to keep the architectural solution space sufficiently open. A stance here is that the field of production planning and cost control is much better managed through the wide range of existing techniques, tools and software programs already available that integrate a lot of technical aspects that can not be included within the framework of this PhD-thesis.

The model is not dealing directly with the question of architectural quality. It is meant as a tool to keep certain aspects – in this case the *system structure*<sup>14</sup> as a newly invented concept – at an arm's length in order to be able better to use it actively as a (new) supportive design aspect. In this way the model is intentioned to clarify the potential of different system structures that lead to different design and construction scenarios. In the hands of the right person (e.g. as a qualified architect) this can support the architectural design work by e.g. reducing complexity in focus through the intermediary model. This can, it is assumed, enhance the probability of architectural quality in the final result. In other words: it is a tool to create a better overview and facilitate the process by *clarifying the potential of industrialised construction* scenarios within architectural design.

- 14 For a definition of this (new) concept and its relation to architecture and construction see II.5

- 15 In Denmark the principal educational institutions, DTU, AAU and AAA as well as research units within SBi (Danish Building Research Institute) and TI (Danish Technological Institute) have research programmes within the field of industrialised building and prefabrication. In Northern Europe can, among others, be mentioned different research programmes at e.g. Chalmers and KTH in Sweden, the private YIT in Finland with e.g. Lauri Koskela, and the Department of Civil and Building Engineering at Loughborough University, UK

### *Contribution to a wider research and practical context*

The project should be seen as research contribution following the line of earlier research produced within CINARK concerning the architectural consequences of industrialisation of construction. Several research units within Denmark as well as in Northern Europe are concerned with this field.<sup>15</sup> In general the subject of industrialisation seems more prevalent in Western industrialised countries with Northern European or similar climate where the weather factor combined with high wages encourages development of more automated and off-site dominated production technique. However, the current project points out that this can never be an either or. Architectural creation and construction will always be a combination of on the one hand on-site and perhaps more labour intensive craft based work and, on the other hand off-site prefabrication of varying degrees of automation and of integration of the final product delivered.

The ambition is – although this project still mainly stays on the theoretical level – to bring the theoretical conceptualisation of this special field of knowledge closer to implementation in architectural and construction practice. The main problem as stated in the problem area section is an apparent gap between how architecture is conceived and how it is or can actually be produced. The model developed as an analytical tool for understanding and potentially as a proactive design tool for early design phases is intended for this purpose – as a step in this direction. By enabling an, in the first case, enhanced understanding of industrialised production scenarios within architecture, it also becomes more probable that architects or other professionals can influence or make active demands to an industry that often (an perhaps logically) seem dominated by technical and economical aspects of construction rather than visionary architectural thought.

## I.5 METHOD AND SCIENTIFIC APPROACH

Creative knowledge production as a special paradigm for architectural research

### *Hypothesis*

A particular research method that better matches the way architecture itself is conceived can be used in the development of (intermediary) analytical models that are specifically suited for an architectural frame of reference – a new paradigm for knowledge production in architectural research.

### INTRODUCTION

This section describes the application of a particular research approach within the field of architectural research. It is, however, not a presentation of a well established and fixed method but rather a method under formation, development, test, and discussion. Compared to other more established fields of research, architectural research does not have the same unison definition of what research and knowledge production actually is. By dealing with a creative field as research object that seemingly employ more ephemeral and often heavily contextual knowledge compared to other disciplines, architectural research often fails to locate and describe any systematic element of architectural creation as well as it fails to establish any systematic research approach. Architectural research sometimes seems relegated to ideographic description and interpretation. But what about using a similar creative approach to architectural research itself? An introductory question here could be whether knowledge about architecture as both discipline and physical result can be produced through creative development and use of intermediary analytical models? – models as tools that help to articulate certain useful aspects and, as in architectural creation, crystallise as a synthesis of on the one hand the exposure of a (design)problem in question to various external conditions and on the other hand the architect's (or researcher's) vision for a solution. By, as a start, assuming that this is possible, this section exemplifies such an attempt in the present thesis and examines its possible perspectives. The approach is inspired by the concepts of *abduction* and *abductive reasoning* that can briefly be explained as the act of suggesting a

probable or satisfying hypothesis about what needs to be explained. Abduction thus implicitly addresses the question about how new knowledge can actually emerge and points towards a new (supplementary?) scientific paradigm for architectural knowledge production.

The objective here is thus to illustrate and discuss the particular approach, its possibilities, and its perspectives through its specific application as a method in the present research project. An assertion is that this method or elements from it is particularly well suited for architectural research by in several ways resembling the way the research object – architecture itself – is conceived through creative processes. Although architecture and knowledge *about* architecture is not the same and can have very different formats, architects and architectural researchers are often converging – in fact it is the most common! This could point towards the appropriateness of a certain degree of methodological convergence. In literature on (architectural) design research such activities are often explained through concepts like research for design and research through design as opposed to more commonly applied descriptive approaches dealing with research into or about design. In this case, the first concept in particular – research *for* design is brought into play. (See e.g. Archer 1995 or Frayling 1993) I will get back to a further discussion of this concept in relation to present research in a later paragraph in this section.

### **Outline**

Initially the concepts of abduction and abductive reasoning will be described as a general scientific paradigm for knowledge production. Abduction is here compared to the most prevailing way of explaining scientific knowledge production found in the concepts of induction and deduction. The main emphasis of the section is put on a procedural description of the research carried out – i.e. the method that has been applied in the specific project in order to develop an (intermediary) analytical model. Furthermore focus is put on the quality and the applicability of the particular kind of knowledge produced by such a method which is tentatively termed as ‘creative knowledge production’. Finally perspectives are discussed.

## ABDUCTION – SHORT INTRODUCTION

Science studies have, as pointed out by the contemporary Danish philosopher Ole Fogh Kirkeby, primarily dealt with questions of the validity and the explanative power of scientific theories. However the *conception* of scientific theories themselves is not a common scientific object of systematisation. How do scientific theories actually emerge? Although creativity has been studied in several occasions it is almost exclusively empirically as listing or classification of different techniques and behavioural patterns. The concept *abduction*, as used by the North American philosopher Charles Sanders Peirce, represents an attempt to make creativity within the sciences into an object of philosophical and scientific theoretical analysis (Kirkeby 1994:122).

Abduction was originally introduced by Aristotle as a third way of inference or leap of understanding parallel to the more widely referred concepts of deduction and induction. Peirce loosely interpret Aristotle's use of the term as including into science 'anything' that seems to make the world more rational while moreover accepting that the same facts can be explained in several independent ways (Peirce 1984:145f). There is in other words no *universal* explanation of real world phenomena. However, this is not the same as saying that science and knowledge are left with hermeneutics and phenomenological *interpretation* as the only way of producing knowledge about the world around us. In Peirce's own more specific definition abduction is '*the act of adopting a hypothesis that is suggested by facts*' (Ibid). Kirkeby clarifies this definition as consisting of examining a number of facts and allows these facts to '*suggest a theory*' (Kirkeby 1994:127) – but a hypothetical theory that that can then be used tentatively and needs to be tested and successively refined. The purpose of the hypothesis lies in its contingent empirical predictions – if they are all true, then the hypothesis is completely true (Peirce 1984:147). The hypothesis proposed through abduction can subsequently be tested theoretically through deduction as well as empirically through induction. But how can these different ways of inference be characterised and distinguished?

### *Three ways of inference*

Deduction is rule based. It is the act of applying a theoretical hypothesis or rule on specific instances in order to generate predictions (results). Through deduction the necessary or probable specific consequences of the general hypothesis

or rule are established theoretically. The reasoning goes from the general to the specific. Peirce uses the following example:

1 Rule: All the beans in this bag are white  
 Instance: These beans are from this bag  
 Result: These beans are white (Ibid:154)

Induction on the other hand is experience based. It is the act of generalising from the results of a number of specific (observed) instances into a general rule or hypothesis. Through empirical examination of reality (the perceived result of the instances) the experience enables the formulation of occurrences or probabilities of these occurrences (rules). The reasoning goes from the specific to the general:

2 Instance: These beans are from this bag  
 Result: These beans are white  
 Rule: All beans in this bag are white (Ibid:154)

Abduction, however, is experimentally based. The difference between the former ways of inference and the abductive inference is that the two former deal with the validation of already existing or available knowledge (inferring from specific to general or general to specific) whereas abductive inference deals with the generation of qualitatively new but uncertain knowledge in the form of a hypothesis. The abductive *reasoning* goes back and forth from a vague preconception of reality to observation of reality to the formulation of a preliminary hypothesis that can then be further tested and validated through deductive and inductive reasoning or modified through new abductive inference. Knowledge – although in the first case perhaps imprecise or even false – is generated through successive approximation by inferring from an intuitive synthetic guess to a satisfactory explanation:

3 Rule: All beans from this bag are white  
 Result: These beans are white  
 Instance: These beans are from this bag. (Ibid: 154)

In this example the content of a bag is examined and turns out to be full of white beans. Some white beans are found close to the bag and a reasonable guess (the hypothesis of the instance) is that these beans are from the examined bag.

Abduction is not an exclusive way of inference. Rather it supplements or precedes the two other more common ways. Thus, according to Kirkeby, an ‘ideal’ sequence for producing qualitatively new and validated knowledge would be abduction – deduction – induction which can then be reiterated for successive approximation of the proposed hypothesis (Kirkeby 1994). This sequence and approach is exactly what is tentatively followed and tested in the current research project.

## MODEL GENERATION AS ABDUCTIVE INFERENCE

Acknowledging the severe difficulties of presenting an abductive process in a linear manner – as in this case dictated by the text as media – the following paragraph however tries to describe the genesis of an analytical model inferred through abduction.

On the most general level the current research project examines systems in architecture. An ambition (i.e. a specified goal) in the current research is to develop a model that in a simple way can visualise the use of systems in architectural design. A building (an architectural work) and the process of erecting it is subsequently defined as a complex system of subsystems brought together in a given context at a certain point of time with a specific purpose (see above). The development of a model should describe these (sub)systems and their interrelations in this complex system, the building. However, as a minimum this still requires an initial definition of what a system or subsystem of a building is. This initial definition is in the first case inferred *abductively* from an explorative study of the project material related to a primary case study – *Cellophane House*<sup>TM</sup> by the architectural office Kieran Timberlake. The building was made as a full scale project for the exposition *Home Delivery* at The MoMa in New York City in 2008.<sup>16</sup>

### *Primary case study*

The primary case study had the purpose of generating a first draft for the model (see above) – a hypothesis about a *generally* applicable analytical model drawn from a *specific* analysis of an existing (although presently dismantled) architectural project.<sup>17</sup> By looking systematically at the different documentation produced before, throughout and after the erection of the actual building an unconventional material view of the building was established: the building

- 16 For a detailed presentation and analysis of this case see the Kieran Timberlake case analyses in Part IV ‘Model’.
- 17 The project was widely prefabricated and rather *assembled* than *built* on the construction site. Furthermore it was designed for disassembly potentially made for complete or partial reuse.



FIGURE I.5.1  
KIERANTIMBERLAKE'S SUPPLY CHAIN  
MODEL FOR CELLOPHANE HOUSE®

- 18 See the work plan in Appendix VI.6.A
- 19 To talk about a final building is intuitively easy to understand. It can however be problematic to conceptualise a building as something stable over time. In the current context we will not go further into this discussion and, at least provisionally, accept that such finished state of a building will exist for an amount of time.

as a node bringing different systems together. The documentation (the empirical material) included digital and analogue drawings and 3D-models, descriptions, press material and picture material (throughout and after production and erection). Furthermore, data collection included a factory visit and the accomplishment of a series of semi structured qualitative interviews with key persons involved in the different phases of the project. The case study was carried out extensively over a four month period working twice a week at the office and following a structured work plan.<sup>18</sup>

KieranTimberlake and the Cellophane House were chosen as a primary case for several reasons one of the most significant being their scope of interest which lies very close to the given frame of the current research project. The firm, a Philadelphia based architectural office, has been increasingly interested in new and more industrialised ways of creating architecture. They have thus worked both theoretically as well as with the practical implementation of such thoughts. In their publication 'Refabricating Architecture' (Kieran & Timberlake 2004) the construction industry and architectural creation within it is compared to other industries as car, boat and aeroplane manufacturing. The book argues for an architecture of *assembly* rather than of traditional construction. Instead of processing and adapting materials on-site in construction processes, buildings could alternatively, it is argued, be brought to the building site as larger off-site fabricated industrialised assemblies. In this scenario on-site processes are (ideally) limited to pure assembly. In e.g. the car industry each car is assembled through a series of tiers (a supply-chain) converting raw materials gradually into more integrated components ending in the finished car ready to use. A similar vision is forwarded for architecture. This leads, for KieranTimberlake, to an interest in how buildings can be divided into subelements or *systems* (author's stress) in different ways, how these systems (through supply chain tiers) can be integrated into larger units or chunks and, finally, how they interface with adjacent systems in the final building – through connection joints, system connections and closure joints (Ibid,101). This points towards a definition of systems in a building as physical systems and their related processes as they are *delivered* and inserted into a building. Systems in this definition of delivery will *always* contain physical elements that become a part of the final building.<sup>19</sup>

### Product architecture and system structure

Applying this system definition to the case material of the Cellophane House subsequently becomes a kind of *coding* into a number of systems (or deliver-



FIGURE I.5.2  
REMODELLED GENERAL SUPPLY CHAIN

ies) expressing the entire building and its coming into being as a simplified – or *focussed* – supply chain.<sup>20</sup> KieranTimberlake themselves use the term supply chain to describe the elaboration of a scheme of different suppliers and products in the Cellophane House™ project.<sup>21</sup> This scheme (see figure I.5.1) draws a distinction between on-site and off-site supply as the main differentiation of the deliveries. Each side (off-site/on-site) has a number of (tier 2) sub-suppliers delivering to a (tier 1) main supplier. Strongly inspired by this model a new version making a clearer focus on the *delivery* as system entity is elaborated. Stressing that *any* delivery at some point of time ends on-site the distinction on-site/off-site is replaced with one single supply chain of off-site deliveries ending in on-site delivery – the final building placed on the construction site (See figure I.5.2). Each sub-system (delivery) can have different degrees of integration and can be nested into other more integrated (prefabricated) deliveries before it arrives on-site and becomes inserted into the building.<sup>22</sup>

The visualisation of these systems of a building project in a model is tentatively termed the *system structure* of a building (see figure I.5.3). The system structure has clear references to what in the product industry is termed the *product architecture*. However, acknowledging the problem of using the word ‘architecture’ in this meaning of ‘structure’ or ‘organisation’ when dealing with architecture in the meaning of ‘architectural work’ and furthermore refraining from classifying architectural works and buildings as products, *system structure* seems a more appropriate term to use for this model. A distinction between product architecture and system structure could thus be defined in the following way: Product architecture refers to the structural organisation of an industrially manufactured *product* whereas the system structure refers to a *project specific* combination of various deliveries (being industrialised and/or manual) into a building i.e. an architectural work.<sup>23</sup> The visualisation provided by the suggested model should in the first place serve scientifically as a retrospective analytical tool for understanding the *system structure* of actual (executed) building projects. In a more developed form the model could potentially become a proactive design tool used both in architectural conceptual and design development phases.

### Generic model

The visualisation of the system structure of the primary case study, Cellophane House™, represents a first hypothesis about how to, in a useful way, visualise the use of systems in architectural design. A premise for the applied coding is

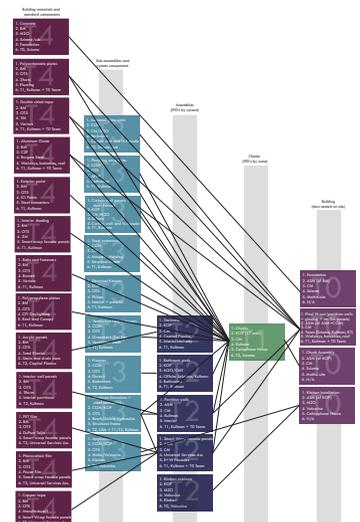


FIGURE I.5.3  
NEW CELLOPHANE HOUSE MODEL  
WITH TIERS AND CONNECTIONS

- 20 By ‘focussed’ is meant that it is not necessarily an exhaustive listing of all material flows but rather a ‘zoom’ showing parts and detailing relevant for the architect and for the architecture of the project in question.
- 21 The same kind of scheme has been applied to ‘Loblolly House’ - an earlier KieranTimberlake project. Loblolly House features as a secondary case study in the present research project. See *Model Presentation*, IV.1
- 22 A detailed description of the new model can be found in *Model Presentation*, IV.1
- 23 A formal definition of *system structure* can be found in *Systems Terminology*, II.5

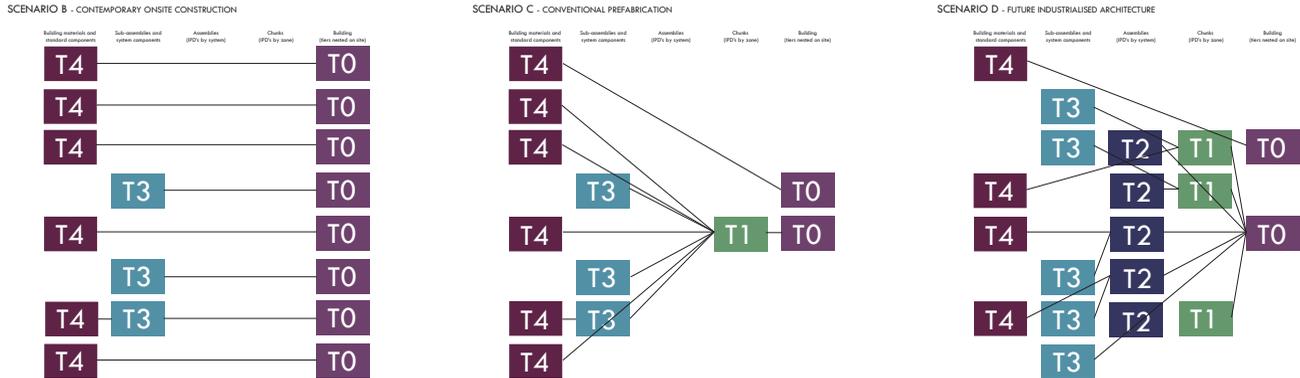


FIGURE I.5.4  
EXAMPLES OF THEORETICAL SCENARIOS

- 24 The different theoretical scenarios will be further introduced in IV.1 *Model presentation*
- 25 The *ideal type* is a theoretical construction meant to create the best possible conceptual clarity from a specific point of view. It is not a specific empirical representation of reality nor is it a normative model: However, it makes it possible to measure a distance between the the constructed ideal type and a segment of historical reality. (Author's translation from Andersen, Brande & Korsnes 1998)

the above definition of these systems as ‘physical systems and their related processes as they are *delivered* and inserted into a building’. From this initial visualisation the more general hypothesis of a *generic* model is inferred – a qualified guess of a useful model that ideally should be able to reflect the system structure of *any* building and differences between buildings being industrialised or not. Through deduction meant as theoretical application of the hypothesis, i.e. the model, to thought instances the generic model is used to produce a number of (theoretical) scenarios within the field of study – the industrialisation of construction vs. traditional ways of building. The theoretical scenarios (based on the thought instances) are: traditional onsite construction, contemporary onsite construction, conventional prefabrication and future industrialised architecture. The different theoretical scenarios display considerable variation in system structure and suggest possible explanative power of the model.<sup>24</sup> The theoretical scenarios can be characterised as a kind of ideal types in the classical definition of the sociologist Max Weber.<sup>25</sup>

Subsequently inductive inference is used. The generic model is empirically tested on a number of secondary cases as analyses of the system structure of recently finished building projects with supposed similarity with the theoretical scenarios as mentioned above. Due to the qualitative character of these analyses and the limited number of secondary cases, representativity is not a primary concern. The focus is rather on an explorative exposure of the model (as hypothesis) to qualitatively different situations in order to see whether it sustains explanative power. Tentatively the secondary cases also introduce the view of different stakeholders i.e. the manufacturer, the contractor, the integrated consultant and the architect in order to see if and how it makes sense to use the same model from different perspectives (different foci). Important to state is that the data findings in the secondary case studies and their analyses are in active dialogue with and possibly modify the model. In the case the model is found partly or fundamentally inadequate to express relevant findings or aspects of the secondary case studies, it can be iteratively improved. By this step we return to an abductive reiteration of the model as successive approximation towards a satisfactory explanation. The ‘ideal’ sequence, as described by Kirkeby (see above), of abduction, deduction and induction is completed and closes in an iterative loop that gradually increases the quality and applicability of an analytical (intermediary) model. Both the model itself and the outcome of its application on specific cases produce, it is claimed, qualitatively

new knowledge in the form of a tool or a language to help describe and handle the structural complexity of any building through the concepts of (sub)systems and system structure.

### **Applicability**

The system structure introduces and offers simplified and focussed visual access to the complex web of processes of production, construction and/or assembly by focussing on deliveries as a relevant system parameter or entity in the architectural design process – independent of whether these deliveries are industrialised or not. The concept of system structure enables an understanding of, and potentially a more conscious decision making concerning how, architectural concepts can be turned into specific building projects – how they are or can be *produced*. This seems to be relevant in the present context – as described in the general introduction of the thesis – where the construction of buildings increasingly become assemblies of industrially produced integrated product deliveries that no longer correspond directly to any of the traditional and established crafts. Examples of these integrated product deliveries are: integrated façade solutions, prefabricated bathpods, integrated partition wall systems or other emerging system products in construction.<sup>26</sup> However, the model is not exclusively a tool for describing an architecture based on industrialised deliveries. As *any* physical delivery can be expressed (manual or industrialised – off-site or on-site) the model can visualise buildings as combinations of more or less industrialised deliveries, their degree of complexity or integration and their combinations, interrelations and nesting into each other in a supply chain always ending on the construction site and in the final building.

<sup>26</sup> For further examples, refer to Part III – ‘Product’

## CREATIVE KNOWLEDGE PRODUCTION

This paragraph returns to the question of what research and knowledge production is within architecture and how the sketched application of an abductive approach and the resulting model can be located within this discussion as what is termed as *creative knowledge production*. According to Archer, who is specifically dealing with the question of research and knowledge production within the arts (i.e. architecture), research can in a general sense be defined as ‘*systematic enquiry whose goal is communicable knowledge*’. By systematic is meant ‘*pursued according to some plan*’, by enquiry ‘*seeks to find answers to questions*’, by goal that ‘*objects of the enquiry are posed by the task descrip-*

27 See *Project grant description* (in Danish) in Part VI – 'Appendix' on enclosed CD

tion', by knowledge that '*findings [...] go beyond providing mere information*' and by communicable that '*findings must be intelligible to [...] an appropriate audience*' (Archer; 1995:6). Using Archer's classification, I try below to relate these aspects to the model and its genesis.

#### **Communicable knowledge**

The current research project is *pursued* according to a predefined research plan originally defined through an externally elaborated document used for a grant application. The document describes in general terms the background, the overall purpose, the main question, and the methodological approach in the project. The approach was stated to be primarily case based and the project is supposed in itself to be generating new theory and model(s) within the predefined research area – system design, systems thinking and building concepts in modern industrialised construction.<sup>27</sup>

The project *seeks to find answers to the question* of: how systems and systems thinking can help bridging the gap between architectural ideation and contemporary industrialised construction – and the *objects of the enquiry posed by the task description* (i.e. the goal) become to propose an analytical structure for clarifying the potential of industrialised construction as positively enabling rather than limiting architectural solution space. This is interpreted as the development of a tool or a model thus referring to the case based model generation stated as methodological approach (above). In this sense, the project seeks to be dealing simultaneously with the development of a (research) method, with an analytical model and with the understanding of a specific research area – the latter being obtained partly through the two former.

Concerning whether *findings go beyond providing mere information*, the elaboration of the model should, if it to some point can be considered useful, make a distinction from mere information by enhancing the understanding of industrialised production scenarios in architectural construction. The model provides a new (supplementary) language for conceptualising architecture while *simultaneously* relating this conceptualisation to the way – or the different ways – in which the architecture can be realised or produced as real world objects. The findings, of e.g. the analyses, expressed with the model as media are intended to *be intelligible* to the architects as *an appropriate audience* or primary target group that, as stated in the general introduction, apparently lack appropriate tools to create the necessary but increasingly complex synthesis of the different

knowledge systems involved in construction processes and bridge the apparently increasing gap between ideation and realisation. This synthesis is perhaps only of *professional* concern for the architect, but indirectly concerns everybody in the sense that architecture deals with the creation of the best possible frames for human life. An assumption is that the model as a simplified (or focussed) *visual* tool provides an intermediary link between the more abstract architectural concepts and specific physical deliveries with different levels of standardisation, integrations and industrialisation. With a capacity of reducing complexity in focus the model bridges the gap between how architecture is conceived and how it is or actually can be produced.

### **Research starts as guesswork**

The argumentation above is not meant as a proof of actually doing true research. It simply tries to follow an external line of reasoning in order to discuss the research aspect of the applied approach and to make the project conditions and their operationalisation accessible to the reader. Archer's point is that there is '*more than one way of defining research*' and that this is expressed through availability of several traditions (Archer 1995:6). Referring to the Austrian-British philosopher of science, Karl Popper. He states that a modern approach to scientific research acknowledges '*that new scientific propositions may properly be, and mostly are, the result of inspired guesswork rather than the product of inductive reasoning*' (Ibid) This points towards Peirce's abductive reasoning that '*suggests a theory*' which is subsequently tested and refined through successive approximation by inferring from an intuitive synthetic guess to a satisfactory explanation. (see above). Archer presents the following (ideal) sequence for producing new knowledge:

- 1) be liberal about the sources of conjecture and hypothesis at the commencement of research
  - 2) be sceptical in the handling of data and argument during research and
  - 3) be astringent in testing findings and explanations on the completion of research
- (Archer 1995:7)

Archer's summary of this modern philosophy of creating new knowledge has obvious parallels to Kirkeby's Peirce-interpretation of the ideal sequence for producing new and validated knowledge (abduction – deduction – induction, see above).

28 This last step is however beyond the direct scope of the current research framework.

### *Validation and reliability*

Archer's specific objective is, within the arts, to distinguish explicit scientific knowledge from the tacit knowledge produced through artistic practice itself – e.g. architectural practice. In most cases artistic practice cannot be characterised as '*a systematic enquiry whose goal is communicable knowledge*' as defined above. Practice is not research in itself just because it produces new knowledge. Although convergence between practitioner activity and research activity (research through practice) is possible through what he terms as '*action research*' (ibid:12) he equally distinguishes between two other relationships between the research object and the research method in the arts (i.e. architecture) which are: research *about* practice and research *for the purpose of* practice. The former, research about practice, is far the most widespread and often draws on well established research traditions in order to validate research findings. Examples are art or design history within humanities or art and society studies within the tradition of social sciences. The second type, research for the purpose of practice, is slightly more problematic concerning the validation of scientific knowledge. However he states that:

” *Where an investigation for the purposes of contributing to a practitioner activity is conducted according to the principles of its field, and is indeed a systematic enquiry whose goal is communicable knowledge, then the investigation can properly be called research.*

(Archer 1995:12)

I have above tried to describe how the current project can be classified as proper research using Archer's concepts. This research would in Archer's terminology be classified as research *for the purpose of* practice in the sense that the goal – the model – is essentially a tool to be used for enhanced understanding and potentially be developed into a proactive supportive design tool for early design phases.<sup>28</sup> In a PhD-thesis like the present work the question of validation is of course highly relevant due to the fact that apart from delivering a substantial contribution to knowledge, a PhD-thesis should also show the students capacity to apply principles and practice of research methodology. However, if knowledge is *exclusively* produced for the purpose of a practitioner activity the question of validation is less pressing – and can in some cases even become redundant. As Archer writes:

” *In the case of research for the purposes of a practitioner activity, however, there may be circumstances where it does not matter whether the research was well done or badly done, or whether the research results turned out to be true or false, or whether the findings were situation-specific or generalisable. It may be sufficient to demonstrate that the practitioner outcome itself is satisfactory.*

(Archer 1995:12)

We are here back to Peirce’s loose interpretation of Aristototele’s use of the concept of abduction as including into science ‘anything’ that seems to make the world more rational. The production of qualitatively new scientific knowledge does seem to require some sort of creativity which in itself is hard to validate. This does not necessarily challenge the question of validation later in the process – at least if we limit the meaning of validity to ‘satisfactory’ or ‘useful’. On the other hand qualitative research, as the present model development, has the advantage of bringing in a more holistic view which actually can enhance the overall validity. Here quantitative research with its (intentionally) limited view runs the risk of applying models or methods that are far too simplified or controlled to actually produce valid explanation on real world phenomena which is often complex and contextual.

The question of reliability is more problematic. Reliability refers to whether the tool or method used to measure or explain a certain phenomena actually is sufficiently reliable so that e.g. repeating the same procedure would always produce the same result. The creative element in abductive reasoning introduces the subject as a factor influencing the result thus making less probable that another subject would come up with exactly the same results – in this case the same model or the same coding of a particular case study within the model. This is a fundamental issue in qualitative research where the question of reliability in some cases is handled by correlating or merging the results or codings of various individuals or by *triangulation* where several parallel methods are used to reach a result.<sup>29</sup> Using Archer’s terminology within the current project it is rather by trying to be ‘liberal about the sources of conjecture and hypothesis at the commencement of research’ that reliability is sought handled in the first case.<sup>30</sup>

#### **Meta knowledge and specific knowledge**

What is here described as creative knowledge production through the development of an intermediary model has two levels. On the one hand the model

29 See e.g. [http://en.wikipedia.org/wiki/Triangulation\\_\(social\\_science\)](http://en.wikipedia.org/wiki/Triangulation_(social_science)) accessed on April 5, 2011

30 For an extended but simple explanation on validity and reliability see [http://www.emu.dk/gym/fag/ps/inspiration/kursus/feltarbejde/reliabilitet%20og%20validitet\\_x.pdf](http://www.emu.dk/gym/fag/ps/inspiration/kursus/feltarbejde/reliabilitet%20og%20validitet_x.pdf) as accessed on April 5, 2011

itself is a kind of meta knowledge in the way that it as a tool or a language – a specific look on a building – enables access to the – on the other hand – project specific knowledge that become visualised through the application of the model. But the model is at the same time created through the use and synthesis of this project specific knowledge it describes. This knowledge is initially data from the primary case study – the Cellophane house – and subsequently the data from several secondary cases. The analyses of the secondary cases, by use of the model, have exposed it to these which have again modified the model. The relation between tool and material become a mutual dialogue with the aim of creating satisfactory or useful knowledge rather than universally true knowledge. The systems theorist, Donella H. Meadows, argues that any model used to describe real world phenomena must have specific point of departure in the reality it seeks to model (Meadows 2008). The assertion in this project is that exactly the creative development of the intermediary model with initial point of departure in an industrially thought architectural work, the Cellophane House, provides for good base for explanative power of these aspects within *any* architectural work. This is however not to say, that general knowledge can be drawn directly from a single incident. Abduction requires subsequent successive approximation. It is my hope that the model can be brought to a level of both generality *and* simplicity that makes it attractive for others to apply it – and possibly modify it!

## PERSPECTIVES

The approach described above suggests through a specific research example the establishment of a special scientific tradition within architectural research based on the general type research *for or for the purpose of practice* – a new paradigm for architectural research based on abductive reasoning. Acknowledging the simultaneously creative and context specific nature of the object of research – architecture itself – it is proposed that scientific knowledge production within this field could be based on similar creative and context specific principles. Architecture as practice is inherently synthesising and cross disciplinary. By using the same principle when dealing scientifically with the field, the actual applicability of this knowledge in the practical field seems more likely. The approach does not exclude the appropriateness of other approaches when it comes to research into/about practice (architecture) or research through practice.

The model developed through the approach does, as a kind of meta-knowledge, not dictate a certain *ideal* way of creating a system structure of a given building. Neither does it promote that this system structure should primarily be based on more integrated product deliveries. Rather it has point of departure in an observed tendency within construction and creation of architecture that it seeks to describe. Through the meta-knowledge synthesised in the model a new or emerging field of knowledge is articulated and structured and thus made accessible as a (supplementary) aspect in the creation of architecture. The present research seeks this way, as mentioned above, to deal simultaneously with the development of a (research) method, with development of an analytical model and with the understanding of a specific research area. Although outside the framework of this thesis, the ambition is to develop the model into a more proactive and more directly design supportive tool applicable from the early design phases, where different production scenarios result in different system structures. Each of these will have specific advantages and drawbacks seen in a holistic and synthesising perspective that includes both functional aesthetic, economical, time and technical aspects that all have influence on the architectural quality of the final result.

It is however important to underline that the use of such a second generation system structure model never in itself can ensure high architectural quality. The model is just proposed as *one* tool among others that in the hands of a qualified architect and/or integrated project team can *support* decision making early in the architectural design process and thus counteract problems of ‘translation’ between architectural concepts and final architectural result. The model potentially *contribute* to or *provides* for higher architectural quality. In a context where the creation of architectural artefacts changes rapidly partly driven by new technological possibilities (pull), partly forced by external factors<sup>31</sup> (push) the model is proposed as a tool to help describe and handle the structural complexity of any building through the procedural and material organisation behind their immediate appearance.

- 31 Economical, ecological, organisational factors, power relations, decline of the old crafts a.o.



# PART II

## SYSTEM

- II.1 SYSTEMS IN ARCHITECTURAL THEORY
- II.2 CLASSIFICATION SYSTEMS IN CONSTRUCTION
- II.3 INDUSTRIAL PRODUCTION THEORY
- II.4 GENERAL SYSTEMS THEORY
- II.5 SYSTEMS TERMINOLOGY FOR ARCHITECTURE  
AND CONSTRUCTION



## PART II – ‘SYSTEM’

The problem area and the scope of present thesis point out some circumstances formulated as a general hypothesis of a gap between architectural ideation and contemporary industrialised building production and construction. In the following two parts this hypothesis is examined, substantiated and discussed through both a theoretical and a practical exploration. These explorations correspond to respectively Part II – ‘System’ and part III – ‘Product’ of the thesis and will be addressed through a number of sub-questions. Finally the main hypothesis is (partly) sought met in the *system structure model* found in part IV – ‘Model’ of this thesis.

The present part, part II – ‘System’, forms the theoretical backdrop of the thesis. Through five sections it examines and evaluates on systems theory and systematic thought applicable in the thesis in the form of a scanning within different fields of knowledge and a concluding attempt, on basis of the findings in these (system) fields, to establish a consistent terminology for the thesis as well as in the general discussion of systems thinking in architecture and construction. With outset in existing knowledge and theory, the overall objective of the thesis is to look into the empirical reality of building construction from a systematic frame of reference – to look upon architecture and architectural creation as a system of constituent parts, elements or subsystems. The sections are the following: 1. Systems in architectural theory (II.1), 2. Classification systems in construction (II.2), 3. Industrial production theory (II.3), 4. General systems theory (II.4), and finally 5. Systems terminology for architecture and construction (II.5).

The five sections do not form an exhaustive evaluation of systematic elements found within the different fields. They rather offer a number of examples through a selection of different ways of approaching architecture and other complex fields from a systematic frame of reference. This is meant to work as a short ideographic contribution within each field as well as a source of inspiration for how the present thesis may contribute to a more systematic approach to architecture and architectural creation in particular – or less pretentious: contribute to a clarification of the *perspectives* of such a systematic approach to architecture. Each section advances a hypothesis derived from the main question and goal of the thesis that subsequently leads to one or two research questions examined within the particular fields.

## II.1 SYSTEMS IN ARCHITECTURAL THEORY

### INTRODUCTION

First of all, it evidently becomes important to have a look at how architectural theory historically has dealt with architecture and architectural creation as a system or a compound of subsystems. What has been subject to classification and categorisation, why or with what purpose, and finally how has it been approached? The following section looks into how architectural theory has treated the theme of systems and systems thinking. Through a number of examples from architectural theory a collection of points will be extracted in order to be used in the later parts of the thesis – or (perhaps) avoided as apparent blind alleys.

#### *Hypothesis and questions addressed*

A gradually growing division has appeared between on the one hand how architecture is conceived as design (conceptual idea and form) and, on the other hand, how it can actually be produced (construction)

The hypothesis is addressed through the following two research questions:

- a) What are the main constituent 'elements' of architecture as expressed in architectural theory?
- b) How can the apparent division between design and production/construction be substantiated and explained through architectural theory?

### THE CONSTITUENT ELEMENTS OF ARCHITECTURE

Any theory can be seen as a systemisation or a structure of thought. However, it is not just a systematisation of architectural thought we are looking into here. The object of systemising the theoretical categories should furthermore address some kind of basic elements of the architecture it seeks to describe.

These theoretical categories, or basic elements, can present considerable variation in nature according to the different theories or systems they circumscribe. These can e.g. be about aesthetics/proportion, form/geometry<sup>1</sup>, function, material, construction, technology, typology, psychophysical laws<sup>2</sup>, social, cultural or economical issues or combinations of these into a coherent whole. The selected examples represent several kinds of these basic elements. It could be said that the character of the constituent elements of architecture within the different systems varies and that this variation to some degree reflects the *purpose* of the theoretical system in question.<sup>3</sup> The historical context equally has importance for the individual theoretical systems and their basic elements and they consequently have to be related to this context. A strongly religiously dominated society as present day India or Central Europe during the Middle Age probably produce other architectural systems and appurtenant elements than a very secularised or technocratic society as present day Germany or the former Soviet Union. Theories and elements have cultural foundation. The theoretical system and its constituent elements make up a ‘language’ or syntax that makes it possible to talk about (or create!) architecture and buildings in a particular way. However, this also means that a theoretical system of elements cannot be neutrally descriptive even if this is initially the intention. This is e.g. pointed out by *Critical Theory* that claims that all science has a normative standpoint. Consequently, the knowledge it produces must be held critically up against this standpoint. This on the other hand makes it possible to pose the same general demands of clarity of argumentation, coherence of the argument and documentation for all sciences – natural, humanistic and social.<sup>4</sup> The particular architectural systems or theories must be seen both as supporting as well as supported by and originated through architectural practice and the cultural setting it forms part of. Architectural theory always oscillates between being reactive and proactive.<sup>5</sup>

“[...] there is a certain ambiguity in the influence on theory on built architecture. It can lay down norms which make it almost impossible to produce really bad architecture; at the same time, making aesthetic conventions normative can stifle, or at least hamper creativity.”

(Kruft:1994:17)

The scanning of architectural theories have been limited to a Western perspective while being conscious that e.g. Asian architecture and architectural philosophy deal extensively with the same questions.<sup>6</sup> Located in and primar-

- 1 In Boullée’s and Palladio’s theories form can be seen as the main subject of an autonomous architecture (see e.g. Hartoornian:1996:15)
- 2 Ladowsky (in Kruft 1994) has this angle – It will however not be followed further in present thesis.
- 3 By *purpose* is referred to in what context, from what worldview, and with what aim the has theory emerged.
- 4 *Critical Theory* has roots in the ‘Frankfurt School’ of social sciences. See e.g. (Andersen et al. 1998)
- 5 See e.g. Kruft 1994:16
- 6 By the broad term ‘Asian’ I primarily refer to Chinese and Japanese systems of architectural thought

			Vitruvius – approx.	84 BC-15 BC	Descriptive rules of proportion, relational standards
			St. Augustine/Boethius	4th & 5th century	Form as a result of number
			Villard de Honnecourt and others	13th century	Lodge-books - architectural drawings, applied architecture
			Leone Battista Alberti	1404-1472	Proportion dictated by nature, six elements of build matter
			Sebastiano Serlio	1475-1553	Practical rules for average person reduced to (five) orders
			Andrea Palladio	1508-1580	Geometry as the basis of all architectural rules, typologies
			Fray Lorenzo de San Nicolas	1595-1679	The concept of truth to materials
			Claude-Nicholas Ledoux (+Boullée)	1736-1806	Architectural system reflects the social order and educates
			Jean-Nicolas-Louis Durand	1760-1834	Grid system of composition, standardisation, metric sys
			Louis-Ambroise Dubut	1769-1846	Utilité – first functionalism and historicism
			Percier/Fontaine	1764/62-1838/53	Local climate, materials and aesthetics, structure/ornament
			Henri Labrouste	1801-1875	Abolition of classical norms, func/hist/cult/reg architecture
			Gottfried Semper	1803-1879	Four elements of architecture connects to crafts & material
			Viollet-le-Duc	1814-1879	Praise the gothic (rational, democratic, expr soc structure)
			Auguste Choisy	1841-1909	Arch as present building technology, module systems
			Sant'Elia	1888-1916	No decoration, beauty in lines and plasticity, not durable
			Malevic (+constructivists)	1871-1935	Right angle – just form, no construction nor function
			Ladovsky	1881-1941	Psychotechnical laboratory experiments => arch form
			Le Corbusier	1887-1965	Architecture as a machine for living, modolor
			Terragni (+Grupo 7)	1904-1943	Strict logic, rationality, type, mass production
			N. John Habraken	1928-	Open building, adaptability – supports and infill (system)
			Christopher Alexander	1936-	Synthesis of form, pattern language – grammar for arch
			Bill Hillier	(1984/1996)	Space syntax – social logic of space and configuration

FIGURE II.1.1  
TIMELINE OF CONSTITUENT ELEMENTS  
OF ARCHITECTURE IN ARCHITECTURAL  
THEORY

- 7 See *Definition of Scope*, I.4
- 8 Unrecorded practice is evidently not retrospectively accessible.

ily dealing with a Western and Northern European cultural environment the choice has been to concentrate on architectural theory embedded in this context. The presentation does, as mentioned, partly limited by the scope of the current research not form an exhaustive overview of systems in architectural theory but rather looks for inspiration that nurtures the specific goal of the thesis which is to propose an analytical structure or a model.<sup>7</sup> The selected examples can subsequently not be considered as a historical presentation describing an evolution step by step. The risk of some fragmentation or arbitrariness in the selection of examples is accepted as a condition within the current scope and extent of the task.

Concerning the first paragraphs of the section, Hanno-Walter Kruft's '*A History of Architectural Theory from Vitruvius to the present*' has mainly been examined and his definition of architectural theory approached as an historical review adopted (Kruft 1994). For practical reasons Kruft restrains his review on architectural theory to written sources thus excluding highly ambiguous analyse and interpretations of buildings themselves or unrecorded practice.<sup>8</sup> Pattern books primarily based on illustrations with some text are also included in his review. All built architecture is based on some kind of principles – a systematic level of thought that could be generalised into a theory or a philosophy of the architecture in question. This does however not mean that these principles are articulated or can be reconstructed (in a written or build form) as they were conceived. Buildings do not necessarily, and only rarely in an unambiguous form, reveal the *architectural* systems behind their physical manifestations (ibid:13). Hence the focus on the written sources. Kruft states that: '*The majority of programmes that purport to be theories of architecture seek to combine aesthetic, social and practical considerations in an integrated whole*' (ibid:14) and then proceeds to a definition of architectural theory as '*compris[ing] any written system of architecture, whether comprehensive or partial, that is based on aesthetic categories. This definition still holds even if the aesthetic content is reduced to the functional [categories]*' (ibid:15). From a different slightly en-



FIGURE II.1.2  
ROBERT VENTURI'S WORKS ARE EM-  
BLEMATIC FOR THE POSTMODERN MO-  
VEMENT. HERE A HOUSE BY VENTURY  
AND RAUCH IN 1962

hanced view the same could be the case even for architectural systems based on many other types of basic elements, as exemplified above. Figure II.1.1 shows an initial scanning of system elements in architectural theories, each with a couple of keywords.

Much of the classical architectural theory deals with the search for universal laws or guidelines concerning what is considered to be 'true' physical form. The logic of the system prescribes or suggests a certain combination of its constituent elements for a given situation. In modern architectural theory the content in some cases become more political or critical of the society it forms part of. Suddenly it deals less with controlling the built form and its aesthetics and is more about the role of architecture as a society forming and transforming force. Through a kind of transcoding or rewriting of systems of thought from other (philosophical) fields and disciplines into architectural code, architectural theory and architecture itself participate in the general cultural and political debate of society. The modernist movement e.g. tries to reconcile or mirror architectural design with the rapid technological advancement in society as expressed in Le Corbusier's architecture as a '*machine for living*'. In the case of e.g. *postmodernism*, the parallel philosophical 'fall' of the big ideologies on the other hand produces an interest in purely abstract form or eclecticism, where the coherence of the work is created as unique narratives that draw simultaneously on many different theories or historical references without any coherent system – or as the American architect and theorist who consolidated the term, Charles Jencks writes:

“*It can include ugliness, decay, banality, austerity, without becoming depressing. It can confront harsh realities of climate, or politics without suppression. It can articulate a bleak metaphysical view of man – Greek architecture or that of Le Corbusier – without either evasion or bleakness. The extraordinary power of tragedy when it is really tragic, or inclusive architecture when it really unifies disparate material, is its disinterested fulfilment*”

(Jencks IN:Hays 2000:309)

In short, systems in an architectural context are to some extent always representing a certain time, societal situation and stage of technology.

## VITRUVIUS AND ANTIQUE ARCHITECTURAL THEORY

Vitruvius' (84-15 BC) ten books represent the first preserved architectural theory. Others are known to have existed but have been lost. However, Vitruvius was the first to cover the entire field of architecture in a systematic form (Kruft 1994:21). About the aim of his effort Vitruvius writes: '*I have drawn up clearly defined rules, so that by studying them closely you will be able to judge for yourself the quality of the buildings you already created and of those to come, for in these books I have laid down the principles of architecture*' (Vitruvius cited in Kruft 1994:23 – author's emphasis).

### *Building principles*

Vitruvius introduces the famous concepts of *firmitas*, *utilitas* and *venustas* – durability, convenience and beauty (Vitruvius, book I, chapter III). This triad roughly divides architecture into aspects of respectively construction (i.e. good foundations and materials), spatial distribution (i.e. proper arrangement and type), and aesthetic qualities (i.e. good taste and correct proportions). This is to be reached through the fulfilment of six fundamental principles (not necessarily presented in the most logical order!):

Order	Gives measure and detailed proportioning of each separate part of a building and relate this to the general proportioning of the building as a whole (= symmetry, below)
Arrangement/disposition	Is dealing with the overall layout and the positioning of the different parts in their proper place (in plan, elevation and perspective) according to the character (type) of the work.
Eurhythmy	Is the resulting beauty and fitness of the order and symmetry
Symmetry	Treats the interrelation between the different parts of the building and their relation to whole by reference to a (chosen) standard unit of measure.
Propriety/décor	Is the correct appearance based on approved elements or principles from precedent. The use of e.g. orders comes under this heading and points beyond mere aesthetic rules to conventions of different types and their use.

Distribution/economy Is about the construction management i.e. selection of materials and cost control as well as choosing a level appropriate to the class of the client and the type of the building

Vitruvius' six principles are primarily addressing the concept of beauty from the triad above and centres particularly around the principle of symmetry and the subordinate concept of proportion as the heart of his treatise: *'There is nothing to which an architect should devote more thought than to the exact proportions of his building with reference to a certain part selected as standard'* (Vitruvius, 6.2). Through symmetry and proportion Vitruvius establishes relational standards as opposed to absolute standards.

As an analogy of symmetrical proportions that are to be found in the design of e.g. temples Vitruvius uses the body, where each element or member according to him has its specific proportional relations to other parts and to the body as a whole:

“*For the human body is so designed by nature that the face, from the chin to the top of the forehead and the lowest roots of the hair, is a tenth part of the whole height; the open hand from the wrist to the tip of the middle finger is just the same; the head from the chin to the crown is an eighth, and with the neck and shoulder from the top of the breast to the lowest roots of the hair is a sixth; from the middle of the breast to the summit of the crown is a fourth. If we take the height of the face itself, the distance from the bottom of the chin to the underside of the nostrils is one third of it; The nose from the underside of the nostrils to a line between the eyebrows is the same; from there to the lowest roots of the hair is also a third, comprising the forehead. The length of the foot is one sixth of the height of the body; of the forearm, one fourth; and the breadth of the breast is also one fourth. The other members too have their symmetrical proportions, and it was by employing them that the famous painters and sculptors of antiquity attained to great and endless renown.'*

(Vitruvius Book III, Ch I)

For temples however the specific proportions specified also depend on what style or class they are to be. Most known are what should later become the established orders of columns but other details as the doorways are equally

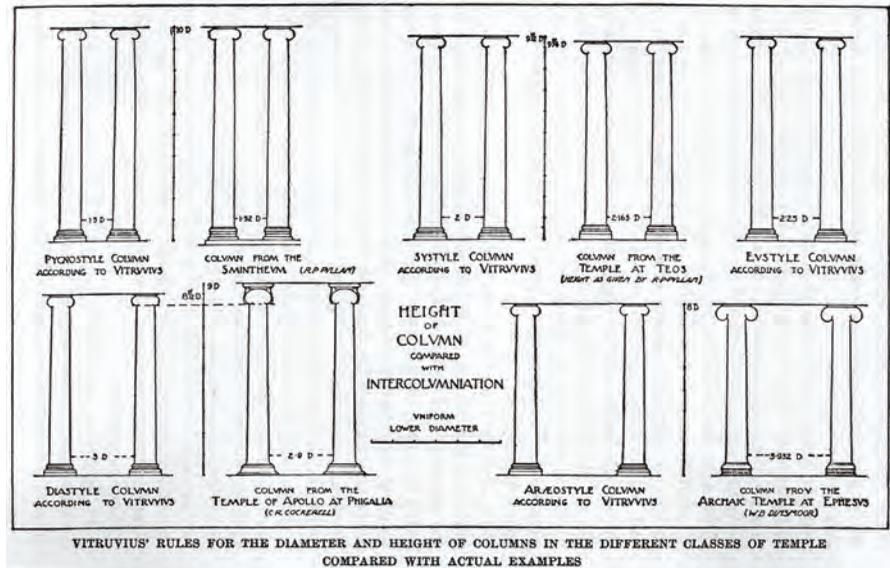


FIGURE II.1.3  
VITRUVIUS' RULES FOR THE DIAMETER  
AND HEIGHT OF COLUMNS IN DIFFE-  
RENT CLASSES OF TEMPLES COMPA-  
RED TO ACTUAL EXAMPLES



FIGURE II.1.4  
PANTHEON – EARLY MODULAR AR-  
CHITECTURE!

specified in relation to the whole and concerning its internal proportions (order and symmetry = eurhythmy):

“*In the Doric [doorway], the symmetrical proportions are distinguished by the following rules. Let the top of the corona, which is laid above the casing, be on a level with the tops of the capitals of the columns in the pronaos. The aperture of the doorway should be determined by dividing the height of the temple, from floor to coffered ceiling, into three and one half parts and letting two and one half thereof constitute the height of the aperture of the folding doors. Let this in turn be divided into twelve parts [...]*”

(Vitruvius Book IV, ch VI)

Much of Vitruvius theory was based on (rough) generalisations of empirical evidence but even though he explains the emergence of rules as evolving from man’s ‘*vague and uncertain judgements to fixed rules of symmetry*’ he also gives them absolute validity (Kruft:1994:24). The British historian, John Ward-Perkins relates the nature of Vitruvius’ concept of symmetry and proportion directly to an architecture of the time based on modular thinking as e.g. the Pantheon in Rome.

“*The type of rules about the application of proportions that fills the pages of Vitruvius’ [ten books] arise naturally in an architecture that depends, for its execution, on the use of multiple fundamental units, or modules, or its simple derivations.*”

(Author’s translation of Perkins 1989:88)

### Building types

Vitruvius also establishes *functional* categories or standards of building types. Apart from clock making and construction of machinery which Vitruvius considered as separate branches of construction, buildings are divided into two general types: Public facilities and private buildings. Public buildings are then subdivides into three (functional) classes: defensive, religious and utilitarian. The latter includes e.g. harbours, markets, colonnades, baths, theatres, promenades (Book I, Ch III) (See figure II.1.5)

In his detailed treatment of the individual building types Vitruvius does not strictly follow the fundamental concepts or relational standards that he claims

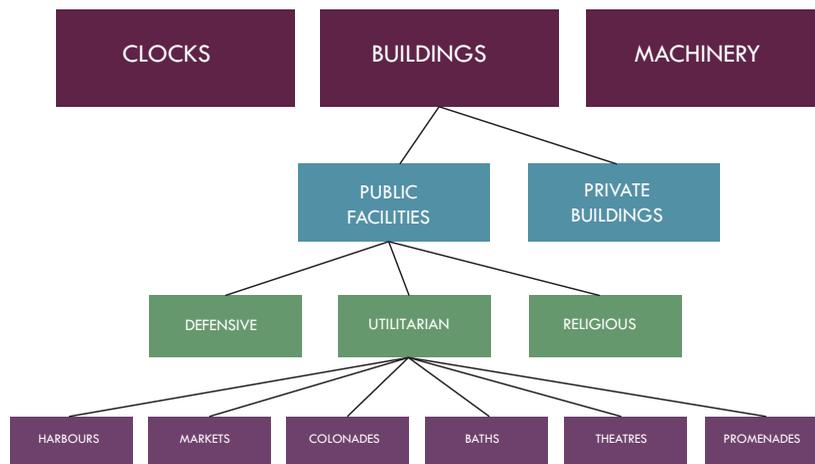


FIGURE II.1.5  
EXAMPLES OF VITRUVIUS' FUNCTIONAL  
CATEGORIES IN CONSTRUCTION

to be universally binding (Kruft 1994:28). There is no systematic connection between the relational standards and the functional standards established. However, from the renaissance and on interpretations of his work has exerted enormous influence on built architecture.

## THE RENAISSANCE AND ALBERTI

According to Kruft the middle age produced no architectural theory on its own (ibid:40). Neither did Vitruvius' system have any significance in this period. Some, as St. Augustine (354-430 AD.) and Boetius (480-525 AD.) promoted with outset in Pythagorean, Platonic and Neoplatonic philosophy '[t]he importance of number as the principle underlying cosmic order [...]' (Ibid:36) and developed a system of aesthetic based on numerical proportion that also influenced architectural expression.

The writings of Leone Battista Alberti (1404-1472) is considered one of the most significant contributions to architectural theory ever (ibid:49). Vitruvius, although claiming absolute validity, de facto was mostly *descriptive* about how buildings up to his time *had been* built. Alberti further develops the antique tradition and is *prescriptive* about how buildings *should be* built (Alberti/Rykwert 1992:x and Kruft:1994:44). Heavily drawing on ideas and concepts by Vitruvius, Alberti also present his work *De Re Edificatori* – on the art of building – in ten books. About his aim Alberti writes: '[...] *We have undertaken [...] to inquire more fully into his (the architect's, ed.) art and his business, as to the principles from which they are derived, and the parts of which they are composed and defined*' (Alberti 1992:5)

### *Building principles*

Alberti adopts Vitruvius basic triad of *firmitas*, *utilitas* and *venustas*<sup>9</sup> but further develops their underlying principles in separate books (of the ten) – still, as his predecessor, giving primacy to beauty over function and durability. *No better way can a building be protected and preserved as through the beauty of its appearance* (ibid:156). Ornament, however, is only a complement to his definition of beauty which is a much broader concept dictated by *concinntas* – the absolute and fundamental rule (of beauty) in Nature. A building is conceived as a body of lineaments and matter. The former (as lines and angles) being product of thought whereas latter (in form of building materials) is obtained

9 *What we construct should be appropriate to its use, lasting in structure and graceful and pleasing in appearance*' (Alberti 1992:155)

from nature. Lines and angles define and enclose the surfaces (of material) in order 'to prescribe an appropriate place, exact numbers, a proper scale and a graceful order for whole buildings and for each of their constituent parts [...]' (ibid:7) The form and the beauty of it is in Alberti's definition detached from the material and its properties which – in some cases – apart from ensuring firmitas become a supplementary ornamental layer (ibid:163). The analogy to mathematical values as found in nature and natural organisms in the definition of beauty as sets of relational standards of proportion is similar to Vitruvius.

” *‘[The ancestors] realized that numbers were either odd or even; they employed both, but the even in some places, the odd in others, Taking their example from Nature, they never made the bones of the building, meaning the columns, angles and so on, odd in number – for you will not find a single animal that stands or moves upon an odd number of feet. Conversely they never made openings even in number; this they evidently learned from Nature: to animals she has given ears, eyes and nostrils matching on either side, but in the center, single and obvious she has set the mouth.’*

(Alberti 1992:303)

Alberti, however, through *concinnitas* introduces an overruling principle that as innate capacity enables man to correct relational standards according to the specific application.

” *‘The shapes and sizes for the setting out of columns, of which the ancients distinguished three kinds according to the variations of the human body, are well worth understanding [...] Having taken the measurement of a man they discovered that the width, from one side to the other, was a sixth of the height, while the depth, from navel to kidneys, was a tenth [...] The ancients may have built their columns to such dimensions, making some six times the base, others ten times. But that natural sense, innate in the spirit, which allows us as we have mentioned, to detect *concinnitas* suggested them that neither the thickness of the one nor the slenderness of the other was suitable. They concluded that what they sought lay between those two extremes [...] and they made a column eight times the width of the base, and called it Ionic’*

(Alberti 1992:309)

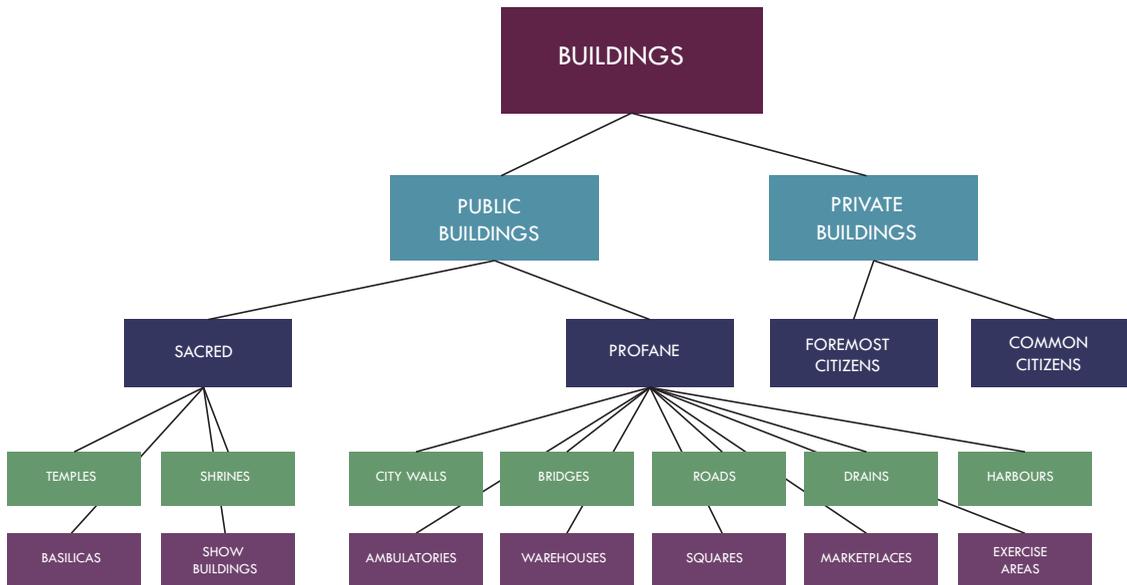


FIGURE II.1.6  
AN 'ACCURATE ACCOUNT OF  
THE VARIOUS TYPES OF BUILDINGS'  
BY ALBERTI

In general both Vitruvius' and Alberti's inductive attempts to or explanations of moving from empirical to general relational standards seem as overstated generalisations.

### ***Building types and elements***

Alberti does mention the existence of various building types that has developed from the original shelter as specialisation of functions. Generally he, as Vitruvius, divides buildings into two types: Public buildings with several functions, sacred as well as profane, and private buildings divided into two groups – those for foremost citizens and those for common citizens. Many of the building types are described in detail. However he stays within antique types and does not deal with the specialisations of his own époque. (See figure II.1.6) More interesting in the context of present thesis is, however, his statement that the whole matter of building is composed of six general elements:

Locality:	The land or region surrounding the building including its climate
Area:	The particular plot of land enclosed by the building
Compartition:	The division of the area (the building) into its different spaces – the floor plan. Like the different members of a body
Wall :	All vertical structure that supports the roof or screen off interior volumes
Roof:	Uppermost part protecting against the rain as well as any horizontal element ' <i>above the head of anyone walking below such as ceilings, vaults, arches and so forth</i> ' (ibid:8) The roof is the most fundamental (and archaic) element of the building.
Opening:	Anything that offers entry or exit for man or thing including as well as light and air. Generally divided into these two purposes as doors and windows. Stairs are included as a vertical door/opening (ibid:28) as well as openings (in and out) for water, smoke etc.

All six general elements relate to and should each be endowed with the attributes of *firmitas*, *utilitas* and *venustas*. Alberti's book III on construction is

10 See also (Kruft:1994:47)

11 (Kruft 1994:273ff)

a detailed description of how the building (and its elements) are put together. Here a similar distinction of the fundamental physical elements is found with subcategories:

Foundation & plinth:	Stones and rubble from solid ground to the level of <i>area</i>
Structure:	<i>Walls</i> subdivided into (structural) <i>bones</i> including columns, beams and arches where openings and <i>panelling</i> consisting of (inner and outer) skin, binders between these and infill. Finally a cornice closes off.
Roof:	Of wood or stone and divided into the horizontal division (ceiling and floor beams) and the covering (the outer roof membrane)
Pavement:	All flooring inside and outside the building

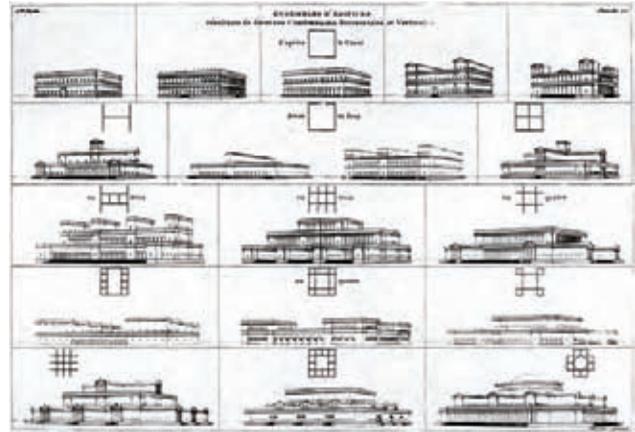
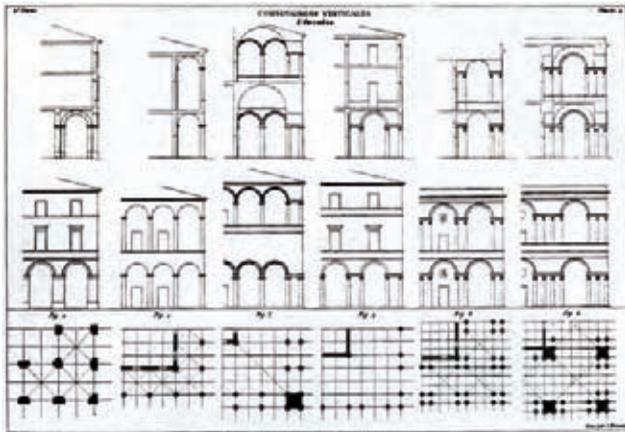
Important to note is Alberti's conscious attempt to avoid a dogmatic and closed architectural system. His directions are rather prescriptive than an expression of fixed rules and set out the possibilities of building while variety (*varietas*) is also a demand. Architectural alternatives should (to some extent) be kept open:

“*I mean that a certain variety possessed by both angles and lines, as well as by individual parts, which is neither too much nor too little, but so disposed in terms of use and grace, that whole may correspond to whole, and equal to equal*”

(Alberti 1992 :426)<sup>10</sup>

## DURAND AND THE GRID SYSTEM<sup>11</sup>

Jean-Nicholas-Louis Durand (1760-1834) was a French architect educated at the Academie Royale d'Architecture. From its start and for 35 years he held The Chair of Architecture at the Ecole Polytechnique – the new engineering school founded 1794. Durand's rational principles represent some of the first traces of functionalism in architectural theory. Kruft states that his simplified architectural schematism partly must be explained in the fact that he taught engineering students, not architects (Kruft:273). As part of his teaching he worked out a typological atlas of architecture aiming at presenting '*the most important monuments of all ages of all nations*' (ibid)



### Architectural principles

The fundamental principles of architecture are by Durand reduced to only two being 'proprietary' and 'economy'— architecture as a combination and weighing of the most fitting and the most economic. The former embraces solidity, soundness and commodity, while the latter includes symmetry, regularity and simplicity. The aesthetic categories classically included in the principle of *venustas* here become subordinated the two others and take form of '*grandeur*', '*magnificence*', '*variété*', '*effet*' and '*caractère*' (Ibid:274) that put considerable distance to Vitruvius' *eurythmy/symmetry* and Alberti's *concinnitas* that were based on proportional rules using analogies to nature. Durand, furthermore, considered architectural ornament superfluous.

### Grid system

Durand's rationalist and functional approach demanded codification into a systematic theory of architectural composition of which he claimed universal validity and which took the form of a grid system. The building volume was not thought as a (three-dimensional) architectural space but produced as a combination of plans and elevations (and sections) that were subordinated the grid. The introduction of this abstract metric system augurs the abandonment of Classical theories of (anthropometric) proportion. Through the neutral grid systems architectural features (i.e. colonnades, walls, arches, windows, roofs etc) were, as separate elements, combined into individual buildings and building types (See figures II.1.7 & II.1.8). Although Durand did not consciously draw his work to this consequence Krufft states that, Durand here '*reached the theoretical point of standardisation enabling prefabricated construction*' (ibid:274) and draws direct parallels to the Crystal Palace built in 1851. Buildings are conceived as individual configuration and addition of a sample of standardised architectural elements.

## SEMPER AND THE FOUR ELEMENTS OF ARCHITECTURE

One of the leading architectural theorists of the mid-nineteenth century was, according to Krufft, Gottfried Semper (1803-1879). While starting studies as mathematician in Germany, Semper quickly moved to Paris and followed an architectural programme in the spirit of Durand whose functional '*schematic procedures*' he however vehemently rejected. His main inspiration as architect and theorist came rather from the German-French Jaques Ignaz Hittorff and

FIGURE II.1.7  
DURAND'S GRID SYSTEM AS PLANS  
AND ELEVATIONS OF ARCHITECTURAL  
ELEMENTS

FIGURE II.1.8  
BUILDING TYPOLOGIES AND RELATION  
TO HORIZONTAL AND VERTICAL GRIDS,  
BY DURAND

- 12 An apparent gap ‘between architectural ideation and its subsequent realisation as process and result in contemporary industrialised construction’ is stated as the main question treated in the present thesis. See *Definition of Scope*, I.4

his treatise on architectural polychromy in Antiquity that was published in 1824 (Kruft 1994:311). Semper sees polychromy in architecture – the use of colors (of materials and paints) – as an expression of a free democratic society that was broken with the (monochromatic) architecture of the Renaissance as an erroneous interpretation of its classical Greek predecessor. Materials and their colour, texture and structural characteristics were important to architecture and should be used by the architect to express the social and historical structure of society and its current technological stage.

“*Let the materials speak for themselves and appear undisguised, in whatever form and whatever conditions have been shown by experience and knowledge to be best suited to them. Let brick appear as brick, wood as wood, iron as iron, each according to the structural laws that apply to it*’  
(Semper IN: Kruft 1994:311)

This could be misunderstood as exactly the functionalism he sought to distance himself from, but the material and the structure are not the only aspects that have to be considered. The connection to the specific society and cultural, regional and climatic setting is also important and modifies this dimension. Semper elaborates a conceptual formula for the relationship between the (architectural) work of art, its style and all its constituent elements. The work of art is thus determined by a *constant* – constituted by the function(s) – and a number of *variables* which are: 1) materials, 2) regional, ethnological, climatic, religious and political conditions, and 3) the influence of the artist (the architect) or the patron (the client) (ibid 312f). The specific combination produces different styles. Interesting here, in relation to the present thesis, is both the insistence on the *contextuality* of architectural creation in a broad sense as well as the connection between *idea* and *realisation*: Architecture is a context specific translation of an architectural idea and specific human needs into the materials and their related tools and technical skills available in a given society at a given time.<sup>12</sup>

In *The Four Elements of Architecture* (Semper 1989), Semper locates the *hearth* – or fireplace – as the first and most archaic architectural element satisfying basic human needs by providing warmth and a ‘*food-preparing flame*’. Furthermore: ‘*Throughout all phases of society the hearth formed that sacred focus around which the whole took order and shape*’ (ibid:102) and thus equally gained moral value. In order to protect the flame and its holders

against the hostile elements of nature, three supplementary basic elements crystallised around the hearth: the *roof*, the *enclosure*, and the *mound* – or terrace. Semper relates each of these four basic architectural elements to a material and the gradually evolving techniques or *crafts* to manipulate them. The creation of the hearth was related to ceramics (and later metal works), the roof and its accessories to wood and carpentry, the enclosure to the weaving and the wall fitter, while construction of the mound was related to the water (regulation) and masonry work (in stone) (ibid:103).

Special attention is paid to the enclosure that becomes part of Semper's – rather forced – argumentation for a nascent polychromatic culture and the development of the ornament finding its (temporary) culmination in Greek antiquity. This will not be followed here. What is more interesting in relation to the thesis and the present exploration of systems in architectural theory is that the four elements and their related materials and techniques, according to Semper, developed into different context specific combinations and emphasis depending on the cultural setting where they were unfolded. Different architectural systems or '*characteristic configuration[s] of spatial relations*' were established (ibid:115).

“According to how different human societies developed under the various influences of climate, natural surroundings, social relations, and different racial dispositions, the combinations in which the four elements of architecture were arranged also had to change, with some elements becoming more developed while others receded into the background” (ibid:103)

The four elements of architecture in Semper's theory should thus be understood as flexible entities that even can infringe the domains of each other exemplified e.g. with Roman architecture where heavy (stone) material and construction techniques that originally were tied to the mound or terrace, now through walls, arches and vaults, began to influence the enclosure and the roof elements.<sup>13</sup> Semper's insistence on the enclosure or wall as rooted in the weaving of (colourful) carpets rather than the stacking of stones can be a little hard to follow and is probably tied to his early argumentation concerning polychrome Antiquity. However, the variables of his formula for the architectural work (see above) and the flexible domains of the four elements represent interesting arguments for the (partial) emancipation of the material in architecture from pure

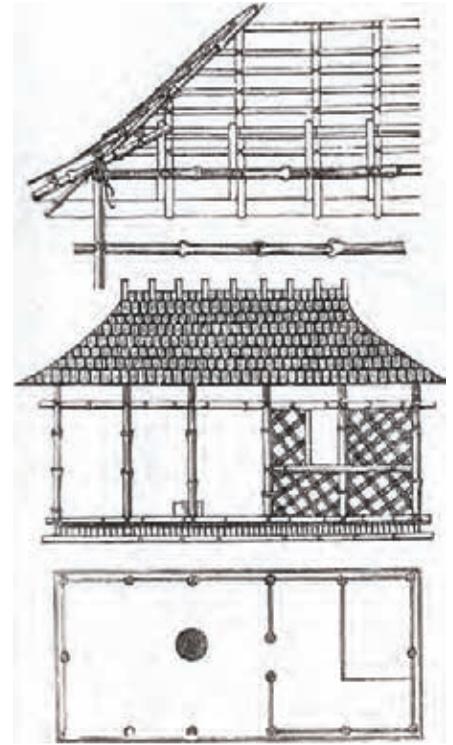


FIGURE II.1.9  
SEMPER'S ILLUSTRATION OF A PRIMITIVE CARIBBEAN HUT FROM THE GREAT EXHIBITION IN LONDON IN 1851 CLEARLY EXPRESSING HIS FOUR ELEMENTS OF ARCHITECTURE

- 13 In Greek (polychrome) antiquity, Semper claims, masonry or stone walls, were '*subordinate features hidden behind a partition wall*' or cladding of weaved textile or painted decoration. (Semper 1989)

14 See *General systems theory*, II.4

functionalism into an object for architectural ideation – as e.g. the selection of decorative forms and colours (ibid:128). A contemporary architecture should not imitate Greek or Roman Antiquity and their architectural systems but, as mentioned above, constitute a context specific translation of the architectural idea and the basic human needs. This can only be done through application of the four elements as they are founded in present day production techniques.

## CONTEMPORARY THEORIES

From the mid-twentieth century and on, architectural theory became a plethora of different competing schools of more or less stable character and historical impact. The continuation of the modern movement and the post-modernism, as some of the major, have shortly been mentioned. Within the scope of this thesis, it has however been chosen not to attempt to describe these or others more in detail. This partly because the relatively short historical distance to these theories makes it more difficult to keep them at an arm's length and value their true impact on systems thinking in architecture. However, two recent theories elaborated by architects – or rather the resulting models – will be introduced in connection with the general systems theory presented in a following section. These are Christopher Alexander's *pattern diagrams* and Bill Hillier's *Space Syntax* that both represent more true systems approaches, as this is defined in the general systems theory.<sup>14</sup>

## THE DIVISION BETWEEN IDEA AND PROCESS

In this paragraph the intention is to trace some of the possible historical explanations for the alleged division between on the one hand how the architectural idea is conceived and on the other hand the physical processes that through the crafts or other forms of production lead to the realisation of the final architectural work. In order to comply with this, help is mainly found in two texts respectively by Gevork Hartoonian on *Montage* and by Kenneth Frampton on *critical regionalism*. Both texts give a kind of historical sectional view of the development or emergence of this division from classical theory and architecture up to modernity and present time (Hartoonian 1994; Hays 2000). Some supplementary references will be used to substantiate their claims as a general perception.

### *Hartoonian and the fragmentation of techne*

According to Hartoonian the classical conception of technology expressed in the greek term *techne* – the art of making – encompassed in one single concept on the one hand the architectural meaning or idea and on the other hand the work or construction needed to realise it as a physical form. The idea of an architectural form in Antiquity intrinsically implied the tools, techniques and materials to bring it to life as a unity of thinking and doing or of theory and practice (Hartoonian 1994:6). Vitruvius' three basic categories of *venustas*, *utilitas* and *firmitas* articulate an integration of the style, the rules of gravity and the property of materials into one single body of architectural knowledge (ibid:7). '[C]lassical architects' conceptualizations of the different functions of architectural elements were integrated with their technical knowledge' (ibid:11). Through examples from Palladio's prescriptions for the design of villas Hartoonian shows e.g. how symmetry (in the modern sense of the word) as an organizing principle in architecture is not only about aesthetics but equally has useful structural implications in the construction of buildings.

The unity contained in *techne* is, as Hartoonian points out, theoretically broken up in the early renaissance by e.g. Leone Battista Alberti who distinguishes between lineaments and matter/structure. Lineaments are, as mentioned above, the abstract lines and angles that define and enclose the form and that are derived from thought whereas the physical result is realised in materials retrieved from nature. Alberti expressly states that '*lineaments remains independent of structure and have nothing to do with materials. They also remain indifferent to purpose and form*' (ibid:7) The act of (architectural) design become exclusively to produce the correct configuration of lines and angles. The architect is here dissociated from the workman. This conceptual split is clearly visible in renaissance architecture where architectural elements in e.g. façade composition often become merely ornamental and detached from the structural logic of the building (See figure II.1.10).

Hartoonian locates the next step in the separation of design from construction activity at the end of the seventeenth century where the traditional guilds in Paris were replaced by the academies and the institution of 'Corps des Ponts et Chaussées' the later 'Ecole des Ponts et Chaussées' (School of Bridges and Pavements). This marked the establishment of the two from then on clearly separated disciplines of architecture and engineering with roots respectively in liberal and mechanical arts. '*A sharp differentiation thus came about between*



FIGURE II.1.10  
FAÇADE BY ALBERTI SHOWING THE  
SPLIT BETWEEN ARCHITECTURAL MEANING AND BUILDING STRUCTURE

*ideative techniques – activities of thinking and translation into precise projects – and the work of execution, whose sole task was to put such plans into effect was so determined.* (ibid:5) The classical *Techne* was now fragmented into different fields of knowledge.

In the nineteenth century in line with the breakthrough in the mechanical sciences the seeds were sown for the cult of the machine that culminated in the modernists of the early twentieth century. The emergence of industrialised materials and techniques were praised to such extent that the status of architecture, according to Hartoonian, was reduced to that of a mere technical discipline focussing on production. Architecture and its elements had lost its metaphoric significance and *technology* with its focus on production had replaced *techne*. (ibid:13)

“[T]he status of architecture was either reduced to that of an *utensil*, as was the case in the *Werkbund* and *Bauhaus* schools, or the field was wrongly assumed by some disciples of the *Russian Constructivists* to be equivalent to *engineering*”

(Hartoonian 1994:6)

From the architectural province Hartoonian introduces Durand’s architectural types based on configurations of ‘standardised’ architectural elements as an example of an autonomous architectural language that was separated from the exigencies of its construction/production (ibid:13). Boullée’s architecture based on pure geometrical forms is another (See figures II.1.11 & II.1.12). The search for meaning in architecture was relegated to the realms of pure form and/or function. The classical conception of architecture as defined by universal laws of beauty had been substituted by architecture as (subjective) expression.

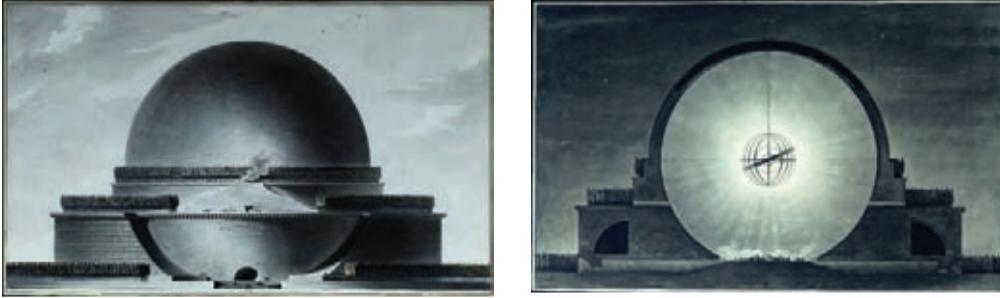


FIGURE II.1.11 AND II.1.12  
BOUILLEÉS PURE GEOMETRICAL FORMS  
ARCHITECTURE. PROJECT FOR A ME-  
MORIAL TO ISAAC NEWTON, 1784

By introducing concept of the tectonic Hartoonian suggests a possible closing of the gap between architecture and construction without returning to *techne* in the classical sense. Through Viollet-le-Duc's statements on the ornament as *'the structure of the architectural features'* or *'the best architecture is that whose ornaments cannot be divorced from the structure'* (p18) he hints that an expressive architectural language freed from the laws of divine classical orders can (re)integrate the element of construction even when adapted to new forms of production. In Gotfried Semper's integration of ur-forms with new techniques and materials he finds an even clearer pointer. Architecture is, as also described above, rooted in four industrial arts with direct connection to four basic elements of architecture (ibid:20). Tectonic form for Semper is neither about expressing the structure (the construction) nor the formal intentions of the architect. Rather it reveals a symbolic intention through the material and the related techniques (skills) embedded.

“*Tectonics deals with the product of human artistic skills, not with its utilitarian aspect but solely with that part that reveals a conscious attempt by the artisan to express cosmic laws and cosmic order when molding the material'*

(ibid:23)

Interesting in the present context is also Semper's interest in *'How to change old forms, consecrated by necessity and tradition, according to our new means of fabrication'* that according to Hartoonian becomes Semper's motto on the tectonic (ibid:24). Through the acknowledgement of the rooting in materials and their related techniques stemming from other industries as a primary condition of architecture Semper anticipates, according to Hartoonian, montage (ibid:1) as an architectural (and tectonic) strategy of the modern era. In montage the relation between the whole and its parts is altered from organic (as in *techne* and the analogy to natural proportions) to cultural (ibid:26) where the whole instead become a juxtaposition of fragments in the act of montage. The “dis-joint” or seam become the tectonic form of montage. Montage (apparently?) introduces a new culturally based autonomy of architecture that is neither based on classic myth nor on the subjective expression or idea of the architect by, in Hartoonian's words, *'problematizing the event of its [architecture's, ed.] inception'* (ibid:27).

” *Montage is a technique that drains the metaphysics of the tectonic and unfolds a new way of being in the world*

(ibid:28)

The architectural idea seems, according to Hartoonian, potentially to recover its connection to construction – or rather to fabrication – through its cultural roots in the contemporary means of production.

#### ***Frampton and critical regionalism as meaning***

In Frampton’s reading of Hannah Arendt’s *The Human Condition* he equally describes a historical origin of the division between the architectural invention and its subsequent fabrication. As with Hartoonian, the renaissance is seen as a decisive turning point where the split between the liberal and the mechanical arts produced a change in the hierarchical organisation of construction work. From a lodge organisation where a master builder/mason co-ordinated the specialised work of different masters in charge of various aspects of a construction job the master builder/mason now ‘*rose to the status of sole planner*’ while the rest were degraded to merely manual labourers – *Animal Laborans*. The master builder had become an architect – a man of invention and speculation (Frampton IN:Hays 2000:367).

With reference to Arendt, Frampton distinguishes between *work* and *labour* as a principle duality of *Homo Faber* – ‘man-the-maker’. Man is both capable of producing useless things such as works of art which are ends in themselves and of inventing and producing useful objects that serves for predetermined ends. The fundamental difference in these two forms of production can be described in the words *what* and *how*. The first one is concerned with representation – or meaning – whereas the second is about utility and process. In architecture this ambiguity is, according to Frampton, reflected in its status as both *edification* (i.e. moral instruction) and as *building* (construction work). Man or *Homo Faber* is ‘*neither pure artist nor pure technician*’ he is both at the time. Both modes of production, he continues, resulted in the ancient world in physical manifest results (art or tools). However, through the emergence of the empirical sciences, production shifted towards equally including the invention of ‘*abstract instruments of cognition*’ – or systems of thought – as they are tentatively termed in the present thesis. Apart from widening the division between thought and fabrication (the latter expressed in *Animal Laborans*) this scientific approach on the other hand also changed the emphasis or esteem of *Homo Faber* from the *what* to the *how*:



“Fabrication which had hitherto disappeared into the product, now became an end in itself since pure science was not interested in the appearance of objects, but in the capacity of objects to reveal the intrinsic structure lying behind all appearance”

(Ibid:367)

FIGURE II.1.13  
THE DOGMATIC BEAUX-ARTS STYLE  
TAUGHT IN PARIS IN THE 19TH CENTURY  
WAS A HEAVILY DECORATED  
NEO-CLASSICAL STYLE AS SEEN E.G. IN  
PALAIS GARNIER FROM 1875

FIGURE II.1.14  
EIFFEL'S CONSTRUCTIONS ARE  
EXAMPLES OF THE NEW AUTONOMOUS  
FORMAL HOW-LANGUAGE OF  
ENGINEERING

*Homo Faber* seem, according to Frampton, instrumentalised himself by promoting the process before the result, the architect or master builder seen primarily as technician – as a means to an end or as action before contemplation (ibid:368). During the Enlightenment (18th century) this change resulted (as Hartoonian also points out – see above) in the formal separation of architecture and engineering. Architecture (and the *what*) was led into ideological distraction removing it from the task of realisation. This was found either through a reformulation of antiquity as in the Beaux-Arts tradition or through utopian ideas as in the conceptual and dematerialised works of Boullée or Ledoux. Architectural ideals separated from construction could only wither in their specific physical manifestation. Engineering on the other hand continued to develop its mechanical understanding of nature and its superior technical performance based on the scientific *how* and produced a formal language of its own as expressed in *‘the viaducts, bridges, and dams of a universal system of distribution’* (ibid:369). Production and process in their own right dominate the man made world and influence from then on and still today, according to Frampton, back on how architectural form can be conceived:

15 See *Findings*, V.1 in Part V – ‘Reflection’

“*Increasingly buildings come to be designed in response to the mechanics of their erection or, alternatively, processal elements such as tower cranes, elevators, escalators, stairs, refuse chutes, gangways, service cores, and automobiles determine the configuration of built form to a far greater extent than the hierarchic and more public criteria of place*’  
(ibid:370)

Buildings (not architecture) become determined by the processes they accommodate rather than being actual architectural (and symbolic) expressions or intentions of a culture to sustain itself. Utility as an end has replaced utility as a tool to reach an end – reach the *what* or the meaning of architecture. As he cites Arendt for: ‘[...] *utility established as meaning generates meaninglessness*’ (ibid:372). The non-functional aspects of architecture – the meaning – are left without connection to society and its cultural foundation being either inaccessible as ‘*introspective abstraction*’ or reduced to a mere commodity as ‘*ideosyncratic vagaries of kitch*’. This is probably also the main problem of a petrified and dogmatic functionalist architecture as expressed in the industrialised mega blocks from the late 1960’s.

Frampton seems, compared to Hartoonian, more pessimistic concerning a contemporary re-integration of construction into a unified architectural thought. The *work* and *labor* duality of *Homo Faber* is broken and man generally reduced to an *Animal Laborans* in the service of (re)production of commodity and not the creation of meaning and culture. Modern life and means of production efficiently destroy the durability of the world through a ‘*ruthless cultural reduction*’ and ‘*the celebration of technique as an end in itself*’ (ibid 370/371). According to Hays – introducing Frampton’s text – architectural practice is however seen by Frampton as a ‘*potentially resistant practice*’ (ibid 259) that can mediate between work and labor: ‘*It affords, above all, a hybrid situation in which rationalised production (even partially industrialized production) may be combined with the time-honored craft practices [...]*’ I will not go deeper into Frampton’s argumentation here but will return in the end of this thesis to this idea of a hybrid situation in present architecture as a possible way of pointing towards an *industrialised* architecture.<sup>15</sup>

## KRUFF AND ARCHITECTURAL THEORIES

In order to substantiate the idea of a *general* perception of the historical emergence of a division between architectural idea and construction work a couple of references from Hanno-Walter Kruff's book on architectural theory will here be summarised shortly. Kruff equally cites Alberti for, in his definition of the architect, making a sharp differentiation between the architect and the craftsman (Kruff 1994):

“*For it is not a Carpenter or a Joiner that I thus rank with the greatest Masters in other Sciences; the manual Operator being no more than an Instrument to the Architect. Him I call an Architect, who, by sure and wonderful Art and Method is able both with Thought and Invention, to devise, and, with Execution, to compleat all these Works [...]*”  
(Alberti in Kruff 1994:43)

The terms of *thought*, *invention* and to *devise* are specific to the architect and opposed to the craftsman which are reduced to merely being *an instrument to the architect*.

In Kruff's description of J.N.L Durand's (1760-1834) architectural thought he equally grants Durand for drawing '*particular attention to the increasing divergence of architecture and civil engineering, recognising that the latter will eventually become a discipline in its own right*' (ibid:273). This break into two disciplines – one of idea and invention and another of process and realisation is equally found in both Hartoonian's and Frampton's descriptions (above). However, Hartoonian and Frampton locate the break already from the seventeenth century and during the Enlightenment. Durand wrote his theories in the early nineteenth century. Durand's architectural types and elements however accentuates architecture's disruption from the exigencies of its construction.

## FURTHER DISCUSSION

Several recent sources outside architectural theory underpin the separation of design and coordination from construction as a fundamental characteristic of the construction sector as opposed to design and production within other industries.<sup>16</sup> It has not fallen within the scope and extent of this thesis to follow

- 16 The separation of design and coordination from production: (Bowley 1966, Nam and Tatum 1988, Groák 1994, Flanagan et al 1998, Miozzo and Ivory 2000, González-Díaz et al 2000) – Citation from (Thomassen 2003)

this track further, but there seems to be good indication for a general and historically substantiated division between on the one hand how architecture and construction is conceived and on the other hand how it is produced.

Related to the main question of the thesis a next question could then be what the consequences of such a division are? The first part of this paragraph dealt with examples of classification of the constituent elements of architecture. If the historical split between the architectural idea and the physical realisation of it is so pronounced; if from the seventeenth century they have even belonged to separate established disciplines then it is equally possible that there will be a considerable difference between these constituent elements of architecture and the constituent elements of *construction*. The consequence of such differences would in very general terms be the need for some kind of translation from the language of one discipline to the language of the other. The next section looks into the question of classification systems in construction – or the constituent elements of *construction* as opposed to the constituents elements of *architecture*.

## II.2 CLASSIFICATION SYSTEMS IN CONSTRUCTION

<sup>17</sup> See *Introduction to the problem area*, I.3

### INTRODUCTION

The previous section concentrated on the historically emerging split between architectural idea and execution and showed examples of how the elements of architecture have been defined in architectural theory. This section concentrates on classification systems used for this second leg – the execution of building projects. These systems both concern the processes and the physical elements in construction and can be legal systems, systems developed within the construction business, IT-standards or looser recommendations for a smoother or better controlled building process. However, they all have in common that they are elaborated as attempts to handle the increasing complexity and fragmentation of knowledge in construction by establishing clearer interfaces between a number of stages (process) or a system of physical elements (matter). As mentioned in the problem area section, the construction sector can no longer draw on the traditional crafts as subsystems together forming a clear and coherent system of knowledge.<sup>17</sup> Through industrialisation these crafts have dissolved, specialised and cross merged into niches that cannot simply be delimited in terms of material, tool and process. Furthermore they have become detached from the architectural conception of the work and its elements and instead focussed on the realisation of it. This section looks into examples of recent attempts to classify processes and elements in the construction sector.

Apart from mostly – not exclusively – concentrating on a Danish context the examples below are primarily introduced as a way to show the diversity and perhaps the arbitrariness and common problems of these classifications. It is also discussed how they contribute to how and what we build.

#### *Hypothesis and questions addressed*

The growing complexity of construction both as processes and as objects has produced a variety of classification systems that either split up or transcend the traditional crafts

The hypothesis is addressed through the following two research questions:

- a) How has the construction sector conceptually systemised building processes and/or physical elements in order to facilitate clear interfaces of responsibility between a growing number of stakeholders and reduce the complexity of the construction process?
- b) Do classification systems used in the construction sector reduce the complexity from the point of view of the architect and what implication does it have for the architectural result?

Due to the size of the field this section will centre around a Danish context with some references to other national and international standards or classification systems.

## PROJECT STAGE MODELS IN CONSTRUCTION

Despite many historical attempts to turn construction into true industrialised mass production as in the product industry, construction is still predominantly project based. Projects are unlike standardised products characterised by having a project specific course. That is what makes them projects! Product *development* in other sectors can also be seen as projects. Companies in construction that generally deal with projects – as architects, engineers, contractors – tend to follow some kind of system concerning how these projects should progress. Construction projects involve many different stakeholders each one having their internal procedures that need to be coordinated in some kind of common system in order to clarify sequence, communication and responsibility issues.

Different project stage models have been used in construction processes in order to provide this coordination and to clarify the project course for the client. Each stage in a model is usually completed by some sort of documentation i.e. descriptions, drawings, models etc. that can provide the basis for a decision of proceeding to the next stage. Stage models are also important because they lay out the basic structure for contracts between stakeholders in the building process. The specific models used are in some cases national standards in others elaborated by trade organisations. The ISO-standard 12006-2:2001 – *Organization of information about construction work – defines a project stage*

as a ‘period of time in the duration of a construction project identified by the overall character of the construction processes which occur within it’. This definition is, in a short introduction to Danish project stage models, also adapted by the Danish organisation *Det Digitale Byggeri* (digital construction).<sup>18</sup> This introduction and a couple of other sources will be used as the basis for the short introduction below (DBK 2006).

In Denmark a general project stage model applicable for all stakeholders in the construction process, ABR89, was made in collaboration between the major construction consulting organisations and the public authorities and was introduced in 1989 replacing a range of earlier models. The model has been widely applied in the construction sector and divides the process into 5 general stages<sup>19</sup>:

- 1) program
- 2) proposal/conceptual design
- 3) design development
- 4) construction and
- 5) use

A later revision of the model, partly caused by EU-imposed procurement rules partly by enhanced industrialisation, added two more stages – *procurement & bidding* and *production planning* before construction. In 1996 the consulting organisations (architects and engineers) made their own 5 stage model exclusively for consultancy services

- 1) pre-design consultancy
- 2) design management consultancy
- 3) design consultancy
- 4) construction consultancy
- 5) operation consultancy

The design stage (including the earlier programming and proposal stages) is further divided into 5 sub stages – outline proposal, project proposal, preliminary project, main project and project follow-up.<sup>20</sup> This model is now generally used among consultants but is too trade specific for general use in the sector as a whole. Instead a simplification of the first ABR89-model into a four-stage model (4 fase-modellen) has been adopted by other parties.

18 *Det Digitale Byggeri* is as a publicly funded initiative since 2003 in charge of promoting tools for a coordinated digitally supported construction process in Denmark. I will get back to this initiative later in this section

19 <http://www.voldgift.dk/regler/abr-89.htm#2> accessed on April 8, 2011

20 The stages can be found in ‘description of services’ in Danish and English on <http://danskeark.dk>

- 21 In fact this is a general problem in the application of systems. However the drawback should be weighed against the gains of a clearer structure or process. Meadows (2008) points out that models should always be adapted to the specific purpose. See the following section, *General systems theory*, II.4, for an introduction to systems thinking
- 22 The 7K-model was developed and tested as a part of some major development projects initiated by the former Ministry of Urbanism and Housing (By- og Boligministeriet) – ‘PPB’ and ‘Projekt Hus’
- 23 See *General systems theory*, II.4 and *Systems terminology*, II.5

- 1) programming
- 2) design
- 3) execution and
- 4) operation

This model is widely used among contractors. All stage models above – as stage models in general – have the drawback that they have a tendency of freezing a specific way of organising construction works that obstruct new or project specific organisation that may be more adequate in certain cases.<sup>21</sup> An alternative, the ‘7K-model’, was introduced as a way to facilitate early procurement, where contractors are brought in already in the (early) design phases (all starting with a ‘k’ in Danish = 7K)<sup>22</sup>:

- 1) contact
- 2) contract
- 3) performance (specification)
- 4) concept
- 5) construction
- 6) control
- 7) consumption

This model was later simplified by the interest group Lean Construction Denmark into a three-stage model – value & concept, construction, consumption.

In practice the models are often used with ‘loose edges’ between the stages e.g. buildings are never completely designed before construction begins. The development shows that while there are evidently advantages in following a common structure, it is very difficult – and probably impossible - to come up with an ideal or definitive model that everybody can agree on even on national level. Organisation and construction itself changes over time and needs furthermore to some extent to be project specific. Industrialisation and more integrated building products have furthermore moved part of the design work to sub-consultants, suppliers or manufacturers. This also blurs the stage boundaries and makes difficult the linear logic of a sequential number of phases. Models should be open for some degree of project specific adaptation by offering what I will later term as *flexible structuration*<sup>23</sup>. General systems theory offers a way to conceptualise such models and will be treated in a following section.

## BUILDING CLASSIFICATION SYSTEMS

24 HFB (1993) p 937

As described in the previous section, in Classic architecture the construction elements and the architectural elements were convergent. Equally the building techniques that were related to these elements were embedded in such a way that each particular element was always made in the same way. The architectural idea unambiguously led to the transformation of specific materials by specific techniques into specific results. Today this coherence is no longer present and this has from the 1950's and on led to the emergence of different classification systems as attempts to make it possible to specify building data as processes and elements in a precise way and make it possible to communicate consistently among stakeholders. These systems, however, has emerged rather from a contractor perspective than from an architectural context and thus largely lacks correspondence with how the buildings are conceived and designed in the first place. Architectural projects need to be translated into these codifications; they do not naturally lead to them, neither do they support the architect's way of working. This in combination with the fact that they are often quite complex have limited their implementation and success considerably – particularly for use in early design stages; Although there are obvious advantages in being able to communicate clearly between stakeholders, the architect still seems to have very little direct incentive to use these systems.

### *The Sfb-system*

One of the first attempts to make a complete building classification system common for all involved parties was the Sfb-system published in the 1950's by the Swedish *Samarbetskomitén för Byggnadsfrågor* (the collaboration committee for construction issues). The system was originally intended to be used for standardised Swedish construction work descriptions but was adopted in various construction related fields e.g. for registration of building materials. In 1972 the Sfb-system was recognised by the CIB (Commission Internationale du Bâtiment) and became widely applied internationally although often in adapted national versions. The format and structure of the system has equally to some extent been found adequate for later IT-adaptation.<sup>24</sup> The system is based on a three layered coding based on values from three separate tables:

- 25 <http://www.byggeklassifikation.dk/Rapport/Slutrapport2.pdf>, accessed on April 5th 2011
- 26 Sources: <http://www.ebst.dk/detdigitalebyggeri>; [www.bips.dk](http://www.bips.dk); [www.hfb.dk](http://www.hfb.dk); <http://www.detdigitalebyggeri.dk/>, <http://it.civil.aau.dk/it/education/> accessed on April 5, 2011; (Ekholm 2011) and (Jørgensen 2010)
- 27 <http://bips.dk/artikel/hvem-er-bips> accessed on April 5, 2011
- 28 Bygherreforeningen, Danske Arkitektvirksomheder, Foreningen af Rådgivende Ingeniører, Dansk byggeri, TEKNIQ, BAT-kartellet and DI-Byggematerialer

- 1) a building component table,
- 2) a construction type table
- 3) a resource table

By *building components* the system refers to the function of the component as outer wall, roof, exterior surfaces, pavement etc. By *construction type* is meant techniques as masonry construction, in situ casting, pipework installation etc. and finally the *resource* describes the material and also includes ‘immaterial’ resources as administration and different kinds of work or service. An example of a coding could be:

(22) G q4 = ‘(interior walls)’ ‘prefabricated base building’ ‘concrete’ = prefabricated structural concrete walls

In Denmark the SfB-system has been adapted and updated and the latest complete revision is from 1978 with a later update of the building component table in 1986 (SC/SfB). However, the complete system and its structure has only sparsely if ever been used in a consequent way that crosses all involved stakeholders in one or several building projects. Insufficient updating according to new construction techniques and application of materials in new ways have complicated a consistent coding and mostly limited the use to building product catalogues, rather than the building processes.<sup>25</sup>

#### *bips and DBK (Danish Building Classification)*<sup>26</sup>

bips – the former BPS – *byggeri, produktivitet, informationsteknologi og samarbejde* (construction, productivity, information technology and collaboration) is a non profit organisation joining consultants, contractors, public authorities, universities, IT-companies, building material & component suppliers and clients dealing with construction into one single entity.<sup>27</sup> The organisation is a fusion of various initiatives in the construction sector working towards both standardisation of construction project descriptions and standardisation of CAD-tools and their application. By March 1st 2011 the organisation took over the responsibilities and management of the results and tools developed under the governmental initiative *Det Digitale Byggeri* (Digital Construction) running from 2003-2006 and from then handed over to the building sector led by its central organisations.<sup>28</sup> *Det digitale byggeri* developed the basis for ICT-demands of public clients in construction projects and were supposed to work as a driver for the construction sector in general. The demands encompassed four fields:

- 1) Procurement and (competitive) bidding via the Internet
- 2) Application of 3D-models
- 3) Use of a common project-web
- 4) Digital delivery of building data relevant for operation and facility management

In order to comply with these demands several tools and guides has been developed. The most important of these is the DBK-system (Danish Building Classification). The standards are based on the international ISO 12006-2 for *Organization of information about construction work*. DBK form the most coherent and at the same time digitally supported information structure that has been made for the built environment in Denmark so far. It encompasses the entire construction industry and the entire life cycle of construction from planning over construction to operation. The overall structure of the system is that certain resources are applied in certain processes in order to create certain results. To each of these separate *domains* properties are associated from a domain of properties.<sup>29</sup> Apart from classifying building complexes, single buildings, spaces and building parts DBK equally encompasses processes, stakeholders, documents and other construction information. The DBK-system and the associated structure for construction descriptions (B100/B1.000) are meant to substitute the use of the Sfb-system and all its different trade-led or company based modifications or adaptations.

Ekholm describes DBK as a *reference system* – a combination of a classification and an identification system. Classification is based on a ‘type-of’-principle while identification is based on a ‘part-of’-principle. (Ekholm 2011:3). DBK is object oriented and more complex than the Sfb-system by enabling different views (called *aspects*) upon each object as e.g. a building component depending on the purpose. Four aspects are defined: a product aspect (what an object consists of), a form aspect (what it looks like), a functional aspect (how it is used) and a location aspect (how it is integrated/installed). An example of the coding of a building component (a window) in the DBK-system following the product aspect (coded as preceded by ‘-’) looks like this:

-205	Wall system
-205.02	Window section inserted into wall system
-205.02.01	Window in window section inserted into wall system
-205.02.08	Seam/joint in window section inserted into wall system

- 29 The Resource Domain (trades, contractors, materials, equipment and documents), the Process Domain (the subprocesses of the different stages in construction), the Result Domain (building complexes, single buildings, spaces and building parts), the Property Domain (classification of properties).

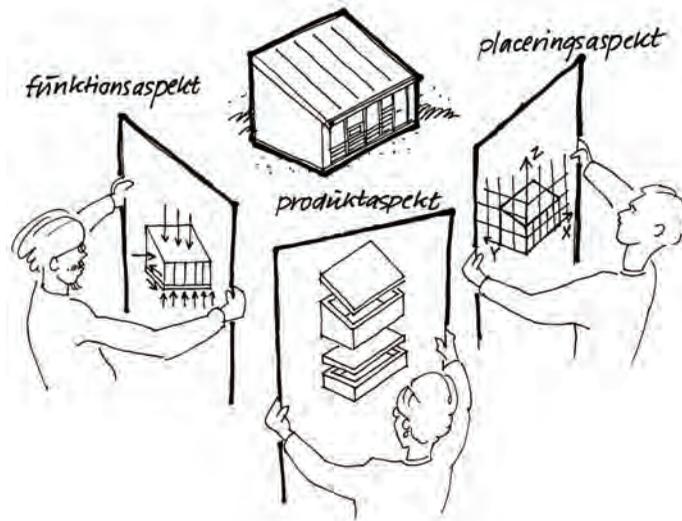


FIGURE II.2.2  
FROM LEFT: FUNCTIONAL ASPECT,  
PRODUCT ASPECT, AND LOCATION  
ASPECT

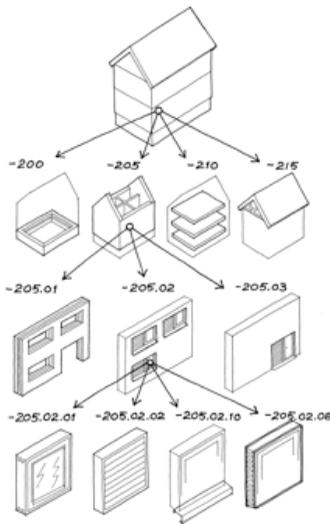


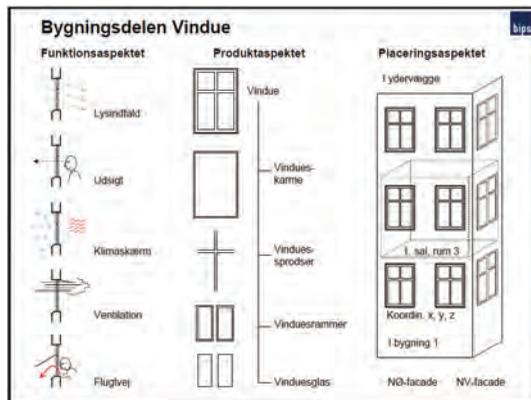
FIGURE II.2.1  
DBK-CODING: EXAMPLES OF NESTED  
ELEMENTS UNDER THE PRODUCT  
ASPECT

30 The concept of aspects is adapted from the Danish standard DS/EN 61346 on structuration principles and reference terms in industry. This standard includes the aspects of function, production and location. The form aspect is DBK-specific. However DS/EN 61346 opens the possibility of working with supplementary aspects. (Ekholm 2011:28)

The different levels of the coding make it possible to describe elements that are integrated – or *nested* – into other larger and more complex elements and facilitate different ‘zooms’ of complexity in focus. In the following section on *general systems theory* this issue of nested system integration and levelled complexity will be further explored. Coding, alternatively, along the functional aspect (preceded by ‘=’) the coding =20.01 refers to ‘illuminating with daylight’ while under the location aspect (preceded by ‘+’) the coding +1.002 would refer to first floor, room 002. The form aspect (preceded by ‘#’) refers to the geometry. Coding in different aspects can be joined into an integrated description as -205.02.01/+1.002/=20.01 thus referring to a ‘window in window section inserted into wall system placed on first floor room two providing illumination in the form of daylight’. A building component can also have various functional aspects simultaneously.

The idea with the *aspect* dimension is that while objects i.e. building components (as simple, combined or nested) are defined in an unambiguous way as classified objects, the relation – or the system – they form part of/can be seen in different ways – as systems of parts, systems of functions, systems of locations or systems of forms. The different aspects are used one by one according to which is the most appropriate for different parts of the building life cycle processes in question (see figures II.2.1 & II.2.2). The production aspect points out the combination of elements into a larger assembly; The functional aspect describes functional relations or interfaces between elements while the location aspect bring out spatial relations between the elements of an object (e.g. a building).

The vision of classifying and identifying any resources, processes and results of the entire life cycle of buildings in a consistent way seems very ambitious. Present thesis does not leave time or space to comment this in a nuanced way and the scope of the subsequent model building is much more confined. However, the aspect dimension is interesting within the current project frame because of its potential capacity to establish *different views* on what is still basically considered the same object – being a building complex, a single building or simply parts of a building. The *system structure* of a building is somehow an alternative aspect of a building project.<sup>30</sup> The integrated product delivery, which is a special focus of this thesis, can be seen as an assembly integrating or *nesting* various elements and can, as for the physical part, thus be grasped by the production aspect. However, as it will be described, it equally comprises process elements and perhaps even elements of thought (or knowledge). Being



a relatively recent phenomenon the integrated product delivery cannot fully be described by existing classification systems.

## OTHER CLASSIFICATION SYSTEMS

### BSAB (96)

In Sweden the original Sfb-standard (see above) was from 1972 and on developed into a new classification system called BSAB by Bygandets Samordning AB (Coordination in Construction Ltd.) The incentive for the development lay in the enhanced importance and sophistication of installation systems in construction that could not be properly classified within the Sfb-system. Later the development in information technology has resulted in further modifications in the latest version BSAB 96 finished in 1998. As the DBK-system this version to some extent follows the international ISO-12006-2 but with modifications and adaptation to Swedish circumstances and experience using the system.

The BSAB system works with a concept of *views* (in Swedish: *vyer*) that to some extent resembles the concept of aspects in the DBK-system. Accordingly it includes an activity view, a functional view, a construction view, a production view, a resource view and a management view.<sup>31</sup> Classification tables has been elaborated within eight main classes of: activity, infrastructural unit, building, space, building parts/components, building component type, production result, resources, management result and geometrical form. The different views (or aspects in DBK-terminology) refer to one or several of these classes and tables (Ekholm 2011:87ff)

### IFC and STEP<sup>32</sup>

The IFC standard – Industry Foundation Classes (today officially the Buildingsmart data model) was originally developed by IAI (International Alliance of Interoperability). IFC is a data model and file format used to exchange CAD-data like BIM-models and drawings between the different software programs used in the construction industry. The standard is not written to a specific piece of software and is in this sense an open international standard. It is not a classification system in itself but can support classification coding as e.g. DBK applied to a BIM-model. IFC objects constitute in this sense a subset of the total number objects or elements in construction focussing on a model oriented work approach. The IFC is originally based on the more general ISO-standard

FIGURE II.2.3  
DIFFERENT ASPECTS OF A WINDOW

- 31 In Swedish: 'Verksamhetsvy', 'funktionsvy, konstruktionsvy, produktionsvy, resursvy and förvaltningsvy
- 32 <http://standards.eu-innova.org>; <http://www.buildingsmart.com>; <http://www.ebst.dk> ; <http://www.steptools.com/> accessed on April 10, 2011

- 33 [http://www.steptools.com/library/standard/step\\_1.html](http://www.steptools.com/library/standard/step_1.html) accessed on April 10, 2011
- 34 Source: Omniclass, Introduction and Users Guide and <http://www.omniclass.org/> accessed on August 18, 2011

10303 informally known as the STEP (Standard for the Exchange of Product model data). STEP describes how to represent and exchange digital product information.

Related to the thesis, IFC and STEP are interesting in the way that they are in their basic idea created in order to reduce ‘translation’ work between systems and the resulting faults. The apparent distance pointed out between architectural ideation and its subsequent construction and/or production has been accentuated by increased division of labour of the latter where many different stakeholders use their own tools and procedures.

“*In design and manufacturing, many systems are used to manage technical product data. Each system has its own data formats so the same information has to be entered multiple times into multiple systems leading to redundancy and errors. The problem is not unique to manufacturing but more acute because design data is complex and 3D leading to increased scope for errors and misunderstandings between operators. The National Institute of Standards has estimated that data incompatibility is a 90 billion dollar problem for manufacturing industry*”<sup>33</sup>

Several earlier national data exchange standards mainly focussing on geometrical data have been used including SET in France, VDAFS in Germany and IGES in the USA.

#### **Omniclass/OCCS<sup>34</sup>**

In the USA the Omniclass Classification system provides an open and extensible classification system for production, storage and retrieval of all information in the construction industry thus providing a structure for e.g. electronic databases. Omniclass is equally based on the international ISO-standard 12006-2, *Organization of Information about Construction Works*, and strongly inspired by the UK-equivalent, Uniclass, but however adapted to North American terminology and practice. Construction information is organised around 15 tables each representing different facets of construction fitting and overall structure of construction resources, processes, and results. The 15 tables classify: *Construction entities* – by function and by form, *Spaces* – by function and by form, *elements, work results, products, phases, services, disciplines, organizational roles, tools, information, materials* and *properties*. Relevant information can be classified within one or as a combination of various facets (read: tables) and

can be used and reused throughout the life of a building or a similar facility. Particularly interesting in present context is the difference between table 23 concerned with products and table 22 for classifying work results. Products are defined as

“[...] components or assemblies of components for permanent incorporation into construction entities. Products are the basic building blocks used for construction. A product may be a single manufactured item, a manufactured assembly of many parts, or a manufactured operational stand-alone system”.<sup>35</sup>

Products are applied in work results onsite that ‘represent completed entities that exist after all required raw materials, human or machine effort, and processes have been provided to achieve a completed condition.’<sup>36</sup> These two definitions seem to provide a distinction between off-site-produced products as being purely physical deliveries (table 23) and on-site produced *results* as combinations of processes, products and raw materials (table 22). Work results can even be purely procedural involving only labour and equipment as e.g. trenching or foundation work. (ibid:3). Integrated product deliveries as they will be defined for later use in this thesis somehow combines the product facet and the work result facet as different *dimensions* of integrating complexity in a delivery.<sup>37</sup>

### Discussion

One of the general problems of all classification is that it points towards a static world based on universal and discrete non ambiguous entities. The systems theorist, Ludwig von Bertalanffy, whose thoughts will be presented further in a following section<sup>38</sup>, presents classification as an old fashioned way of conducting scientific work with roots in Greek Antiquity:

“The Greek conception of the world was static, things being considered to be a mirroring of eternal archetypes or ideas. Therefore classification was the central problem in science, the fundamental organon of which is the definition of subordination and superordination of concepts. In modern science, dynamic interaction appears to be the central problem in all fields of reality. Its general principles are to be defined by system theory’  
(Bertalanffy 1968:88)

35 *Omniclass*, Table 23, page 2 – accessed via <http://www.omniclass.org/> on August 18, 2011

36 *Omniclass*, Table 22, page 3 – accessed via <http://www.omniclass.org/> on August 18, 2011

37 See *Systems Terminology*, II.5

38 See *General Systems Theory*, II.4

39 The cases of *Arup Associates* and *NCC* are both examples of such company internal use of classification systems. See part IV – ‘Model’

In a complex modern society it is difficult to formulate definitive all-encompassing classifications and although many national and international attempts – some of them described above – have been made, they all seem to face the problem of trying to be both detailed (read: specific) and structural (read: general) at the same time. The main problem of all of these elaborated classification systems is that they, through mechanistic aggregation of parts, seek to arrive at wholes in a way that is very foreign to the way these wholes are actually conceived as architectural designs. They are rather conceptualised as integrated wholes that subsequently have to be split up in its constituent elements. However if we are to bridge the gap and avoid troublesome translations between how architecture is conceived and how it is subsequently produced or constructed neither of these strategies are a plausible path and the consequence is that the supposedly universal classification systems are used only in simplified versions.

More sophisticated classification and management systems are sometimes, as will be described in some of the later case studies, developed within large companies for their own internal use – often as modifications of one the national or international standards.<sup>39</sup> Although fairly elaborated, by being local these systems often cause considerable translation work when other parties get involved and rather produce company internal sub optimisation that real benefits for the construction process and the architectural result as a whole. None of the existing classification systems seems to have root in how architecture is conceived – or at least have taken into consideration this (necessary) aspect. They do not facilitate the translation from architectural concept to ‘project production’. The following sections take a peek into the product industry to see how industrial production theory seeks to manage complexity of industrial production and sophisticated products.

## II.3 INDUSTRIAL PRODUCTION THEORY

### INTRODUCTION

The two previous sections have concentrated on architecture and the construction sector where building projects are mostly regarded as discrete projects rather than as products on a continuous line of production. However, as construction become more industrialised and more processes move from the construction site into factory environments, the links to and the inspiration to draw on from the general production industry become evident. Standardised and industrially produced building materials and components are not a new phenomenon – probably as old as industry itself – but the complexity and sophistication of these deliveries have increased although not to the same extent as within the production industry in general.<sup>40</sup> The link to the industry has lately been further enhanced by the fact that while industry originally was based on the idea of mass production of uniform objects, new processes, techniques, and business models have yielded more individualised and customised products. The one-off projects of construction and the standardised products of production seem to be approaching each other from different sides and intersect e.g. in concepts like mass customisation and configuration. The current section introduces core concepts from industrial production theory that are relevant in the context of industrialised architecture and construction and thus addresses the question of how the industrialisation of building processes and their results – the architecture – can be conceptualised. Based on a literature survey, this section mainly draws on Ulrich & Eppinger's *Product Design and Development*, Baldwin & Clark's *Design Rules – the power of modularity*, *The Power of Product Platforms* by Meyer and Lehnerd, and *Essentials of Supply Chain Management* by Hugos. Furthermore several paragraphs from *Arkitektonisk Kvalitet og Industrielle Byggesystemer* (Architectural Quality and Industrialised Structural Building Systems) co-authored by the author have been adapted for the present use (Ulrich & Eppinger 2008; Baldwin & Clark

40 The degree of prefabrication does not necessarily have a direct linear relation to the complexity and sophistication of industrialisation. Much of the so-called prefabricated construction is merely construction under roof with only limited use of industrial techniques, processes and business models.



FIGURE II.3.1  
TAASINGE TRÆ, DENMARK: INDUSTRIALISED PRODUCTION OR CONSTRUCTION UNDER ROOF?

2000; Meyer & Lehnerd 1997; Hugos 2006; Beim, Vibæk & Jørgensen 2007)

#### *Hypothesis and questions addressed*

Industrialisation within the production industry has moved from standardisation of products towards standardisation of processes thus extending the concept of ‘the product’ to include processes, techniques and business models that are equally applicable within construction – even when it comes to one-off building projects.

The hypothesis is addressed through the following research question:

- a) Which concepts from industrial production theory are applicable within the context of building projects and architectural design?

## CONCEPTS FROM THE PRODUCTION INDUSTRY

### *Product architecture*

A concept widely used within the production industry when discussing design issues is *product architecture*. According to Ulrich and Eppinger the ‘*product architecture is the assignment of the functional elements of a product to the physical building blocks of the product.*’ (Ulrich & Eppinger 2008). In order to reduce the complexity of a product (architecture), the different physical elements are assembled into a number of major building blocks that often are referred to as ‘chunks’ (Ibid: 165). This division into a number of major constituent elements – the chunks – is often called *modularisation*. The functional elements are the different functions that together constitute the overall performance of the product. For e.g. a mobile phone some of the usual functions are emitting and receiving sound (i.e. conversation), displaying the status of calls and other information, storing contact information, protecting sensitive electronic parts etc. whereas the corresponding physical building blocks for these functions are loudspeaker, microphone, LCD-screen, memory unit and casing. The relationship between the two genres of elements, however, is not necessarily one to one: Where each building block can encompass various functional

elements, the performance of a functional element can equally comprise several building blocks. These are cases of integration – integration *within* chunks or integration *across* chunks. The opposite is modularisation – clear physical separation between different functional elements. Following from this distinction, the product architecture of a design cannot be derived simply through the functional definition of a product. Assigning functions to physical elements – thus establishing the product architecture – is an act of design itself and often has several more or less adequate solutions. It can be predominantly integrated or predominantly modular but mostly have (functional) elements of both kinds. Modules, modularity and modularisation vs. integration will be introduced more thoroughly below.

In product development, the concept of *system level design* designates a phase between the concept development and the detail design. A system level design is required when developing complex technical systems with many interacting subsystems and components as e.g. automobiles, airplanes or even smaller systems like a photocopier. Ulrich & Eppinger (2008) defines the system level design phase as including:

“[...] *the definition of the product architecture and the decomposition of the product into subsystems and components. The final assembly scheme for the production is usually defined during this phase as well. The output of this phase usually includes a geometric layout of the product, a functional specification of each of the product's subsystems, and a preliminary process flow diagram for the final assembly process.*”  
(Ulrich & Eppinger 2008:15)

It is in this phase – and before the detail design is determined – that the product architecture is established. In the earlier conceptual phase multiple product architectures may be considered as competing concepts (ibid:21). Interesting here is that it thus integrates the way the product is produced and assembled from its constituent elements – subsystems and components – into to the way the product is designed. For the product industry, this to some extent addresses the problem of the gap between conception and production process as stated as a main issue in this thesis for architectural creation and construction.<sup>41</sup>

Important to point out is the – for an architect little confusing – use of the word ‘architecture’. Particularly within engineering and computer science the

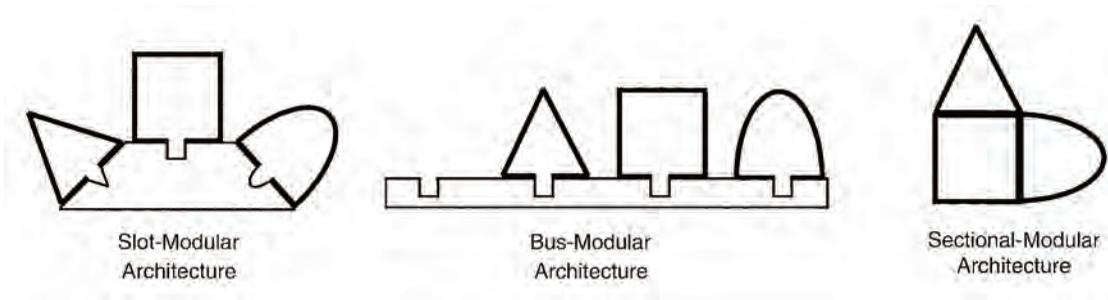
41 That such a problem also exist(ed) in the product industry is suggested by e.g. Meyer & Lehnerd as described further below.

- 42 A formal definition of this new term can be found in *Systems Terminology*, II.5
- 43 Structure in the sense of *organisation*.

term is widely used as referring to the structural organisation of elements of both physical and non-physical nature and has little to do with the spatial, material, constructional and other less tangible qualities of an integrated architectural approach within building design. The structural organisation of elements – the product architecture – in the production industry is touching upon how people, production processes and products are organised in order to reach a coherent final result. The choice of a specific product architecture in product development can have various strategic agendas: economy and time will often have important weight and be an inherent part of other agendas like e.g. life cycle considerations, design for manufacturing, design for disassembly, complying with a product platform, or market availability for subsystems or components. In order to avoid confusion and to adapt the notion of product architecture to a context of construction, the product architecture of architectural design and construction will tentatively be termed the *system structure*.<sup>42</sup>

### *Modularity and integration*

Modularisation and integration are, as reflected above, closely related to the concept of product architecture. Both are as opposites concerned with structure<sup>43</sup> and describe how the different functional and physical elements of a product architecture are respectively on the one hand either isolated as modules (grouped together or one by one) with clear interfaces to surrounding *modules* or – on the other hand – integrated across the product architecture. The latter situation can be compared to traditional construction where many different systems as e.g. structural system, heating system, façade openings and insulation are distributed over the entire building. Ulrich and Eppinger point out that integral design solutions often aims at the highest possible performance of the particular product in mind (ibid:166). Modularisation rather aims at combining product variety and production advantages concerning both time and price and introduce the possibility of *delayed differentiation*. An example used by Ulrich and Eppinger is the power converter of e.g. a printer that, although the printer itself is the same sold all over the world, has to vary according to national differences in voltage. By adding this element as separate and later in the supply chain, the differentiation is delayed thus meeting both the demand for rational mass production and adaptation to local market conditions (ibid:179). However the question of modularisation and integration is about a balance and seldom, or perhaps never, an either/or choice. Three generic types of modularity of product architecture are described. The types have to do with different ways of defining the interface conditions of the modules and are (See figure II.3.2):



- slot-modular (product) architecture
- bus-modular (product) architecture
- sectional-modular (product) architecture

FIGURE II.3.2  
ULRICH & EPPINGER'S THREE GENERIC  
TYPES OF MODULARITY

While the slot-modular interface condition dictates that different elements or chunks have different interfaces to a basic structure, a bus-modular interface condition refers to a uniform interface between modules and basic structure. The sectional-modular interface condition is also characterised by a uniform interface but here non-hierarchically and directly between modules themselves as opposed to between the modules and a basic structure. The basic structure is also called a platform and will be explained further below.

Joseph Pine among others work with a similar but enhanced taxonomy of modularity with six types that is less concerned with the specific interface condition and rather focus on the strategic aspect of how the module form part of the whole (Jørgensen 2007:47f). The six strategies are:

- component sharing modularity
- component swapping modularity
- cut-to-fit modularity
- mix modularity
- bus modularity
- sectional modularity

*Component sharing* is about using the same module in different contexts like the same Black & Decker motor in various power tools – or a bathroom pod in different buildings. *Component swapping* is the other way around about coupling different modules to an otherwise identical context. Examples could be the Swatch watches – or later added different sunrooms to an otherwise homogeneous group of dwellings. *Cut-to-fit* is when an otherwise standardised module is size-adjusted to the specific context. *Mix* can involve the three former strategies but the different ‘modules’ are mixed together and practically indistinguishable from each other like in a bucket of paint in a specific (mass) customised colour. *Bus* covers both the slot-modular and bus-modular type from above and is about the idea of a basic structure – a platform – where a number of different modules are ‘plugged’ into – either via a standard interface (bus) or a module specific interface (slot). Examples of both can be found in a personal computer where the USB-plug (Universal Serial Bus) enables bus-

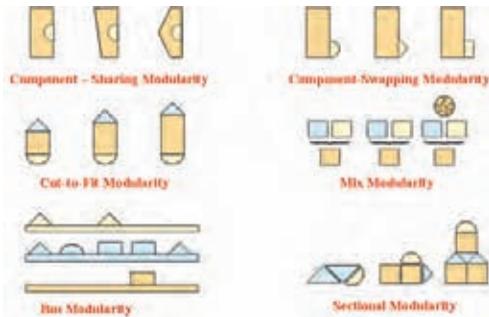
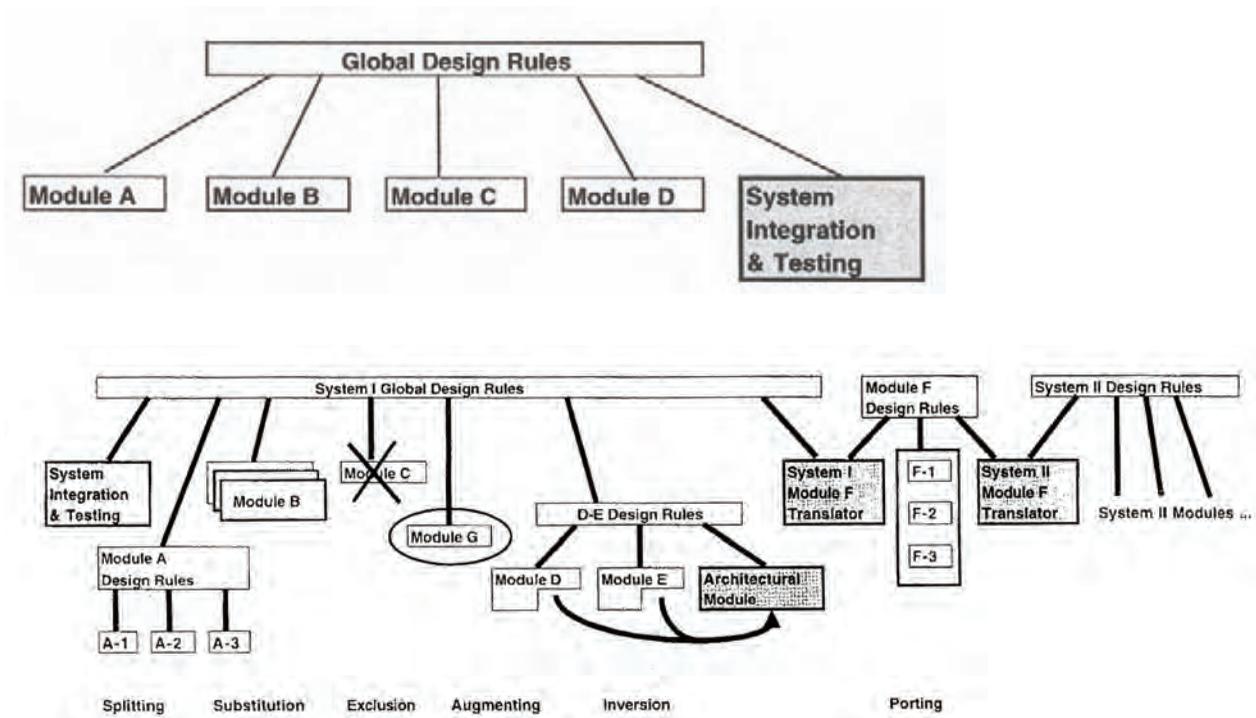


FIGURE II.3.3  
PINE'S SIX MODES OF MODULARITY

44 Here is a parallel to the *Omniclass* distinction between *product and work result* in construction works as presented in the previous section, *Classification systems in construction*, II.2

modularity to many different modules whereas the monitor plug represents the more specific slot-modularity. In construction a structural frame can be seen as a bus (a basic structure or platform) based on either bus or slot modularity or a combination of these. Finally, the *sectional* strategy equals the sectional-modular type above where there is no hierarchy of a basic structure (or platform) and added modules but just coordinated modules that all have one and the same standardised interface. The LEGO-toy is a good product example of this strategy. The sectional strategy and modularity is seldom found in construction but is also the hardest one to achieve due to the requirement of one common interface between widely varying functional and physical modules (Ibid:50). This is e.g. much easier in the USB-plug where only electric power and digital signals are exchanged through the interface. (See figure II.3.3)

According to Baldwin and Clark that deal specifically with the impacts of modularisation in the product industry, integration requires a high degree of overall design coordination in each specific case whereas modularisation in the sense of isolating discrete systems within chunks makes possible to '*change pieces of a system without redoing the whole. Design becomes flexible and capable of evolving at the module level*' (Baldwin & Clark 2000:6). Here lies the power of modularity that has resulted in considerable innovation and growth in the product industry by facilitating the elaboration of complex products made out of several simpler subsystems that can be designed independently while still working together as a whole (Ibid). Modularity eliminates the factor of limitation of individual human capacity to learn, think and act. Baldwin and Clark consider these complex products as complex adaptable systems that apart from the products themselves also encompass the applied technologies (processes), the involved firms and the receiving market (ibid:2). Modularity can not be isolated to the physical structure of the product alone – it integrates process and organisation.<sup>44</sup> A certain physical division yields a certain procedural and organisational division and equally the other way around. One could say that these different structural dimensions of a product display *isomorphism* = similar structure (ibid:11). The next section, *General systems theory*, returns to this notion of isomorphism as a specific systems property. Another characteristic of modularity is the *nested hierarchical structure*:



“Here we define modularity as a particular pattern of relationships between elements in a set of parameters, tasks or people. Specifically, modularity is a nested hierarchical structure of interrelationships among the primary elements of a set [...] a pattern of nested hierarchical blocks’ (ibid:11)

In the attempt to operationalise modularity as a specific design strategy, Baldwin and Clark arrives theoretically at the establishment of six modular operators as “things that designers can do” to a modular system’ (ibid:123). The operators express some of the important dynamic possibilities that lie in working with modules as an active part of the design process. Again modules can be physical chunks, tasks or people:<sup>45</sup>

1. *Splitting* a design and its tasks into modules
2. *Substituting* one module design for another
3. *Augmenting* by adding a new module to the system
4. *Excluding* a module from the system
5. *Inverting* to create new design rules
6. *Porting* a module to another system

In complex adaptive systems operators are actions that change existing structures – or design concepts – into new structures in well defined ways. The operators constitute a set of actions that make sense for hierarchical divisions and arrangement of blocks (ibid:131) – as modular product architectures are examples of. Other operators could also be formulated. The *integration* of two or more sub modules into one could be an obvious one.<sup>46</sup> The ideas behind the six operators above are relatively easy to understand except perhaps for the two latter. *Inverting* refers to the splitting, generalisation, and transfer of a sub module or part of a module (of function or process) to a higher level thus serving various sub levels. An example from the computer industry is a printer

FIGURE II.3.4 & II.3.5  
MODULES AND MODULAR OPERATORS  
BY BALDWIN & CLARK

- 45 In their conceptual integration of product and process Baldwin and Clark claim to be inspired by John Holland
- 46 Baldwin & Clark regards integration as the exact opposite of modularisation which is probably why it has been left out as a specific operator for modularisation. However, changes made to a given product architecture could easily result in a combination of integration and modularisation as defined by the six operators above.

47 Commoditisation in construction is later in this thesis presented as a strategy to reduce the complexity of the architectural design task. See *Commoditisation in architectural construction*, III.1

driver that is needed in many programs to communicate with the printer (word processors, drawing programs, web browsers, picture manipulation programs etc.). Instead of integrating a driver in each program this driver is generalised on a higher level in the hierarchy and redundant repetition is avoided (ibid:138). In construction, the delivery/production of a certain function, material or component found in various chunks of a modularised structure could be coordinated in order to reduce space need or facilitate bulk buying. The *porting* of a module to another system points towards the *commoditisation* of a module thus making it applicable and potentially even reusable in other design contexts.<sup>47</sup> (see figures II.3.4 & II.3.5)

The appearance of modular designs – a process that according to Baldwin & Clark began around 1970 – has led to the forming of *modular clusters* which are ‘group[s] of firms and markets that “play host” to the evolution of a set of modular designs’ (ibid:16). If certain modules and their particular interface definitions become sufficiently established, industry will adapt to it and emerge around them. In construction this effect is so far mostly known on a relatively simple component level as e.g. bricks, chipboards or windows. More complex systems as e.g. bathroom pods and façade cladding are beginning to form networks of sub suppliers but they can so far not be characterised as modular clusters.

### ***Product platform and product family***

In accordance with the bus- and slot-modularity introduced above, many products based on modular principles are based on a combination of a basic structure and a number of modules that are connected to this structure. True and complete sectional modularity (see above) where modules of a product architecture are structured in a non-hierarchical way based on one or few standardised and universal interfaces is marginal within the product industry and practically non-existent in the construction industry. Complex artefacts – as e.g. buildings – simply include too wide a range of functional elements too make it plausible to have a common interface. A basic structure of a set of common components or a core technology where different modules are added, attached or inserted is, within product development, called a *product platform*. The platform itself can also be modular facilitating the possibility of evolution over time. As with modularity, the constituent elements of product platforms can be both products and processes. The combination of a product platform and a number of different modules that can be combined in different ways to form different products are called a *product family*. Meyer & Lehnerd

defines a product family as *'a set of products that share a common technology and address a related set of market applications'* (Meyer & Lehnerd 1997:16). Product families can also evolve over time thus representing various generations of one or several products – a 'family'. The idea is that the re-use of the platform can save both time and money in the development of new products that consequently can hit the market faster and at a more competitive price. Quality-wise, platforms can be seen as a way to integrate well tested solutions into new products.

Black & Decker is an early and well studied example of the advantages in developing a product platform as the base for a product family of power tools. The outset was the following:

*'As with most established companies, Black & Decker's product portfolio had evolved over many years; by 1970 it was a collection of uncoordinated designs, materials and technologies. Its power tools relied on thirty different motors, each manufactured by a different set of tooling. Sixty different motor housings were needed to accommodate variations in power and application (e.g. a drill versus a saw or a sander). Besides the company relied on 104 different armatures, the part that connects the motor to the "business end" of the tool (e.g., to the drill bit or the saw blade). Each of those armatures, in turn required its own tooling. Dozens of different switches and buttons populated the company's parts bins and bills-of-materials'*

(Meyer & Lehnerd 1997:3)

Due to an external legislation demand imposing double insulation in all power tools in order to protect users from electrical shock in the case of failure of the first insulation system, Black & Decker was forced to adapt their entire product portfolio (ibid:4). This was used as the occasion to a) redesign all consumer power tools at the same time and b) redesign manufacturing simultaneously. The goal was to offer the new double insulated products at no increase in price.

The most common part of the different tools were identified as the motor which subsequently became a major subsystem of the new product platform in the form of a universal motor that replaced the 30 different independently developed motors of the earlier product line. Furthermore the production of it was fully automated and it was designed with a plug-in connection thus

eliminating the need for manual wiring at assembly. The new motor had a fixed diameter and the power of different versions for the different tools (drills, sanders, jigsaws or grinders) could be varied simply by increasing the stack length of wrapped copper and steel – all possible within the same automated process on the same production line. Equally the armature of all tools were standardised as a major subsystem and became part of the platform. Gears and other elements were also standardised and integrated into the platform while other parts, as e.g. the drill chuck (device to tighten drill bits), became modules used within parts of the product family (the drills). The increased volume of purchase of each standardised sub-element or material also facilitated bulk buying and good pricing from suppliers (ibid:9f).

In the Black & Decker example, manufacturing became a key driver – although not the only one – for the design solution. The specific manufacturing solution became a *'key enabler of a radical new product platform design'* (ibid:6). Similar to the gap between architectural ideation and subsequent construction, the product industry also traditionally distinguished between initial engineering (design) and subsequent manufacturing. This was radically changed at Black & Decker and supported organisationally by integrating manufacturing engineers in the design team from the outset thus *'bridg[ing] the traditional divide between engineering and manufacturing'* (ibid:15)

Meyer & Lehnerd sums up a *thought management architecture* (read: structure, ed.) of five principles based on the idea of product platforms and families that they claim powerful and generalisable to any product-making company (ibid:16):

1. Use of product families and platforms as basis for management and planning
2. Simultaneous design for production – as the integration of product and manufacturing design (product and process)
3. Global product design and market development – concerning both sourcing and sale
4. Discovery of latent, unperceived customer needs as basis for new platforms
5. Endeavour for elegance and simplicity in design – not just adding functionality

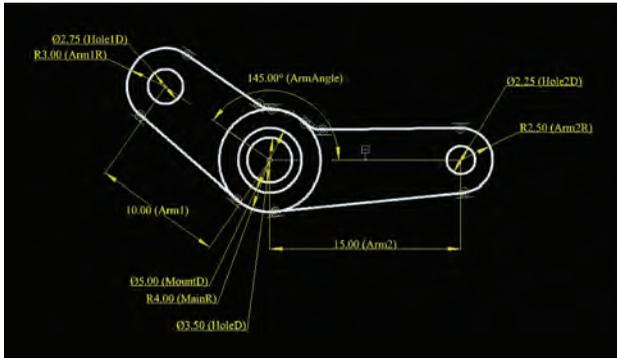


FIGURE II.3.6  
A PARAMETRIC MODEL AS E.G. HERE  
FOR A LINK ARM CAN QUICKLY BE  
MODIFIED BY USING GEOMETRICAL  
AND DIMENSIONAL CONSTRAINTS

### Configuration and mass customisation<sup>47</sup>

While originally used exclusively within the field of geometry, the notion of *configuration* is today widely used within the product industry, particularly referring to products that production or sales wise have some degree of openness as systems that make them adaptable to different context or different customers. Configuration is about the ordering of a number of elements into a whole and the shape or (organisational) structure that results from this. To *configure* is then the act of ordering or joining elements into a whole. As used within the product industry these elements are often drawn from an already existing or known ‘pool’ (conceptual or physical). The concept is inextricably connected to the concept of *mass customisation* that will also be treated in this paragraph and also have connections to what within CAD-programs today is referred to as *parametric design*<sup>48</sup> (see figure II.3.6). Instead of virtually having limitless possibilities, configuration implies the establishment of a solution space defined through a number of standards and parameters. This does not necessarily lead to a finite number of solutions as standards and parameters can have continuous ranges of value. However, in its true meaning it does establish clear limits to what is possible. Through configuration in the product industry, at least theoretically, a unique solution is produced in each case by adapting the variable parameters within a certain platform or *product configurator*.

A product configurator is typically a piece of software that generates a digital parametric model of a given product (e.g. a building component) based on a number of variable values or simple design parameters. Parameters could be length, height, material etc. This model can be visually accessible to the user but can also simply be (numerical) values on e.g. an Excel-sheet feeding a production system directly with instructions. The configurator can be accessible on the web page of a manufacturer or supplier and can be directed towards different user groups: On the one hand, the configurator can be developed for use in the manufacturing company as a way to rationalise and make more efficient the internal information and workflow. It can form the basis for the elaboration of e.g. production drawings, parts lists, price determination, and bidding or in some cases be directly linked to the digitally controlled production machinery. On the other hand, the configurator can be developed as a tool for use in detail design/design development and execution phases. A product configurator in a way automates the integration of the expert knowledge from the manufacturer thus supporting a design for manufacturing approach in the design and avoiding expensive and time consuming ‘translations’ from concept

47 This paragraph is mainly (author’s own) adapted translation from (Beim, Vibæk & Jørgensen: 2007:28ff). Other direct sources are stated as references.

48 Behind the concept of *parametric design* lies an intention of defining a ‘design engine’ or model that can generate manifold designs from a given set of parameters that in each case are assigned individual values. Although this system produce different answers to a well defined design problem, the design of the system – the design engine itself – is not a well defined problem with a clear purpose.



FIGURE II.3.7  
VELUX HAS A WEB-BASED END USER  
CONFIGURATOR

- 49 The IT-revolution has from the invention of the integrated circuit provided increasingly better possibilities for handling information but has also resulted in an explosion in the amount of available information through new (digital) distribution channels (internet pages, e-mail, e-communities etc). A precise measurement of available knowledge and information in the world is hard to define but some sources estimates that knowledge is doubled in 6-7 years. See e.g. [http://www.ebst.dk/publikationer/rapporter/eksport\\_kontrol\\_system/kap04001.html](http://www.ebst.dk/publikationer/rapporter/eksport_kontrol_system/kap04001.html) accessed on August 31, 2011

to actual production. Finally, a configurator can be a tool purely for communication and visualisation in a sales situation providing customer information about product appearance, price, delivery time for a (mass) customised solution etc. Ideally, configuration integrates all of these issues into one single integrated configurator. This, however, is seldom found. Configuration can be understood as a shift from traditional drawing, project design and planning to an object based ‘intelligent’ digital modelling with continuous and direct reuse of data created during the different phases of the design process.

“*The fundamental principles of modularisation and configuration can be summed up as an attempt to develop modules that have common characteristics related to the internal workflow of the manufacturer – i.e. construction/customisation, production, assembly and installation – that at the same time can be varied in order to meet customer needs. In that context, one of the big challenges is to develop modules that can vary according to the parameters that the customer focusses on and that gives the customer value. As an example, the car manufacturers seek to standardise all ‘hidden’ parts that do not have direct importance for the customer whereas possibilities for variation are created for the parts that are directly visible and important for the customer valuation of the car*’ (author’s translation from Mikkelsen et al 2005 cited IN: Beim et al 2007:29)

Within construction, the notion of configuration has also gained currency in the more general meaning of adaptability – e.g. in the context of the built-in capabilities of a plan layout to adapt to changing needs of the inhabitants i.e. relocation, removal or installation of partition walls. Configuration in this meaning is not so much about the production of a configurable product as it is about a continuous relation between product and user over time.

The notion of *mass customisation* was first time introduced in the book *Future Perfect* by the North American Stan Davis in 1987 and subsequently elaborated by the other North American business theorist Joseph Pine II e.g. in *Mass Customization: The new frontier of Business competition* (Davis, 1987) (Pine, 1993). *Mass customisation* encompasses the combination of the advantages in mass production on the one hand and the ‘tailor made’ unique solutions on the other hand. This combination has primarily been made possible through the application of modern IT-technology.<sup>49</sup> Crucial for a successful *mass customisation* is the determination of an appropriate solution space.

*“The solution space can be very narrow thus not enabling variation that can satisfy a broad range of customers – hence Mass Customization is not achieved. Or, the solution space can be very broad thus making possible great variation that gives the individual customer a better possibility of getting a personally suitable product – hence Mass Customization is achieved.”*  
(Jørgensen, 2007:43)

The German professor of management, Frank Piller formulates the concept of mass customisation in the following way thus integrating the aspect of (end) user or customer involvement (and not only the customisation itself) as an important characteristic:

*“Following the simple definition, mass customisation means to produce unique objects with the efficiency of mass production. The traditional balancing between either producing individual objects expensively or producing standardised objects cheaply has been overcome. When you look upon mass customisation over the last ten years I will however add that the most brilliant is that it involves the consumer in the design process. The unique thing is that in order to create individualised objects you have to involve the customer or the consumer in the process”*  
(author’s translation from Mossin 2006 cited IN: Beim et al 2007:30)

The notion has its origin in the product industry’s attempt to meet the increasingly pronounced demand for individualised and flexible user and context adapted products. For the *construction* industry it must be decisive to relate to whether a building can be seen as a product and, if yes, how! Is the building e.g. rather to be seen as a complex and unique whole of (industrialised) products than as one single product? An important difference between ‘contemporary’ industrialised products and construction projects is the significance of the platform. In e.g. the car, industry variation of the platform even across different manufacturers is quite limited while most product variants deals with relatively superficial properties as colours, surfaces etc. In construction, if the platform is defined as the structural building system, its possible variations have much more direct significance for the end-user – the inhabitant. This platform does not constrain the choice of colours, surfaces etc. but is decisive when it comes to the spatial and organisational possibilities and flexibility in the final design – and its possible change over time and during use.<sup>50</sup> Changes in (choice of)

50 Flexibility can have different connotations in construction. For authors own discussion of the notion of flexibility in architectural systems distinguishing between design flexibility, conversion flexibility and flexibility of use see (Beim, Nielsen & Vibæk 2010:26ff)

- 51 See explanation of delayed differentiation above
- 52 See definition of *design for X* further below

structural system are much deeper and design decisions and production of the structural system is mostly located earlier in the design process making delayed differentiation difficult.<sup>51</sup>

### **Supply Chain (Management)**

As division of labour has evolved in modern complex societies, the specific task of each individual and/or company has become ever more specialised. From having a close connection between the work performed and enjoying the fruit of it, most people on earth today engage in an extremely complex web of exchange of matter and services ultimately coordinated by one single means: money. A supply chain is a kind of systems approach that expresses how products (or service products) come into being through a sequence or web of processes performed by a sequence or web of different operators that transform resources into end user products to be used and/or consumed. Company internal supply chains are often referred to as logistics. According to Nagurney:

“*A supply chain, or logistics network, is the system of organizations, people, technology, activities, information and resources involved in moving a product or service from supplier to customer. Supply chain activities transform natural resources, raw materials and components into a finished product that is delivered to the end customer. In sophisticated supply chain systems, used products may re-enter the supply chain at any point where residual value is recyclable*”

(Nagurney 2006)

Interesting about Nagurney’s definition is also the latter part that indicates the possibility of an after life of a product or parts of it through recycling after the end of its useful life. This ‘second half’ of the supply chain has lately gained increased attention due to raised awareness of the finite number of resources available for man on earth. Consequently design today must to some extent take into account this after life as well as the other way around actively use recycled resources in new product design. Designing the supply chain has become an integral part of product design itself and is e.g. expressed in terms like *design for manufacturing and design for disassembly*.<sup>52</sup> Another point is that supply chains both express the operators, the operations and the product as it advances through the chain – or as Hugos puts it: ‘*Supply chains encompass the companies and the business activities needed to design, make, deliver, and use a product or service*’ (Hugos 2006:2). Simple supply chains focus exclusively

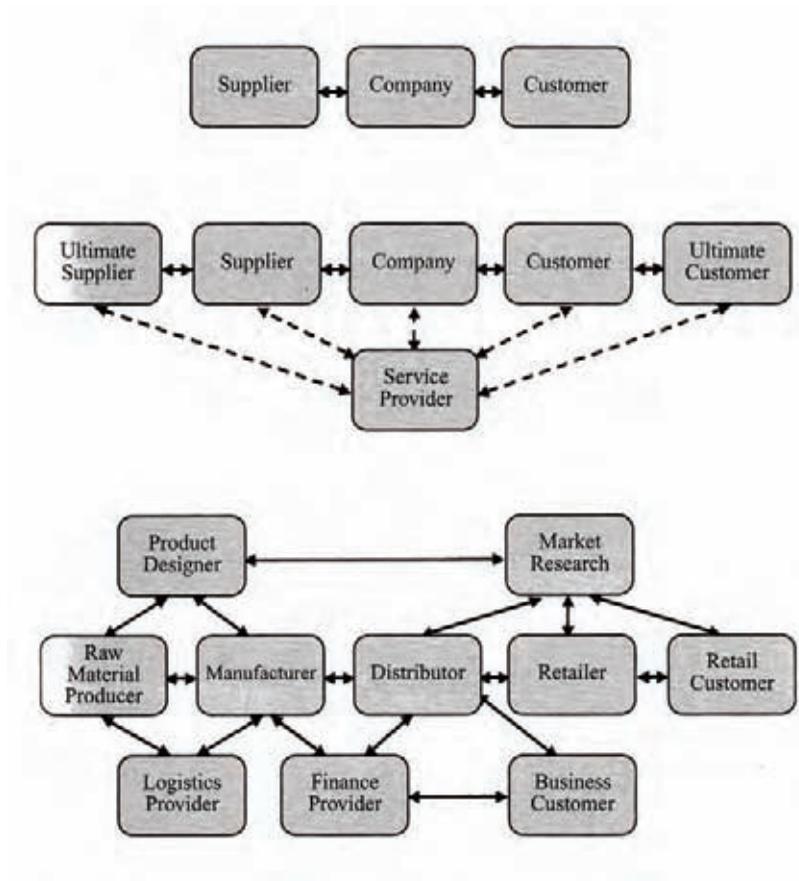


FIGURE II.3.8  
SIMPLE SUPPLY CHAIN DIAGRAMS, BY  
HUGOS

on the material flow from a supplier over a processing company to a customer whereas extended supply chains can include the entire material flow as well as the different service providers delivering immaterial contribution i.e. design, transportations, finance etc. The terms *upstream* and *downstream* are commonly used in relation to supply chains. Upstream refers earlier in or in the beginning of whereas downstream refers to later in or at the end of a supply chain. Using the metaphor of a creek or a stream (of water) makes it intuitively easy to understand that upstream is prior to downstream. Processes or operators are located along the stream while the material flows through the supply chain from raw material to finished product. In practice, supply chains are often purpose specific (focussed) in the ways that they are designed or viewed from a certain standpoint i.e. a manufacturer's only including what in their perspective is relevant upstream (suppliers) and downstream (customers). In such supply chains *tiers* refer to the number of supplier links between the manufacturer and the suppliers. On the first tier (1) are the direct suppliers whereas tier 2 are indirect suppliers (suppliers of suppliers) and tier 3, 4 etc are further upstream. In some cases the tiers are also used as a way to define the complexity level of a (physical) supply as e.g. tier 1: complete components, tier 2: sub-components, and tier 3: raw materials.<sup>53</sup> Tier categories can vary. Simple diagrams of supply chains including immaterial supplies can be seen in figure II.3.8.<sup>54</sup>

The discipline of designing and managing adequate supply chains in order to meet customer demands efficiently is simply called *supply chain management* and arose as a common term in the late 1980's to become widely used from the 1990's (Ibid:3). Adequate supply chains are a trade-off between what Hugo calls responsiveness and efficiency and the goal is ultimately to *'increase*

53 See e.g. <http://www.witiger.com/internationalbusiness/SupplyChainManagement.htm> accessed on July 24, 2011

54 The distinction material/immaterial is not completely consistent in the sense that even the product itself can be more or less immaterial as e.g. a piece of software, a service in itself or merely an experience cf. *experience economy*. See *Commodification in architectural construction*, III.1

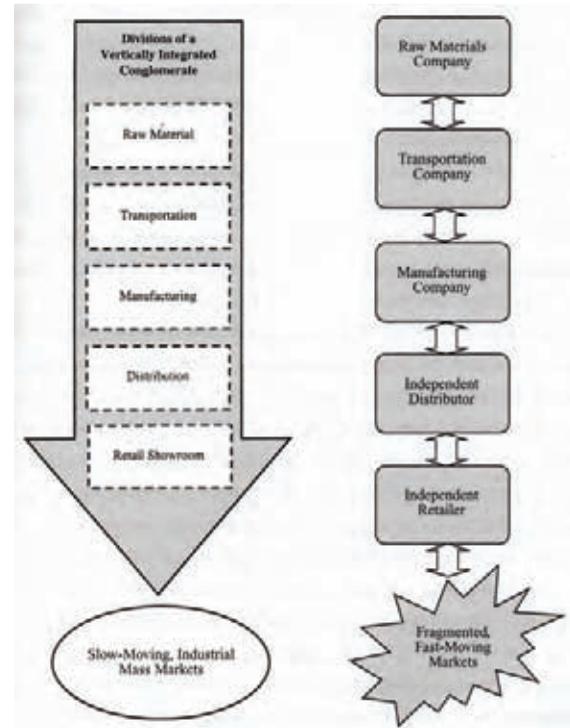


FIGURE II.3.9  
TRADITIONAL VERTICALLY INTEGRATED  
VS. NEW VIRTUALLY INTEGRATED SUP-  
PLY CHAIN

*throughput while simultaneously reducing both inventory and operating expense*' (ibid:9). The latter indicates the competitive business environment that all products and product development face in today's globalised market economy. Products are not just made in isolation to definitively solve a problem or meet a demand. They are constantly pushed by other similar attempts to do the same in better, cheaper and/or faster ways. This drives towards efficient coordination of the realms of production, inventory, location, transportation as well as information – the latter binding the former four together. *'Timely and accurate information holds the promise of better coordination and better decision making'* (ibid:6). In a traditional industrial economy based on slow-moving mass markets this was ultimately handled through vertical integration where business conglomerates as e.g. Ford is ended up controlling the entire supply chain from mining of raw-material over production to the sales of the finished car to the end customer. Ford success was based on what is called economies of scale meaning reducing the average cost per unit. In modern fast moving markets, however, responsiveness – the ability to meet fluctuations in demand or rapidly changing needs – compromises efficiency and rather calls for *virtual integration* where companies choose to focus narrowly on core competencies and partners with other companies and together form flexible supply chains that can constantly be adjusted according to changes in the market (ibid:20). Instead of encompassing entire supply chains manufacturers of complex products use materials, components or assemblies prepared by other manufactures as sub-deliveries for their production. (See figure II.3.9). This strategy is rather based on what is often termed economies of scope meaning the ability to make product diversification economically viable. Product platforms and product families, as introduced above, can be seen as strategies for obtaining both economies of scale and economies of scope by combining standardised parts or modules with customised parts or modules into unique products. This again can be combined with a virtually integrated supply chain. A prime example of this is e.g. the iPhone or other smartphones that act as product platforms for a multitude of apps that are produced by many different suppliers without any direct connection to Apple, HTC or whoever produces nor the phone nor the operating system.

### Systems engineering

Systems engineering is a special (scientific) field within engineering seeking to respond to the problem of increased complexity of engineered products as result of enhanced sophistication in their design (evolution) and the resulting growing amount of specialised knowledge involved. Systems engineering can e.g. be defined as *'a method by which the orderly evolution of man-made systems can be achieved'* (Skyttner 2005:43) or as the *'[...] scientific planning, design, evaluation and construction of man-machine systems'* (Bertalanffy 1968:91). Systems engineering is focussed on the orchestration of the most optimised combination or sequence of available work processes and tools in order to achieve a predefined goal and has roots in cybernetics (control theory) and operations management. Many sophisticated methods and (software) tools have been developed particularly to address systems engineering's particular focus on looking at wholes of interdependent means, processes and elements. One of these, the *design structure matrix*-approach (DSM) will be introduced below.

Systems engineering has greatly enhanced man's capacity to manipulate the resources of our physical environment into products serving human needs. The engineer occupied with this field is sometimes called a *system architect*.<sup>55</sup> Important in relation to (architectural) building design, however, is to note that systems engineering as a strictly technical field is concerned with the *how* of (well) defined problems or goals. *What* the need or goal is, is defined *a priori*. This has roots in the historical split between the liberal and the mechanical arts as pointed out e.g. by both Gevork Hartoonian and Kenneth Frampton as they are referred in the previous section on *Systems in architectural theory*<sup>56</sup>

Peter Checkland, an American systems theorist that will shortly be introduced in the following section exemplifies it in the following way:

” *'The [systems engineering] approach then boils down to expressing the need to be met in the form of a named system with defined objectives (say, a system to build a supersonic aircraft meeting a defined specification within a stated time and to a stated budget; or a system to supply a small town with pure water at a certain rate for a given cost). If the system and its objectives are defined, then the process is to develop and test models of alternative systems and to select between them using carefully defined criteria which can be related to the objectives.'*

(Checkland 1990:17)

55 See e.g. (Maier & Rectin 2009:6)

56 See II.1

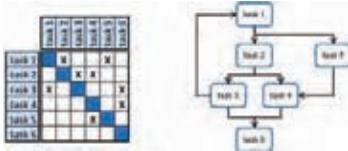


FIGURE II.3.10  
SIMPLE TASK DSM AND THE CORRESPONDING DIGRAPH BOTH SHOWING DEPENDENCIES AND SEQUENCING OF A NUMBER OF TASKS

- 59 See e.g. [www.dsm.org](http://www.dsm.org) and [http://en.wikipedia.org/wiki/Design\\_structure\\_matrix](http://en.wikipedia.org/wiki/Design_structure_matrix) accessed on July 20, 2010
- 60 See e.g. (Lindemann et al 2010:55). For an elaboration of the notion of ill-defined problems see also (Maier & Rechting 2009)

Supply chain management, as introduced above, can be seen as a kind of – or sub-discipline to – systems engineering. It is primarily in this sense that it will be used in present thesis but also the idea of looking at wholes (and selecting between alternatives) will be elaborated as main focus of the following section on *General systems theory*.

### Design Structure Matrix (DSM)

Design structure matrix (DSM) is a matrix representation of a (complex) system like a product/project, process or organisation and can be used as modelling tool or technique that expresses dependencies between elements or modules in this system thus helping to manage the design and organisation of these. The DSM was originally invented by Donald Steward in the 1960's exclusively dealing with time based dependencies of a process. The matrix lines up all elements – or modules – on both a vertical and a horizontal line thus forming a matrix where the interdependencies between the different elements can be registered. In some versions dependencies can be directional (e.g. 'a' depends on 'b' but not opposite) and/or weighed through the use of different values placed on each dependency (See figure II.3.10).

Various manual and algorithmic procedures exist to e.g. sequence elements of a process (*tearing*) in process-DSM's or grouping functional/physical elements into chunks of a product architecture (*clustering*) in product-DSM's. A third 'domain' of DSM's deals with organisational entities. The DSM methods are mostly applied in systems engineering, product planning or project management where products, processes, or organisation entities as well as the design problem are well defined.<sup>59</sup> The traditional DSM-method is less adequate for early design stages as it lacks clear mechanisms to construct the matrix when the constituent elements are ill-defined.<sup>60</sup> However, considerable research and practical application of the DSM and related methods constantly develop the field and the range of techniques. DSM's can in a way be seen both as product architectures and as supply-chains (product DSM's vs. process DSM's or organisational DSM's that can be both simultaneously). This idea of duality or integration of domains has advantages that will be explored later in Part IV – 'Model'. A disadvantage of the DSM's is that they are not so visually accessible. Even with only a small number of elements the matrix quickly disables the overview for manual operations/manipulations and leaves you dependent on the related mathematical algorithms. With a high number of elements the DSM's become very big and the issue of focussing attention and choosing the

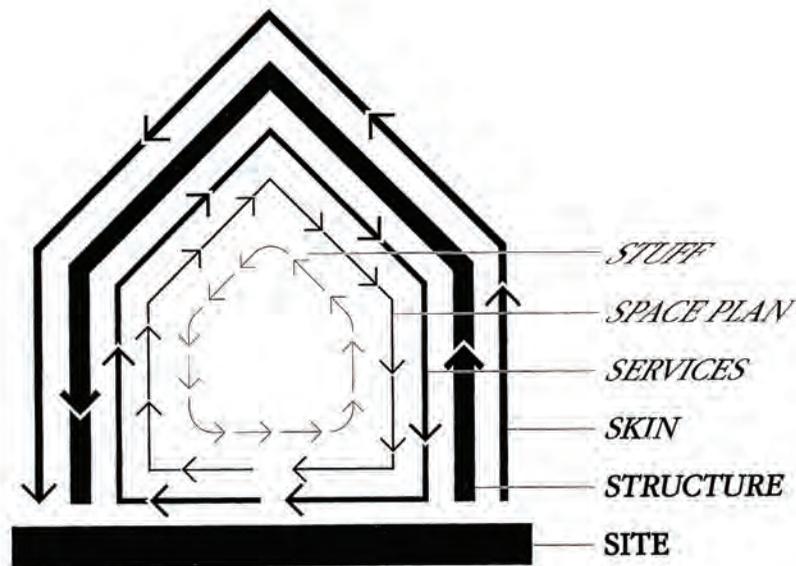


FIGURE II.3.11  
THE SIX LAYERS OF CHANGE IN BUILDINGS BY STEWARD BRAND

right level of abstraction is therefore important.<sup>61</sup> The architect Christopher Alexander has early used similar matrices in his attempts to formulate a more systematic approach to architectural design.<sup>62</sup>

A few international research environments work with the direct application of DSM to construction processes. One is a process focussed *Lean Construction* track around the Finnish Lauri Koskela currently based at the University of Salford, UK. Another is a more product focussed approach dealing with how buildings accommodate to change (adaptability), and is inspired by Steward Brand's model of different building layers. This approach is, among others, found around Professor Simon Austin at Loughborough University in the UK.<sup>63</sup> Brand's model introduces the view that buildings should be designed according to a conception of different layers (of building parts) with different life spans. His fairly simple model which is an elaboration of earlier concepts by Frank Duffy contains six layers (the six S's): Site, structure, skin, services, space plan and stuff. Site is 'eternal', structure (load bearing elements) last 30 to 300 years, skin (exterior building surfaces) change on an average of 20 years, services (mechanical, electrical and control systems) last 7 to 15 years, the space plan (interior layout) 3 to 30 years, while the stuff (furniture and other accessories) change constantly. At Loughborough, the layers are used as a base for coding dependencies (in DSM's) between building parts and components in specific projects in order to understand and provide for a more conscious way of putting buildings together in this sense.

### *Design for X (DfX)*

The notion of *design for x* refers to a wide range of approaches to product design that take on a specific focus during the design process. The 'x' should be understood as a 'variable' that can be replaced by such foci that subsequently leads to different design methodologies. The first of these was *design for manufacturing* and *design for assembly* originally coined by Boothroyd, Dewhurst and Knight in their book '*Product Design for Manufacture and Assembly*' (Boothroyd et al 1994). The idea was that product design from the outset should include considerations about how the product was to be produced and/or assembled. This would generally reduce costs and make product development more efficient and profitable. The issue could, according to the authors,

61 See the following section, *General systems theory*, II.4, for an introduction to notions as *levelled complexity* and *flexible structuration*, dealing with this issue.

62 See *General systems theory*, II.4

63 For an example of the DSM product-approach combined with Brand's layers in construction, see (Schmidt, Deamer & Austin 2011)

- 64 <http://www.betterproductdesign.net/guide/design4x.html> accessed on July 23, 2011
- 65 See *KieranTimberlake-case*, IV.2
- 66 There is e.g. no particular need to elaborate a product architecture for the relatively simple physical composition of a brick.

be addressed through specific procedures concerning the selection of production processes and materials. Design for X methodologies in general address different issues of a product's life cycle or its performance rather than its form or aesthetic appearance and marks within product design a concern for avoiding a too narrow design approach.<sup>64</sup> Other examples are design for installation, design for maintenance, design for ease of use, design for demolition, design for reuse or design for disassembly. The approaches are not necessarily mutually exclusive. The two latter and in particular *design for disassembly* has lately gained special attention due to increased environmental concern whether it be for true altruistic dedication or merely for branding reasons. When an overall aim of the present thesis is to discuss the possibilities and the potentials of bringing architectural ideation and the way buildings are subsequently produced closer to each other it touches upon the same issue within architectural design. Design for X somehow represents a rejection of (architectural) design as a free art and points – used in a general way – towards the reunification of idea, process, and matter. One of the case studies in Part IV – ‘model’ shows a general concern at the office of KieranTimberlake for such a broader design approach bringing in the process as a design parameter. It also analyses a project by this office that specifically addresses the design for disassembly issue.<sup>65</sup>

## INDUSTRIALISED PRINCIPLES IN BUILDING PROJECTS

Product architecture, modularity vs. integration, product platforms and families, configuration, mass customisation, supply chain (management), and the use of DSM-methods as they are used in the product industry can all be seen as strategies used to handle increasing complexity and – perhaps – as ways to reduce the complexity *in focus* when products become complex (adaptable) systems.<sup>66</sup> This does not mean that overall complexity of products is necessarily reduced. Actually the case is most probably the exact opposite: It enables control of more complex products, processes and organisations by introducing system properties that exceeds the scope of the individual product thus combining economies of scale and economies of scope, as explained above. It furthermore enables the partition into relatively independent elements that can be treated separately and in a parallel fashion thus saving both time and resources. The result is a more open and flexible industrialised product solution than the traditional standardised and mass produced product that, however, still encompasses many of the qualities of mass production i.e. uniform quality, fast and (relatively) cheap

production, and the ability to draw directly on earlier experience (i.e. products in a product family). This makes systematic product development easier than for both its mass produced and its handcrafted counterparts. A returning question in this thesis is of course whether such system properties have isomorphic counterparts within the construction industry if buildings and the processes of bringing them into being are regarded as complex systems.

Faced with the problems of coherence in construction, the present section has looked into how (structurally) similar problems within the product industry have been met and partly overcome. It seems plausible to propose that some degree of technology transfer (of concepts, methods and techniques) should be possible between the two fields.<sup>67</sup> This is probably what is already happening in many parts of the construction sector – in particular concerning the processes that are already located in factory environments. Lean-production principles that have not been explicitly treated here are widely applied and have a parallel, *lean construction*, that concentrates on ‘*project based production management in the design, engineering, and construction of capital facilities*’.<sup>68</sup> This track leads rather to a focus on industrialisation of on-site construction processes and has less focus on systematic product development and enhanced commoditisation of such products within the construction industry. Such a project based approach for development – as most traditional construction – in the worst case fails to provide incentives for the development of robust platforms, modules or principles that exceeds the project level and can thus result in sub-optimisation of each project and within a project. Through what Mikkelsen et al. calls ‘*developing in projects*’ instead of ‘*producing in projects*’ (Mikkelsen et al: 2005:7) the learning and knowledge transfer become embedded in the projects and in the work culture bringing them into being rather than in discrete and robust industrialised products that can easier move across borders and find new markets while continuously ‘mutating’ through e.g. the modular operators of splitting, substituting, augmenting, excluding, inverting and porting as described above. The distinction between off-site production and on-site construction is, as will be described in the case analyses of Part IV – ‘Model’, substantiated by e.g. KieranTimberlake and their use of supply chains whereas e.g. Arup Associates in the Ropemaker Place project rather integrates on-site and off-site processes into opaque supply chains of parallel deliveries along new lines of division. The *system structure* model developed as a part this thesis can, among other things, be used to illustrate this basic difference of approach to industrialised architecture and construction.

67 The problems of coherence in construction are mentioned in the ‘*Introduction to the problem area*’ I.3 of the present thesis.

68 See <http://www.leanconstruction.org/> accessed on July 5, 2011

69 See *Findings*, V.1

If concepts and techniques from the production industry are – or can be – used within the construction industry, the next evident question would be what this does to the architectural outcome. Does the architectural expression change parallel to the means and methods to produce it? This latter question will among others be treated in the concluding discussion of the thesis.<sup>69</sup>

## II.4 GENERAL SYSTEMS THEORY

### INTRODUCTION

A previous section looked into ways that the construction sector, through use of classification systems, has sought to address the increasing complexity and fragmentation of knowledge in construction. The result is extremely elaborate classification and identification systems for elements and processes in construction that however, as pointed out, have the side effect of an over specification that only has weak connection to the way architecture is conceived and conceptualised in the early design phases. It can even constrain or complicate this work unnecessarily.<sup>70</sup> The attempt to handle complexity through extensive classification actually seems to further enhance the *fragmentation* of knowledge. On the other hand, the production industry has, as described in the previous section, to some extent managed to combine product complexity with systematic approaches and elements of repetition. The current section widens the scope a little further and introduces (general) systems theory as a way to look at wholes as *relations between* different parts of an interconnected system as e.g. a building or a construction process. By downplaying the individual characteristics of each of the elements in a system, system models represent an alternative and a supplementary way of handling complexity. The basic assumption of general systems theory (GST) is that complex systems present general characteristics (or behaviour) that are relatively independent of the characteristics of their individual parts. This capacity of abstraction could make system models a useful intermediary tool between architectural concept and realisation that could be applied already from early design phases. Another point is the contextuality or openness of system models; they always express a specific viewpoint according to the specific purpose of the model.

First the systems view is introduced as an alternative to traditional worldviews. This leads to an introduction of general systems theory as a distinct scientific discipline and its possible application to the field of architecture. Subsequently architecture and architectural creation is presented as complex systems made of sub-elements being systems in their own right.

<sup>70</sup> For a similar assertion see e.g. (Berlemont 2009): *'The knowledge to be found within the domain of (construction) technology is not structured in such a manner that it facilitates this transfer[into tacit embodied design knowledge]'*

71 I will here not go into a discussion whether this asserted increase in the general material standard of living has been equally distributed among people. Neither will this section deal with the possible long term environmental effect of such human control.

### *Hypothesis and questions addressed*

**Widespread specialisation in construction caused by growing complexity has resulted in fragmentation into isolated fields of knowledge and has produced a need for intermediary models capable of grasping *relations between* these rather than their individual characteristics**

This hypothesis is addressed through the following research questions:

- a) How does (general) systems theory address the balance between specialised knowledge and wholes?
- b) How can (general) systems theory point towards answers to the need for an intermediate model that can help combining specialised knowledge (of architectural construction) into coherent wholes?

## MECHANISTIC VS. HOLISTIC WORLD VIEW AND THE SYSTEMS VIEW

From the emergence of modern science and until recently the world has *either* been seen as a sum of its constituent parts *or*, where science stops, as an integrated entity explained through holistic assumptions established through intergenerational tradition, intuition, faith or pure imagination. Both strategies have their eligibility and usefulness for understanding and navigating in the world but also present clear limitations and severe problems of combination.

Modern science is based on the assumption that exact and highly detailed knowledge can be used to describe real world phenomena and that the degree of detail ‘automatically’ enhances the level of understanding and the explanatory power. This world view is often referred to as *mechanistic* or *atomistic* and has created an enormous amount of specialisations and new sub disciplines within the sciences as knowledge has developed and available information has increased. Modern sciences are *analytic*. Apparently the sciences seem to have enhanced man’s control over the natural world and have enabled an increase in the general material standard of living thus shifting the everyday focus of a considerable amount of human beings on Earth from immediate satisfaction of basic physiological needs and survival towards higher levels on Maslow’s famous pyramid or hierarchy of needs.<sup>71</sup> (See figure II.4.1) This fact has again



FIGURE II.4.1  
MASLOW'S HIERARCHY OF NEEDS

72 See e.g. Vitruvius and Alberti in *Systems in architectural theory*, II.1

further accentuated man's capacity to produce new and specialised knowledge at an ever growing rate. The world is seen as a machine composed of a number of parts each having their particular function. The specialist looks at and describes facts of the separate parts and simple causal relationships between these isolated phenomena in the form of cause-and-effect or stimuli-response. Relationships can be either deterministic or probabilistic the latter (statistical) version softening the hard fact character of knowledge while however still maintaining the focus of one-to-one linear relations. The Hungarian philosopher of science and systems theorist, Ervin Laszlo (1932-), describes the basic problem – or limitation – within this mechanistic worldview through the observation that real world relations seldom are these simple one-to-one or one-to-few relations. What such explanations lack is the capacity to explain or predict how even small groups of elements interact when they are exposed to several different influences at the same time (Laszlo 1996:3). He exemplifies with the behaviour, techniques, and tactics of an athletic team or a business corporation whose properties cannot be meaningfully reduced to the sum of their individual members who can be replaced without causing noticeable difference in the whole represented by these social entities (ibid:5). This problem of the mechanistic world view can be generalised to anything from atoms or molecules in the small scale to entire societies or ecosystems in the large scale. The specialised sciences pursue knowledge in depth but also in isolation that often – and increasingly – fails to integrate this knowledge in breadth. The result is fragmentation where different fields of knowledge even within the same discipline potentially lose the capacity to intercommunicate and coherence is lost. Without coherence between the different fields of knowledge the value and real world applicability of the specialised knowledge is challenged.

In architecture and construction an explosion in new materials and components with different static, thermal, visual, acoustic, tactile and other (physical/chemical) properties as well as sophisticated static calculation methods, business and investor models, long term cultural and short term market trends, new construction methods and machinery, architectural discourse, legislation etc altogether create a cacophony of aspects of knowledge that has little in common with the classical well established and clearly defined 'divine' compositional rules that were grounded in clear construction techniques around few and simple building materials.<sup>72</sup> Although the classical pursuit of harmony is not necessarily a goal of contemporary architecture even just the technical and managerial challenge in combining the aspects above into a whole is almost



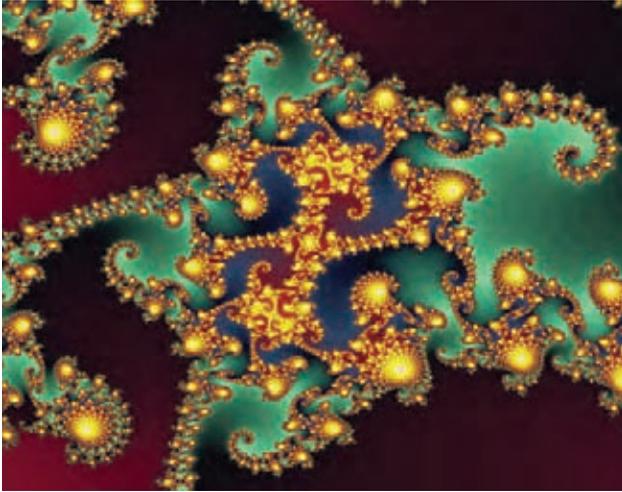
FIGURE II.4.2  
VERNACULAR RAMMED EARTH CON-  
STRUCTION IN OMAN

- 73 In Hannah Arendt's terms – as referred by Frampton – it is connected with the *how* and not the *what*. See *Systems in architectural theory*, II.1
- 74 Focus should move from a dichotomy of states to a dialectic of tendencies.

insuperable. Coherence has – also in architecture and construction – largely been lost and the isolated fields of knowledge run the risk of sub-optimising from each of their compartmentalised viewpoints causing undesirable or even detrimental effects on the whole.

Traditional holistic thinking and knowledge is not a scientifically viable alternative due to the problem of explicating and testing it. Although this predominantly tacit form of knowledge has many foundations in real life experience the consciousness of this fact has been lost in the fogs of tradition. Furthermore it is often very locally founded, context specific, and dependant knowledge and the direct connection to its context has been lost through rapid technological and societal change. In a context of architectural construction, vernacular building represents a traditional holistic entity of knowledge encompassing (tacit) knowledge about the applied local materials, the specific tools and techniques used to manipulate these materials, their application in adequate, economical and durable ways, and, finally, knowledge about the vernacular forms it leads to that are embedded into and at the same time framing the specific culture it forms part of. Holistic thinking and knowledge is grounded in reproduction rather than production and inventiveness.<sup>73</sup> Today architecture as a creative (and globalised) generalist discipline as well as all the related and specialised disciplines that bring buildings into the world have been detached from a considerable part of these local vernacular traditions that no longer represent coherent answers to present needs.

However, instead of seeing the distinction mechanistic/holistic as diametrically opposed and irreconcilable concepts, a point could be to look into how to bridge between them.<sup>74</sup> While the mechanistic approach on the one hand fails to grasp the larger picture that a subsystem is part of, the problem in the holistic approach is the difficulty of applying any analytical means due to the complexity and interconnectedness of the whole. An intermediate 'layer' providing tools for understanding of the interaction between subsystems in a whole or a supra-system could be a way to facilitate creation of coherent wholes of



discrete subsystems. As the Northern American environmental scientist Donella H. Meadows (1941-2001) points out:

“*Much can be learned by taking apart systems at different hierarchical levels [...] and studying them separately. Hence system thinkers would say the reductionist dissection of regular [mechanistic (ed.)] science teaches us a lot. However, one should not lose sight of the important relationships that bind each sub-system to the others and to higher levels of the hierarchy [...]*”

(Meadows 2008:83)

### The systems view

A new recently emerged scientific paradigm – the systems sciences – represents quest for an alternative or at least a supplementary scientific world view. Systems thinking is at the time both holistic and analytic and could thus constitute elements of an intermediate layer bridging the two extremes.<sup>75</sup> The definition and delimitation of a system depends on the purpose of describing it. Hence a system in one perspective can often be a subsystem in another. In his description of natural systems, Laszlo uses the notions of *holarchy* and *holarchic structuration* to describe how different levels or scales of systems are connected – a hierarchy of hierarchies where the entities (the holons) at the same time are both parts and wholes depending on the focus (Laszlo 1996:51fff).<sup>76</sup> Important however, Laszlo states, is that systems should be understood as *‘integrated wholes of their subsidiary components and never as a mechanistic aggregate of parts in isolable causal relations’* (ibid:10). Interesting within the framework of this thesis is that Laszlo points out that such *‘systems method does not restrict the scientist to one set of relationships as his object of investigation; he can switch levels, corresponding to his shifts in research interest’* (ibid:10). Through the capacity to deal simultaneously with various levels (or scales) of interconnections or interfaces systems thinking presents a sort of levelled complexity that enables a dynamic management or a flexible structuration (or ordering) of the focus of attention. A visual analogue to such a *levelled complexity* and *flexible structuration* could be geometrical fractals (see figure II.4.3). A discussion of these notions will be elaborated below.

### System definitions

There are myriads of more or less general system definitions. One particularly clear can be found e.g. in Maier & Rehtin: *‘A system is a collection of differ-*

FIGURE II.4.3  
FRACTALS PRESENT A SORT OF LEVELLED COMPLEXITY

- 75 The systems approach is a general term used for the organization and management of complex systems and is the foundation for both analytic and holistic methods (Jackson: 2010:29)
- 76 *‘A holarchy, in the terminology of Arthur Koestler, is a hierarchy of holons – where a holon is both a part and a whole’* <http://en.wikipedia.org/wiki/Holarchy> accessed on April 24, 2011  
Structuration means order or organisation.

77 Bertalanffy refer to the *system sciences* as applied science distinguished from *systems theory* as a basic science. The applied system sciences are systems engineering, operation research and human engineering (Bertalanffy 1968:91)

*ent things that together produce results unachievable by themselves alone. The value added by systems is in the interrelationships of their elements.'* (Maier & Rechlin 2009:27). Another one by Meadows: '[A] system [is a] set of elements or parts that is coherently organized and interconnected in a pattern or structure that produces a characteristic set of behaviors, often classified as its "function" or "purpose"' (Meadows 2008:188). A complex system is usually defined as one where its elements are in themselves systems that serve relatively independent purposes (as the holons above). Meadows characterised complex systems as inherently hierarchical – Laszlo would expand this to holarchical. Hierarchies or holarchies give a system stability and resilience and reduce the amount of information that any part of the system has to keep track of. Complex systems are partially decomposable into their subsystems – or holons (ed.) (ibid:83). Generally, complex systems are defined as systems consisting of many often composite and different parts or subsystems of which their internal organisation or interrelation and relation to surroundings cannot be described in simple terms. Maier, from a systems point of view, terms a complex system as a system-of-systems: '*an emergent class of systems that are built from components which are large-scale systems in their own right*' (Maier 1998:267). Integrated product deliveries in construction can, as it will be explained in the following section, be seen as an example of such systems.

### **Science of organised complexity**

Acknowledging that the characteristics of complex wholes remain irreducible to the characteristics of their parts the systems sciences as '*sciences of organized complexity*' has emerged (Laszlo 1996:8). In Laszlo's terminology these has developed as supplementary applied branches within the established sciences of e.g. physics, chemistry, biology, sociology and economics. However, as we will see in the next paragraph these applied system sciences also point towards the emergence of a *general system theory*.<sup>77</sup>

## **BERTALANFFY AND GENERAL SYSTEM(S) THEORY**

From his standpoint in theoretical biology in the mid 20th century, Karl Ludwig von Bertalanffy (1901-1972) observed how developments in engineering and computer science intended to overcome the fragmentation caused by technological over-specialisation as described above. Presented with similar problems within his own discipline he conceived, as one of the first, the idea

that a general system theory as a distinct scientific discipline should be concerned with general system characteristics crossing traditional fields of knowledge (Bertalanffy 1968:viii).

“[...] it turns out that there are general aspects, correspondences and isomorphisms common to “systems.” This is the domain of a general system theory; [...] General system theory, then, is scientific exploration of “wholes” and “wholeness” which, not so long ago, were considered to be metaphysical notions transcending the boundaries of science”  
(ibid:xix)

This idea of *isomorphism* (= similar shape or structure) between systems stemming from widely different fields points towards a *structural* approach with focus on organisational aspects among entities rather than description of characteristics of the entities themselves.<sup>78</sup> In his definition of systems Bertalanffy distinguishes between *real systems* and *conceptual systems*. Where the former are ‘*entities perceived in or inferred from observation, and existing independently of an observer*’ the latter are not accessible for direct observation but are ‘*symbolic constructs*’ as logic, mathematics, music etc.<sup>79</sup> In practice however, he points out, this distinction cannot be drawn in any clear way as perception of e.g. real everyday objects are determined by a considerable amount of mental and cultural factors. Perception is not a mere reflection of “real things” and ‘*[knowledge] is an interaction between knower and known, this dependent on a multiplicity of factors of a biological, physiological, cultural, linguistic etc. nature*’. Knowledge and science is a way man deals with the world – it is not a one-to-one description of it. By acknowledging this “intertwinedness” of humanistic and mechanistic aspects of knowledge Bertalanffy claims his vision for a unified general system theory to bridge the opposition between sciences and humanities or between technology and history (ibid:xxi ff). This is somehow parallel to the gap between construction (technology) and architectural idea (concept) that present thesis seeks to investigate as an increasing problem in architectural design.

Bertalanffy lists and shortly describes an array of different formalised approaches to investigate systems some being (descriptive) models other proper mathematical techniques.<sup>80</sup> The approaches, although often evolved within specific scientific disciplines present some level of generality applicable to various fields. However, ‘*diverse system models will have to be applied according*

- 78 Bertalanffy argues that ‘investigation of organised wholes of many variables requires new categories of interaction, transaction, organization teleology etc.’ (Bertalanffy 1968:xxii)
- 79 The distinction resembles the one between soft and hard systems drawn by Checkland presented later in this section.
- 80 “classical” system theory, computerization and simulation, compartment theory, set theory, graph theory, net theory, cybernetics, information theory, theory of automata, game theory, decision theory and queuing theory (Ibid: 21ff)

- 81 Both Meadows and Laszlo equally states hierarchy as a fundamental characteristic of (complex) systems.
- 82 The juxtaposition of product and process in relation to systems thinking has a parallel in the DSM-metodology that, as described in the section on *Industrial production theory*, in the same kind of model (but separate) is able to describe and treat the different ‘domains’ of processes, product architecture or organisation. An extension to DSM also works with multiple domains simultaneously (DMMs). This track has however not been further followed here.
- 83 See *Model presentation, IV.1*

*to the nature of the case and operational criteria’* (ibid:28). None has shown all encompassing answers to the vision of a *general systems theory*. They can only be seen as steps towards it. A fundamental principle of such a theory is, according to Bertalanffy, that of *hierarchic order*.<sup>81</sup> Interesting here is that he locates this general principle of hierarchy both in ‘structures’ understood as the order of parts and in ‘function’ understood as the order of processes that, as he proceeds, *‘may be the very same thing: in the physical world matter dissolves into a play of energies, and in the biological world structures are the expression of a flow of processes’* (ibid:27). The often drawn distinction between process and matter – between process and the product (as result of this process) is not that clear. If we bring this insight into construction it could indicate a systemic connection between how buildings come into being and how they actually are composed as physical objects.<sup>82</sup> If we combine this with the intertwinedness described above we might even tentatively suggest that systems of matter, processes and *thought* can be integrated into one and the same model. This idea has been followed in the development of the model described later in Part IV – ‘Model’.<sup>83</sup>

Although Bertalanffy mostly uses mathematical equations and algorithms in his exemplifications and descriptions of systems and their properties he underlines that non-mathematical i.e. verbal or conceptual models can be preferable to forcibly imposed mathematical versions. In his view these models are important as preliminary expressions of new system aspects to be evolved into a more hard-fact model description.

” *‘It may be preferable first to have some nonmathematical model with its shortcomings but expressing some previously unnoticed aspect, hoping for future development of a suitable algorithm, than to start with premature mathematical models following known algorithms and, therefore, possibly restricting the field of vision’*

(ibid:24)

However, one thing is to elaborate system models that in a precise way can describe (general) structures of and interaction between a number of elements in an existing system (its behaviour). Bertalanffy’s point of departure is biology and is mainly descriptive and primarily concerned with understanding existing and observable natural or social phenomena. Another slightly different thing is to elaborate models that seek to describe systems that are (to be) *designed*

through human ingenuity. As long as the design problem or the *purpose* of the system can be clearly defined, a mathematical or algorithmic model might be imaginable.<sup>84</sup> In creative processes, as architectural design, where problems or purpose are mostly ill-structured and multifaceted and often rise and evolve in iterative interaction with a proposed (system) solution it is more difficult to imagine how this could be expressed through mathematical formula.<sup>85</sup> The concept of *parametric design* deals to some extent with this issue.<sup>86</sup> This brings us to two useful distinctions in systems thinking that can be applied to clarify what kind of systems that are dealt with in the present context: Open vs. closed systems and soft vs. hard systems.

## OPEN AND CLOSED SYSTEMS

A closed system in its strict definition is a definite set of elements in a relation without any input from or output of energy, information or material to the environment surrounding the system – it is a system in isolation.<sup>87</sup> Conventional physics following the mechanistic world view is exclusively dealing with the description of closed systems. Most real world systems are open systems in the way that they exist and are maintained – or maintain themselves – for a certain period of time through a continuous inflow and outflow of energy, information or material. Through these input and output an open system can either: a) be in a dynamic but steady state, b) evolve towards such a steady state, or c) develop towards a different state.<sup>88</sup> Living organisms are good examples of such open systems. Where e.g. a full-grown horse is in a dynamic but steady state, its foal evolves towards this state (of full-grown horse). Finally, through reproduction over generations the natural evolution has brought forward the horse a species distinct from its earlier stages and from other animals.<sup>89</sup> Any closed system will reach a final state defined by its initial conditions. If conditions are changed, the final state will change correspondingly. This is not necessarily the case for open systems that in some cases can reach the same final state from different initial conditions or in different ways. This principle of open systems is called *equifinality*. An example from biology is the growth of similar organisms exposed to different nutritional conditions. (See e.g. figure II.4.4). In natural phenomena the (equi)finality or purpose of a system has either been directed to the combinations of physical laws, genetic mutation and Darwin's theory of evolution (survival of the fittest) or to a so-called metaphysical '*soul-like vitalistic factor which governs the processes in foresight of the goal*' (Bertalanffy:1968:39f).

84 This kind of hard fact modeling is the object of systems engineering as shortly described in II.3

85 Ill-structured or ill-defined problems are also mentioned in relation to product design in *Industrial production theory*, II.3

86 Behind the concept of *parametric design* lies an intention of defining a 'design engine' or model that can generate manifold designs from a given set of parameters that in each case are assigned individual values. Although this system produce different answers to a well defined design problem, the design of the system – the design engine itself – is not a well defined problem with a clear purpose. See also *Industrial production theory*, II.3

87 Within the general systems theory, as summarised by Davidt Bowler, 'everything that exists, whether formal, existential, or psychological is an organized system of energy, matter and information' (Skyttner 2005:52).

88 The dynamic equilibrium of the first is also called *homeostasis* – maintaining a steady state by adjusting internal environment. '*Homeostasis stands for the sum of all control functions creating the state of dynamic equilibrium in a healthy organism*' (Skyttner 2005:93)

89 The two latter are also referred to as ontogenesis and phylogenesis – the process from embryo to human and the intergenerational evolution. See e.g. (Laszlo 1996:43). As pointed out by Skyttner, the distinction open/closed systems can be defined relatively: '[...] *taken together with its environment, [an organism] might be considered as a closed system*' (Skyttner 2005:63).

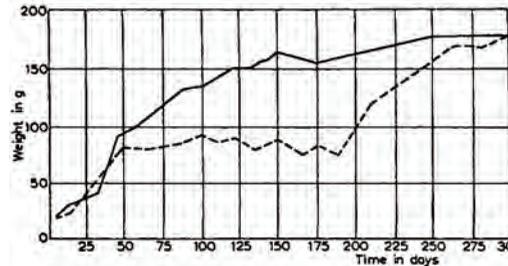


FIGURE II.4.4  
EQUIFINALITY EXEMPLIFIED AS  
GROWTH OF RATS WITH DIFFERENT  
NUTRITIONAL CONDITIONS, BY BER-  
TALANFFY

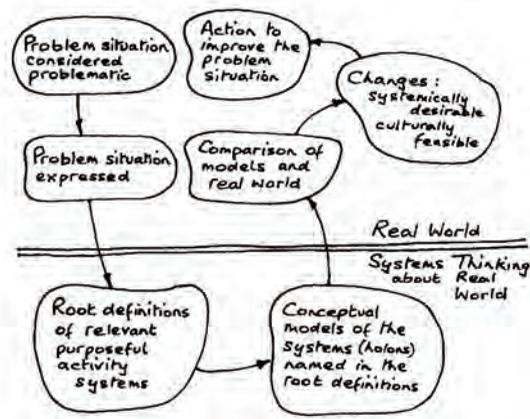
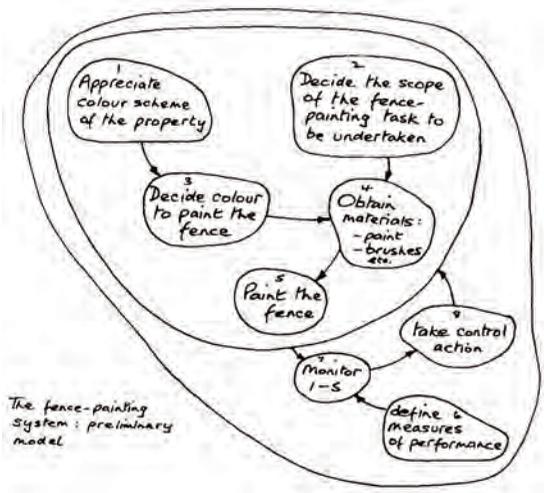
- 90 Of course physical laws apply to and in many ways co-structure the final outcome – the physical building. However, these laws can never by themselves lead to a building. Architectural creation always contains human intention. See also the *formula* of Semper in *Systems in architectural theory*, II.1
- 91 While method and methodology is often used parallel in American literature, *methodology* originally refers to a more general *theory* of method while *method* simply refers to a procedure or procedural description.
- 92 Systems engineering as a hard method technical approach has been briefly touched upon in the previous section on *Industrial production theory*, II.3
- 93 Fictionalist: One who subscribes to fictionalism, the belief that certain concepts are simply convenient logical fictions. <http://en.wiktionary.org/wiki/fictionalist> - accessed on April 22 2011
- 94 Aspect as used here have conceptual links to the notion of aspect in the DBK classification system described in *Classification systems in construction*, II.2

### Architectural creation as an open system

In architectural creation, the purpose of a building is neither defined by physical or evolutionary laws nor by vitalistic or divine intervention. It is ultimately defined by the conscious or intuitive choices of the architect as an integration of an architectural concept and the various demands, potentials and visions for the project – resulting in an ill or loosely defined design problem expressed as the building itself.<sup>90</sup> Architectural creation can, as the combination of concept and process leading to a final product, tentatively be seen as an open system of respectively information (concept/thought), energy (process) and material (product/matter) that evolves from idea or concept towards a dynamic but steady state – the ‘final’ building’ expressed physically through the applied building materials. The idea or architectural concept is the goal or finality – but the ways to reach that goal can be manifold. In this sense architectural creation express something similar to the principle of equifinality as explained above. This point will be brought into the model building of this thesis as the quality that various (system) structures can lead to the fundamentally same architectural result.

## SOFT AND HARD SYSTEMS AND THE SOFT SYSTEMS METHODOLOGY

The British professor in systems science, Peter Checkland, introduces a second system dichotomy that is concerned with the *application* of general systems theory in the systems sciences – the distinction between soft and hard system approaches (Checkland 1981). The distinction was the outset for the so-called soft systems methodology (which is actually rather a *method*),<sup>91</sup> or SSM, that was introduced as an alternative to e.g. systems engineering<sup>92</sup> in order to solve problems that could not be defined clearly in technical or mathematical terms – so-called ill-structured problems (Skyttner 2005:481) – like architectural design problems! The method(ology) is used to build what Checkland calls ‘*conceptual models of human activity systems*’ (Checkland 1981). In SSM the notion of system is to be understood as a mental construct. This resembles what Skyttner calls the fictionalist view:<sup>93</sup> ‘A system is in itself always an abstraction chosen with the emphasis on either structural or functional aspects. This abstraction may be associated with, but must not be identified with, a physical embodiment’ (ibid:57).<sup>94</sup> The system becomes an epistemological rather than an ontological entity that serves as an intermediate conceptual model or tool for



human understanding. Depending on the system perspective – i.e. its particular structure of subsystems and their interrelations as seen from a particular (stakeholder’s) viewpoint – the system can give very different understandings of the phenomena it seeks to describe. In SSM these conceptual models – or systems – can be expressed in bubble diagrams (See figure II.4.5). The idea of viewpoints in a model will be tested in the case studies of Part IV – ‘Model’.

FIGURE II.4.5 SMM: A FENCE PAINTING PROCESS AS A SUBSYSTEM OF DEFINED MEASURES OF PERFORMANCE, BY CHECKLAND

The original version of SSM has seven stages. The stages span from understanding and defining the problem over model building to real world application and contain *iterative loops* in the model development stages. The seven stages are:<sup>95</sup>

FIGURE II.4.6 CHECKLAND’S SEVEN STAGE MODEL MOVING FROM REAL WORLD OVER SYSTEMS THINKING AND MODELING AND BACK TO REAL WORLD.

1. entering the problem situation,
2. expressing the problem situation,
3. formulating root definitions of relevant systems,
4. building conceptual models of human activity systems,
5. comparing the models with the real world,
6. defining changes that are desirable and feasible, and
7. taking action to improve the real world situation.

95 [http://en.wikipedia.org/wiki/Soft\\_systems\\_methodology](http://en.wikipedia.org/wiki/Soft_systems_methodology) accessed on April 22, 2011

While stage 1 and 2 takes point of departure in a real world problem, stage 3 and 4 move into systems thinking about this real world through model building. The root definitions (stage 3) are formulated by considering a number of elements (CATWOE): Customers (victims or beneficiaries), Actors (those who act), Transformation process (from input to output), ‘Weltanschauung’ (worldview which makes transformation meaningful), Owner(s) (who can stop transformation) and Environmental constraints (elements outside the system taken as given). Subsequently conceptual model(s) are built from the root definitions (stage 4). Now these models are brought back and compared with the real world (stage 5) in order to point out possible/desirable changes (stage 6) and propose actions to improve the problem situation (stage 7). Iterative loops can take place between stages 4-6 before final action is taken. (See figure II.4.6)

Interesting here seen within the framework of the present thesis is the idea of modeling a flexible intermediate tool of understanding/describing particular systemic aspects – perhaps even seen from varying particular viewpoints – of what is or will ultimately become an entity with (hard) physical existence fulfilling a given purpose namely a building..

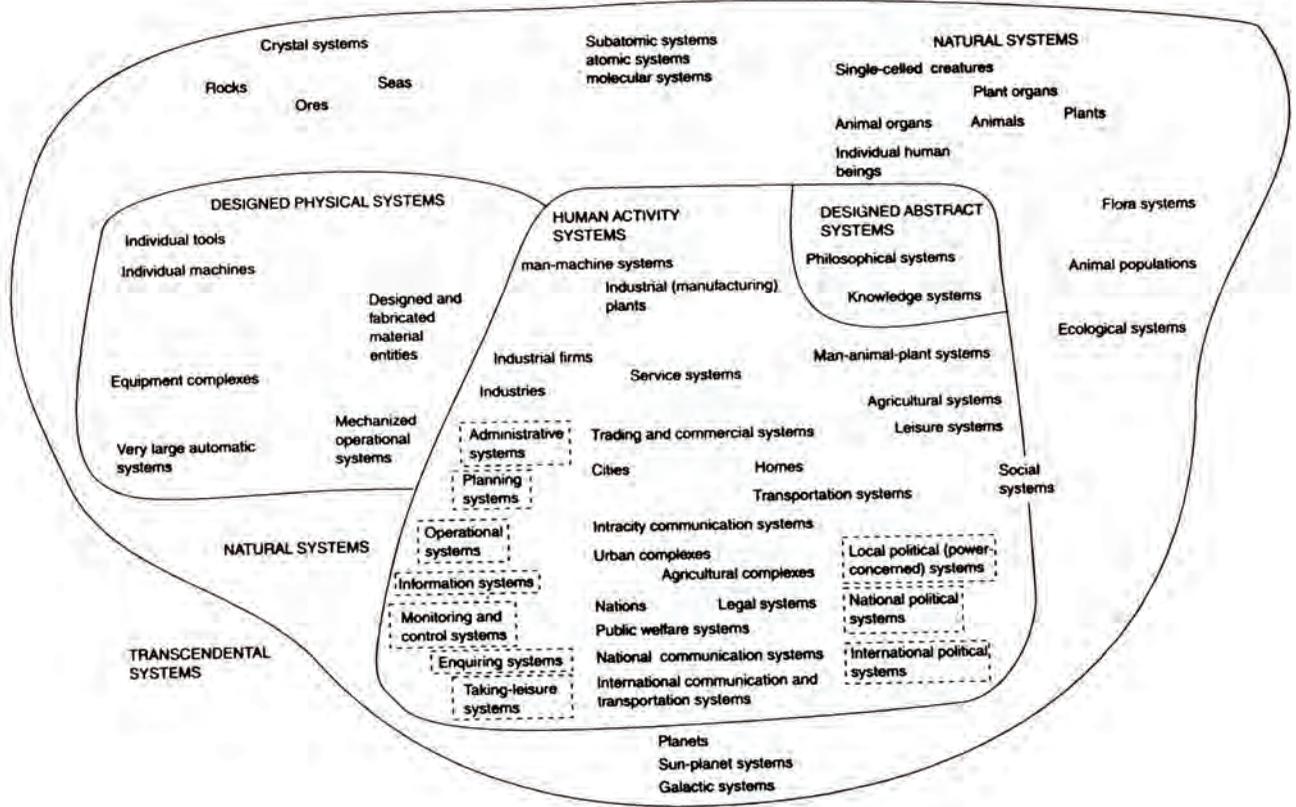
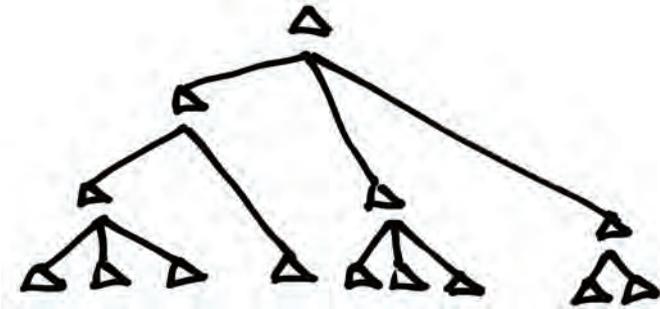


FIGURE II.4.7  
CHECKLAND'S SYSTEM TYPOLOGY  
WITH EXAMPLES

Checkland also establishes a *typological map* of systems and system classes as a kind of system hierarchy. At least four classes of systems are necessary in order to describe the existing reality. These are: a) natural systems, b) human activity systems c) designed physical systems and d) designed abstract systems. (Skyttner 2005:175). The natural systems are, contrary to the others, 'systems which could not be other than they are, given a universe whose patterns and laws are not erratic' (Checkland IN:ibid:175). They are not merely mental constructs. The natural systems are ordered as a branched hierarchy from subatomic systems to entire ecologies (or ecosystems). Within these natural systems, the human activity systems are embedded with social systems as the most fundamental. The human activity systems are again coupled to designed physical and designed abstract systems (see figure II.4.7). While buildings in this typology would be classified under designed physical systems (as designed and fabricated material entities) they would come into physical being through the human activity systems (man-machine systems and industrial manufacturing) by application of designed abstract systems (knowledge systems). The entities from the general systems theory of energy, material/matter and information is clearly recognisable in the triad of human activity, designed physical and designed abstract systems – or as they are termed and used in this thesis: systems of matter, process, and thought.

### *Soft system approaches in architectural design*

Although the use of conceptual diagrams and abstract representation is very common in architectural ideation it is seldom used as a systematic procedure or repeated as general elements across different projects. The architect and theoretician Christopher Alexander (1936-) has practiced the use of intermediary conceptual models already from the initial design phases. For Alexander, the goal of his models, which he call diagrams or patterns, is to get a purely



structural description (a conceptual or physical organisation) of a design problem (Alexander 1964:126). Subsequently, this structural description can be used synthetically to produce an integrated diagram of the solution as a whole. This overall structure both represents a solution (= an element in itself) and the internal structuration of this solution in the form of a pattern. It is the expression of a *holon*.

“It is the culmination of the designer’s task to make every diagram both a pattern and a unit. As a unit it will fit into the hierarchy of larger components that fall above it; as a pattern it will specify the hierarchy of the smaller components which it itself is made of”

(Alexander 1964:131)

Instead of splitting the answer to a design problem up into known designated categories (as e.g. *entrance door, living room or roof*) and using intuition to conceive the adequate configuration of these elements, the idea is alternatively to split (analyse) the problem up into neutral requirements that can be expressed as single – although seldom numerically expressed – variables, or *basic requirements* (Chermayeff & Alexander 1965:154). These requirements constitute the programme of the design task. A couple of examples of such basic requirements from the elaboration of a housing development scheme are a) ‘*rest and conversation space. Children’s play and supervision*’, b) ‘*access point that can be securely barred*’, c) ‘*arrangement to keep access clear of weather interference*’, and d) ‘*partial weather control between automobile and dwelling*’ (ibid:155). Subsequently the basic requirements are analysed for interactions or dependencies. The two latter (c and d) has obvious links whereas the two former (a and b) seem independent. In the example of the housing development scheme, 33 basic requirements are defined and their interaction analysed (see figure II.4.9).

The analysis clearly expresses the impossibility to consider all of these at once in order to suggest a coherent answer. They must be considered in groups. These are created by joining requirements with rich mutual interactions into major components that have no or only little interaction with requirements in other major components (groups). Even for a model of this relatively modest size, this has to be done with the help a computer in order to process the more than ten billion possible joints (ibid:160). This more ‘hard system’-process resembles the *clustering* algorithms found in component based DSM analy-

FIGURE II.4.8  
AN EXAMPLE OF A HIERARCHY OF  
HOLONS BEING BOTH SYSTEMS IN  
THEIR OWN RIGHT AND SUBSYSTEMS  
OF LARGER SYSTEMS

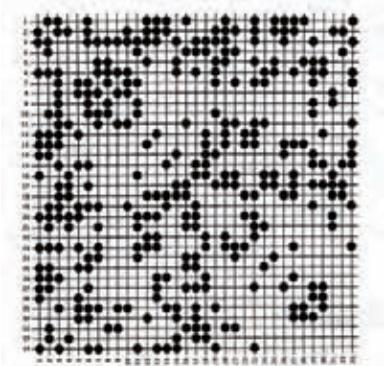


FIGURE II.4.9  
DEPENDENCY ANALYSIS OF 33 BASIC  
REQUIREMENTS FOR A HOUSING  
DEVELOPMENT SCHEME

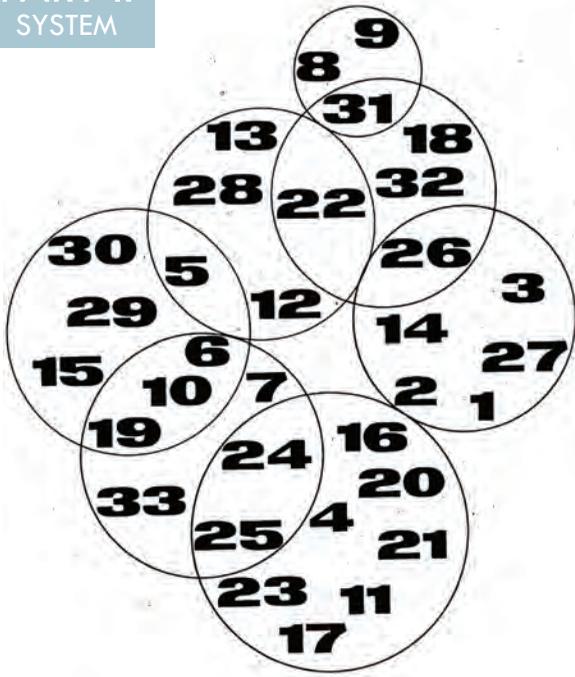


FIGURE II.4.10  
CLUSTERING OF THE DIFFERENT RE-  
QUIREMENTS INTO PARTLY OVERLAP-  
PING MAJOR COMPONENTS

- 96 For a short introduction to *design structure matrix* methods (DSM), see *Industrial production theory*, II.3
- 97 Internal interactions are not shown in figure II.4.10
- 98 The total list of basic requirement was divided into seven major components. However two of these primarily affect materials and mechanics and have consequently not influenced the organisation of the plan (again: not the plan solution itself) (Chermayeff & Alexander 1965:163)
- 99 Cf. the notions of levelled complexity and holarchic structuration as introduced earlier. See also (Alexander 1964:131)

ses.<sup>96</sup> Figure II.4.10 shows how groupings – or major components – of the 33 requirements interact. While some only interact within the major component, others interact between them and should be considered within both major components – as either overlapping or alternatively doubled as separate answers to the same requirement in separate major components.<sup>97</sup> Important to point out is that there is no correct clustering solution. As interaction between different major components can seldom be avoided completely, the strength of these as well as the total number of major component will have importance when choosing between various alternatives.

Now structural *pattern diagrams* (Alexander 1964:130) can be elaborated for each of the different major components in isolation while considering the now considerably reduced number of basic requirements. This process is ‘soft’ in the sense that here the architect’s more traditional intuitive grasp of the whole is made possible through the reduced complexity of each component as compared to the whole. These pattern diagrams should not be understood as plans but are still ‘just’ abstract representations of an integrated functional organisation that can meet the basic requirements. The next exercise is to integrate these pattern diagrams of the major components into one single diagram of the entire organisation of all the requirements – a complete but purely *structural* description of the design problem (ibid:126). Figure II.4.11 shows examples of how five of such pattern diagrams of major components (B,C,E,F) have been integrated into one single pattern.<sup>98</sup> In order to make a consistent integration and not just a juxtaposition of the sub diagrams, the overlaps between the different components become important to consider. To make a detailed description of this is not within the scope of the present thesis and this section. In larger more complex (physical) systems, the integrated diagram can even become a component among others thus constituting a subsystem. The method and the resulting model can consist of various integration levels reached step by step from the basic requirements to the overall solution (see figure II.4.8 above).<sup>99</sup>

Interesting about the sketched systematic design method and the intermediary model of pattern diagrams is Alexander’s insistence on that it is possible to separate analysis and synthesis as two equally important parts of architectural creation. The models – or pattern diagrams – are examples of flexibly

structured soft systems that are structured around specific design problems but with systematic and procedural elements that are repeated across projects and combined with a relatively high abstraction level. '[...] because it concentrates on structure, the process is able to make a coherent and therefore new whole of incoherent pieces.' (Ibid:110) – The model forces organisation in the designer or architect's mind; it does not make her think in a specific way or produce a specific result. The specific way that Alexander reaches the initial basic requirements (the analysis) is however a little hard to understand as a purely analytical procedure. It still seems to include a great deal of intuitive interpretation to define these so-called neutral elements.<sup>100</sup> Still, the idea of handling complexity through a hierarchy of flexible integrated patterns rather than fixed entities suggests a more architectural approach for the modularisation of buildings or built environment. Alexander's 'soft system' methods has subsequently been developed into a more formal *pattern language* that, as other languages, has vocabulary, syntax and grammar that was intended to enable ordinary lay people to engage directly in solving complex design problems. This language, however, has never really gained currency.<sup>101</sup>

#### *Hard system approaches in architectural design*

Hard system approaches are seldom found strictly engaged with architectural design. The integration of many variables of both hard (quantitative) and soft (qualitative) character, as mentioned, make up ill-structured and multifaceted design problems that are usually not adequate for formulation of mathematical formula at least not in their entirety. Although parametric design engines does represent attempts in this sense, they are often far too limited to constitute general models applicable to virtually any or a least a broad range of projects. Within construction planning and execution phases, where the problem or goal is often easier to define clearly, some attempts of system theoretical approaches have been used inspired by the product industry and the applied field of systems engineering. The graph theory-based *Design Structure Matrix* method (DSM), shortly presented in the section *Industrial Production Theory*, is one example.<sup>102</sup> However, even if an architectural design problem cannot be put on formula in its entirety, aspects of it can be treated using a systems approach that through a probabilistic connection to the success of the architectural whole could help to qualify choices even in early design phases. By dealing with only one or few but *system characteristic* aspects – or emergent properties – of the architectural whole such an approach is both holistic and analytical.

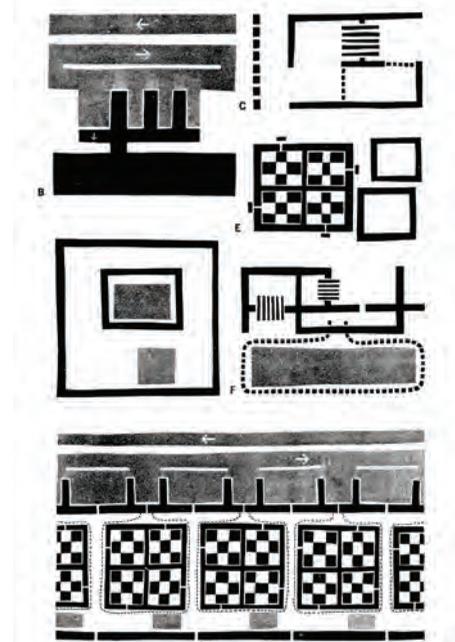


FIGURE II.4.11  
FIVE STRUCTURAL PATTERNS OF THE  
MAJOR COMPONENTS OF A HOUSING  
DEVELOPMENT AND THEIR INTEGRA-  
TION INTO ONE SINGLE DIAGRAMME.

100 Alexander refers to precisely defined mathematical operations, but these are not further defined (ibid:118). A note (2) however leads to several external sources.

101 See e.g. [http://en.wikipedia.org/wiki/Pattern\\_language](http://en.wikipedia.org/wiki/Pattern_language) accessed on August 10, 2011

102 See II.3

103 Parts of this paragraph has been adapted from author's bachelor thesis: 'Rummet som faktor – en sociomateriel discussion af det byggede miljø' - Space as factor - a sociomaterial discussion of the built environment. (Jensen 2003)

### Space syntax<sup>103</sup>

Space syntax can be seen as such an approach that presents some of the characteristics of a hard system approach while still dealing strictly with architectural design issues. Space Syntax was originally established in the 1970's by Bill Hillier and some colleagues at the Bartlett School of Architecture and Planning in London. Best known are the two books *The Social Logic of Space* and *Space is the Machine* (Hillier & Hanson 1984; Hiller 1996). Space Syntax can be applied to numerical analysis of aspects of spatial configuration or patterns that have probabilistic connection to the social performance of a building. The intention was originally to develop a theory of space that, based on objective properties of human environments, can determine underlying spatial laws (invariables) and cultural/social variables. In Space Syntax, *spatial configuration* has to do with the interrelationship, organisation and order of the different spaces while it does not directly deal with the function, form or specific design features of these spaces. This relational aspect and focus rather than focus on the properties of the parts is a typical characteristic of a systems approach.

“Architecture is not a ‘social art’ simply because buildings are important visual symbols of society, but also because, through the ways in which buildings, individually and collectively, create and order space, we are able to recognise society: that it exists and has a certain form’

(Hiller & Hanson 1984:2)

The theory consists of several specific methods and analytical measures applicable to existing or potential designs from regional and urban planning to architectural building design scale. One of the main points of the theory is that spatial order or structure emerges as limitations of an otherwise random accumulative process. Intuitively, this is most intelligible related to settlements and urban structures that to a greater extend than buildings can be said to develop gradually and accumulatively over time. Concerning the building scale it has however been applied to building *typologies*. The generating force is the principle of randomness (everything is possible) while the structure is the invariance that emerge when spatial laws and cultural/social variables constrain the amount of valid choices (only some possibilities are applicable). An example of a spatial law could be that every space has at least one opening while a cultural variable could be that the toilet is not accessed directly from the living room or that all living spaces should have a window towards the exterior. Both spatial laws and cultural/social variables work as (mostly) non-conscious motives or

indicators in the conception of a building and thus reproduce certain patterns or structures. Equally *movement patterns* in built space (buildings or urban contexts) can be studied. The spatial organisation or structure generates or, in softer terms: supports, a certain pattern of movement – in space syntax termed ‘*natural movement*’ (Hillier 1996). A wall obstruct passing while a door – if it is open – on the other hand makes it possible. The theory does not claim that other factors as e.g. different functions defined by the building’s programme does not equally have influence. However it *does* assert that the *natural movement* can either support or work against this programme. Large discrepancy between natural movement and programme can be compensated through (bureaucratic) rules.

Configuration is a central concept in Space Syntax and concerns a building, a part of a building or can even be a complete urban system of streets, squares, buildings etc. What connects spatiality and sociality<sup>104</sup> can, according to the theory, not be seen in static terms as characteristics of specific spaces in isolation. Rather it is, as mentioned, a question of their mutual interrelation – or configuration. This makes movement within and through space central for the perception of this space seen as a configuration. Equally it points towards the assumption that each space and its specific connection to other spaces influence the configuration as a whole. What is interesting and perhaps less evident is, that even small changes in parts of the configuration often has ‘syntactical’ consequences for all other parts. A couple of mathematical measures – or *syntactic parameters* – have been developed to enable description and operationalisation of this through what is termed ‘*configuration analysis*’ (ibid).

A given ‘*depth*’ is defined by the number of spaces you physically need to pass to get from one location to another.<sup>105</sup> If in a dwelling you move from e.g. the kitchen to the living room passing by a hall then the depth from kitchen to living room is equal to ‘2’. The amount and location of doors or openings defines the depth of a space seen from another space. Depth in this definition is non-metrical and therefore independent of scale. The depth value is used in a measure of ‘*relative integration*’ of each of the spaces in a configuration. By using the sum of all depth values from one space to all others (of e.g. a building) and divide this with the number of spaces minus the space itself you get the average depth of the space to/from all other spaces. Maybe intuitively it can be perceived that the resulting value express whether a space compared to others is more or less integrated understood as more or less relatively segregated from

- 104 The purpose of the theory is exactly to be able to describe aspects of this connection between the physical and the social properties (laws and variables) of the built environment.
- 105 ‘Spaces’ here refer to sequences of the largest possible convexly delimited (two dimensional) areas of a building plan or, in urban settings, as the spaces located around the longest possible axial lines drawn through urban space (Hillier 1996)

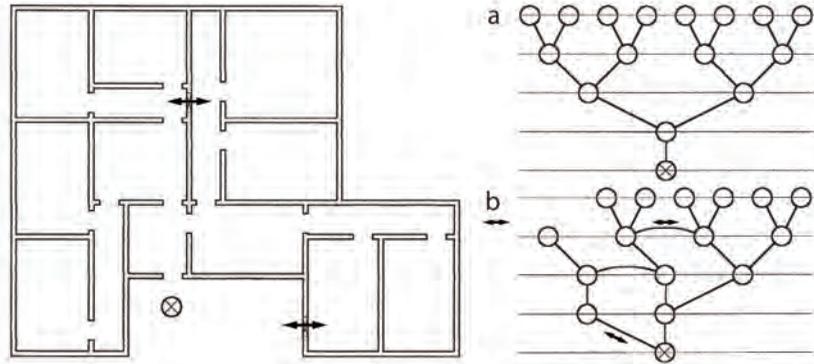


FIGURE II.4.12  
SPACE PLAN AND JUSTIFIED PERMEABILITY MAPS WITH TWO DIFFERENT CONFIGURATIONS, A) 'IDEAL' TREE AND B) TWO RINGS DUE TWO THE EXTRA DOORS ADDED

- 106 The standardised measure is termed 'real relative asymmetry' (RRA). Asymmetry is analogue to depth (Hiller & Hanson 1984)
- 107 The 'control value' is calculated in the following way: A space has ' $n$ ' adjacent spaces and cede  $1/n$  to each of these. The control value for a space is then the sum of the  $1/n$  values it receives from the adjacent spaces. Values over 1 express strong control while spaces with values below 1 have weak control and consequently are rather controlled from somewhere else.

the other spaces of the building. A low value expresses high integration while a high value expresses a peripheral or remote location. In buildings with high relative depth different users will often be more clearly segregated than if the opposite is the case. In its practical application the integration measure is often standardised thus eliminating the significance of the number of spaces and facilitating comparison between systems, i.e. buildings or urban settings.<sup>106</sup>

Another important measure is the extent of 'trees' and 'rings' in a given configuration. Tree refers to a system or parts of a system (spatial) where getting from one space to another only give one possible connection – often passing through several other spaces. Such a configuration can e.g. be a building where a hall leads to two rooms that each leads to two corridors (four in total) that each leads to two rooms (eight in total) (See figure II.4.12 and graph a). An 'ideal' tree connects a given number of spaces with the lowest possible number of connections. 'Rings' on the contrary refers to a case where the movement from one space to another can be conducted using at least two different routes. Using the example from before, a connection between two corridors or from a space directly to the outside would express different rings in the configuration. (See figure II.4.12 and graph b). Rings add permeability and 'ideally' connect all spaces directly to each other. The presence of rings thus fundamentally changes the possibilities of moving around in a building (or an urban setting) and the degree of interconnection between parts. Trees will often bring depth while rings will reduce it by literally adding alternative shortcuts. The specific combination of trees and rings has influence on what one could call the control of the building seen from different locations and bring in a social dimension of power (Hanson 1998:27). There are two control measures in Space Syntax. 'Relative ringiness' expresses the relation between a given number of rings and the maximum possible amount in a spatial setting. This value is 'global' inasmuch it gives one value for the system as a whole. On the contrary 'control value' is a local measure looking at the individual spaces and the number of adjacent (connected) spaces.<sup>107</sup>

Configurations can be expressed visually through so-called 'justified permeability maps' – a kind of graph that in principle can be drawn by hand. The graphs give, through circles connected with lines, a simple and direct visually perceivable idea of the depth of a building seen from a specific location or space. Figure II.4.12 displays such justified permeability maps. By using different locations the graph expresses different relative depths and shows (even without

the mathematical values) which spaces are more or less centrally located or segregated in the building. The graph is read ‘bottom-up’ with each level expressing more depth seen from the chosen point of origin.

I will not go more into details about the practical implication and explanatory power of the concepts and measures of Space Syntax. Having existed and evolved for more than 40 years does however point towards some degree of usefulness.<sup>108</sup> Within the present frame of research it can be seen as an extensively elaborated example of how even soft values can be addressed through a predominantly hard systems approach that bring out certain aspects – not all aspects! – of a whole, and to a certain extent makes these aspects quantifiable.

108 Usefulness as a ‘soft’ validity criteria has references to Peirce and abduction as introduced in *Method and scientific approach*, I.5. Similarities are equally found in Simon’s concept of *satisficing* that will later shortly be introduced in *Customisable architectural subsystems*, III.2

## ARCHITECTURE AS A COMPLEX SYSTEM

In current thesis, the focus is on how systems in general (of thought, process and matter) can support architectural ingenuity – not lead to, determine or constrain but exactly support architectural creation while recognising the impossibility of reducing considerably the complexity without damaging the coherence of the architectural outcome. Systems thinking and general systems theory, as a general embracing discipline, is at its core aiming at explaining real world phenomena by ordering, categorising and describing entities and their interrelations within delimited fields while at the same time acknowledging its broader context. Architectural design (processes) are about creating frames or tools for these same real world phenomena. Whereas the former – as a scientific discipline – is primarily analytical and explanative the latter is rather synthesising and creative. Both disciplines deal with one common basic question about handling complexity.

Alexander states that ‘*Although ideally a form should reflect all the known facts relevant to its design [...] the technical difficulties of grasping all the information needed for the construction of such a form are out of hand – and well beyond the fingers of a single individual*’ (Alexander 1964:4). The human mind has limited capacity for processing information and thus quickly requires simplification and abstraction. Even the so often claimed intuitive capacity of the designer has according to Alexander insufficient integrative potential for solving present design problems: ‘*The intuitive resolution of contemporary design problems simply lies beyond a single individual’s integrative grasp*’

(ibid:5). While other disciplines as engineering and most natural sciences relatively successfully – in the mechanistic tradition – have been able gradually to split elements (of thoughts, processes and matter) into an increasing number of subelements, that through specialisation can be handled independently and by different persons, architectural design is fundamentally a discipline of integration (Bachman 2003:6) – a holistic exercise of balancing incomparable parameters into a coherent whole.

Although deeply determined by physical properties and natural laws of material placed in a physical environment the traditional architectural design process tends to a great extent to rely on singular or collective human experience primarily accessible in a tacit non-explicit form stored in individual minds. With the ever increasing production and accessibility of explicit knowledge within all fields combined with (and partly resulting in) a general increase of complexity in architectural design problems this intuitive synthesising process become ever more problematic. The days of a simple sketch outlining an architectural concept strong enough to determine all subsequent design choices are long gone. New IT-tools and forms of automation make it possible to process larger amounts of data thus handling an increased amount of complexity of both formal design itself and the technical information required to realise it. However grasping e.g. material cycles of all components and materials of an entire building quickly become like counting the grains of the sand on the beach. So how can complexity and the integration of this be handled by the architect without either reducing critically the complexity of the architectural result or getting lost in details?

#### *Intermediate models – supporting architectural ingenuity*

One way, as suggested above, is the idea from systems theory of using intermediate simplifying models that focus attention on critical issues throughout the design process. A simplifying model is not the same as simplifying reality and the design solution itself. The American ecologists Howard T. Odum (1924-2002) builds his version of a general systems theory on systems ecology and compares models to human knowledge: '*Models are the simplifications of the human mind used to help understand, and modelling in its broad sense is almost synonymous with knowledge*' (Odum 1983:x) This conception corresponds to Bertalanffy's symbolic constructs and Checkland's designed abstract systems (see above). Important equally for Odum, is that this does not mean that knowledge of a particular field can be expressed in one single optimal

model: *'Part of the excitement in the area [of systems and systems study] comes from the rich variety of alternative ways of organizing knowledge'* (Ibid:x).

Models can be seen as languages for describing, handling and communicating complex real world phenomena. They are not one to one fits, but enhance specific characteristics of reality – perhaps even caricature it – as a framework to hold up against and make more tangible the nuances of its complexity. In this thesis models are conceptualised as descriptions or visualisations of systems and their interrelations – they describe the structure and the organisation of systems. Systems expressed through a model can both be conceptual, processual and physical.

### **Flexible structuration**

A central assumption related to the search for an intermediate model to handle complexity is that models that permit expression of a *flexible structuration* based on *levelled complexity* in a system, its subsystems, and their interrelations reduce the risk of pernicious simplifications of closed all-encompassing systems or classifications (for both thought, process and matter). Flexible structuration and levelled complexity mean that e.g. the scale of the individual system entities or the hierarchy in focus can vary according to each case/scenario or viewpoint/focus where the (general) model is applied – cf. 'switching levels' as pointed out by Laszlo.<sup>109</sup> What constitutes a system entity or subsystem in one version of the model can fold out its own internal system hierarchy or structure in another version. A strategy of flexible structuration enhances the explanative power of the model for analytical purposes as well as making it more robust or resilient to change through the models capacity of adaptation to scale, context or time. The model become more general and thus potentially has a wider scope of application.<sup>110</sup> Seen as a more proactive design tool a model based on flexible structuration can potentially enable comparison of different production scenarios (system structures) leading to potentially similar results (equifinality).

- 109 Flexible structuration and levelled complexity are in many ways comparable to Laszlo's 'holarchic structuration' – see above
- 110 The drawback of a more general model can be the lack of capacity to explain important detail. What is important is however relative to the purpose of the model itself (cf. above: the model as epistemological rather than ontological)

## **NESTED SYSTEM INTEGRATION AND INTEGRATED PRODUCT DELIVERIES**

The examples and concepts that has been drawn from the (general) systems theory, and some examples of its application in architectural design, points in several ways towards the adequacy of looking simultaneously at a building and the construction of it as one coherent system. The building and its genesis

- 111 The notions of delivery and integrated product delivery are further introduced in the following section Systems  
*Terminology for (industrialised) architecture and construction,*  
II.5

can be seen as an open system that, using Checkland's terms, applies designed abstract systems (or systems of thought) in human activity systems (or systems of process) in order to create and maintain a designed physical system (or system of matter) which is the physical manifestation of the building. So, how can such a model of (flexible) system entities, following this idea, be defined and structured so that it, as asked above, helps combining specialised knowledge (of architectural construction) into coherent wholes?

Buildings can be seen as much as expressions of the concepts and process that led to an actual result as the result (the building) itself. Looking at the physical structure of a building tells us about the process that brought it to life as well as the structure of the architectural design process tells us about the conceptual and physical structure of the building – this interdependency is a characteristic of a complex system.

#### *Suggestion for the model*

Buildings and architecture – understood as complex systems – are tentatively defined as assemblages of subsystems of independent materials, components and integrated product deliveries.<sup>111</sup> In their integrated form (the building), these subsystems form coherent wholes that are more than the sum of the constituent parts. Each subsystem includes both the system as conceptual entity, the process required to deliver it, and the physical matter to become part of the building. All subsystems are systems in their own right (holons) as e.g. a structural system, an electrical system, a building envelope, or a window as a subsystem of the latter. Such systems thus express varying levels of complexity - or *integration* of such complexity. Still all are equally subsystems that interface conceptually, procedurally and materially, in the building.

The idea of systems of varying complexity nested into other systems (here termed *nested system integration*) is connected to the moment of delivery of a certain system. Nested systems indicate chains of deliveries that precede the final delivery and installation in the building. Some degree of *prefabrication* or preparation has taken place. All systems are integrated into the final building constituting the principal system – or supra-system. The 'picture' expressed in such a model of a building as a system of these different subsystems will, as introduced earlier, tentatively be called the *system structure of architectural design*. The model can, as a more general system level, potentially point out and make operable both *isomorphisms* (equal structures across projects) and *equifinalities*

(different possible structures for one project leading to equal end results). The enhanced use of off-site preparation or prefabrication accentuates, it is argued, the need for such a conceptual model that can handle levelled complexity (as *holons*) and flexible structuration (through *soft system* modelling). The following section aims at giving concise definitions of some of these concepts around the system structure as they will be used later on in the thesis.

## II.5 SYSTEMS TERMINOLOGY FOR ARCHITECTURE AND CONSTRUCTION

### INTRODUCTION

The previous sections of the present Part II – ‘System’ have, with reference to the topic of this thesis introduced key theoretical themes from related fields of knowledge i.e. architectural theory, classification systems in construction, industrial production theory, and general systems theory. The idea is that these themes form the theoretical and conceptual framework or backdrop used for the rest of the thesis. This both in the sense of underlining and further clarifying the problems that the thesis sets out to treat as well as introducing useful concepts for use in the subsequent practical exploration in Part III – ‘Product’ and for the case analyses and model presentation found in part IV – ‘Model’. The current section seeks to distil key concepts and other findings into a more condensed form in a so-called *systems terminology for (industrialised) architecture and construction* that furthermore tentatively establishes a taxonomy relating some of these key concepts to each other.

### KEY CONCEPTS AND CONCEPTUAL UNIVERSES

A considerable amount of the vocabulary introduced above can seem unfamiliar for use in architectural design. Many terms are closely connected in small ‘conceptual universes’ of subsidiary concepts gathering around a central key concept or theme. Below, such key concepts and their subsidiary concepts are defined as to how they will be used throughout the rest of the thesis. A hope is that they will also be useful within the more general conceptual universe of architecture and construction as a contribution to a province of it under development – *industrialised architecture*.

#### **System**

*System* as used in this thesis refers principally to the interconnected whole of materials, processes, and information that constitutes the intentional human creation of a building or a similar discrete and fixed physical entity of our



everyday physical environment (i.e. urban space, bridge, tunnel etc.). Materials refer to physical matter put into the building or consumed during its creation, processes refer to the manipulation of these materials by use of tools, machinery and personnel, whereas information represents immaterial resources i.e. knowledge and ideas. Although conceptually these systems of *matter*, *process* and *thought* can be separated, in practice they are always integrated when it comes to a building and cannot independently lead neither to a building nor to elements of it.<sup>112</sup> Matter without processing and knowledge about this processing yields no result. Equally, intentional processes as building construction originate from knowledge and ideas and are only expressed through the application to matter.<sup>113</sup> Finally knowledge and ideas about buildings stay immaterial if not directed towards processes that manipulates material.<sup>114</sup> A building in the definition above is furthermore, as argued previously, a *complex system* where many of its constituent elements or subsystems can be characterised as *systems* in their own right (e.g. the structural system, the heating system or the building envelope). As with other complex systems a building is more than the sum of its constituent elements: A structural system carrying a heating system and enclosed by a building envelope provides shelter from the natural elements even in cold climates or seasons. The combination of subsystems contributes to the provision of a liveable space serving many functions that are not inherent in its subsystems seen as isolated (See figure II.5.1). The building as system can also be regarded as a subsystem of other *supra-systems* such as blocks, cities, cultures and social systems with more or less tangible physical substance. This is here termed *levelled complexity*. The choice of focus or system scale defines the primary and subsidiary system elements and their complexity level.

FIGURE II.5.1  
INTEGRATION OF DIFFERENT SUB-  
SYSTEMS SERVE FUNCTIONS THAT  
CANNOT BE REDUCED THE SUM OF THE  
CONSTITUENT PARTS

- 112 Peter Checkland uses a similar division of *designed physical systems* (matter), *human activity systems* (processes) and *designed abstract systems* (thought). See explanation and reference in *General systems theory*, II.4
- 113 Natural processes and systems as opposed to human processes and systems are not governed by external intention but creates and reproduce themselves. In systems theory such systems are termed *autopoietic* (self creative) as opposed to *allopoietic* systems where ‘producer’ and ‘product’ are separate entities. A building can be seen as the product – or subsystem of an allopoietic system. The building itself is then called a heteropoietic system which means that it is created by something or somebody exterior to the system itself. See e.g. <http://en.wikipedia.org/wiki/Autopoiesis> accessed on July 22, 2011
- 114 A drawing or a description of a building is still only a representation – not a building it itself.

- 115 Systems organised hierarchically within other systems are called *holons* – simultaneously constituting wholes and parts. See *General systems theory*, II.4
- 116 The notion of *dimension* is inspired by the Danish DBK and the Swedish BSAB classification systems respectively working with *aspect* (aspekt) and *view* (vy) as different ways to look at an object or a building. See *Classification systems in construction*, II.2
- 117 Both Meadows and Bertalanffy point out the need to model specifically according to the purpose of the model. See II.4
- 118 For a definition of flexible structuration, see *General systems theory* II.4
- 119 This quality of the model is pointed out by e.g. Odum and Bertalanffy. See *General systems theory* II.4

Again, focus here (in present thesis) is the building as the primary (complex) system with appurtenant subsystems. Furthermore, the focus of the subsystems is exclusively delimited to elements that integrate some physical matter to be inserted in the primary system (the final building). Such (physical) subsystems form hierarchies spanning from simple materials to complex integrated systems and can be integrated into each other.<sup>115</sup> This is here termed *nesting*. Present system definition also operates with what is termed as different *dimensions* of the system and its subsystems. A *preparation dimension* expresses different levels of preparation of the physical (sub-)system (upon delivery), a *standardisation dimension* expresses different levels of standardisation (of product and/or process) upon delivery, and a *service dimension* displays different levels of service (in the delivery process).<sup>116</sup> Below, the dimensions will be used in an attempt to establish a taxonomy for classification of integrated product deliveries and their degree of integration. As an overall consideration, it can be said that the notions of *system* and *network* are closely related in the present system definition stressing interconnectedness and interdependency rather than separation and classification.

### Model

The notion of *model* is in the present thesis used as referring to a visually perceivable coded structure that as an intermediate tool displays a focussed view of a system seen on a specific abstraction or complexity level (cf. system and levelled complexity as defined above). Such a model is always modelled for a *context specific* purpose and this purpose defines the right level of abstraction for each of the elements contained in the model.<sup>117</sup> Models are in the present thesis used to represent and display *structural organisation* or specific *configurations* of subsystems in a main system (a building) in the form of a specific pattern. However, as focus and complexity level can change according to the context specific purpose of coding, the model should enable *flexible structuration* of both elements and their interrelations.<sup>118</sup> Although thus being a purely mental (or epistemological) construct with no claimed ontological categories, the model still represents a tool for understanding complex reality through a simplified but flexible lens. It is a way to deal with the world. This is not the same as simplifying reality itself.<sup>119</sup> The systems view inherent in the model aims at focusing on relations between rather than on specific content of each of the elements (as patterns) thus reducing the amount of information needed for keeping track of each element and its position in the system structure. In this way the model can potentially reveal *isomorphisms* (equal form or here:

structural patterns) between various systems (buildings) coded within the model even if these from a formal design point of view are completely different. Equally, systems or buildings that from a formal design point of view are equal or similar can have different configurations of subsystems and thus result in different coding of the model (equifinality). Structural patterns expressed visually through the model can potentially be manipulated through the model as a tool. Again, following the system definition above, the model focuses on elements with some kind of material presence in the overall system being the final building. Different codings of the model represent different *system structures* – a main concept coming out of this thesis which will be formally defined below.

### *Delivery*

In order to formally define the *system structure*, a clearer definition of the elements – or *system entities* – of such a structure initially needs to be done. Using the idea from *supply chain management* that each link in the (supply) chain encompasses both the operator, the operation and the product or material as it advances through the chain, the basic element or subsystem of the system, of the model, as well as of the resulting system structure is here defined as a *delivery*.<sup>120</sup> This delivery has, as the simple supply chain link, physical substance (material), represents a process (operation), and is provided by a supplier or a manufacturer (the operator) and thus overcomes the traditional product/process dichotomy.<sup>121</sup> This integration helps to reduce complexity of structures comprised of such system entities. The physical substance of a delivery needs, in present definition, to become part of the final building. The process of a delivery comprises as a minimum the possibility of buying or acquiring and transferring the physical substance from the supplier for integration in the building or for nesting it into another delivery that ultimately is equally integrated in the building. However, processes can equally include higher levels of the service dimension of a subsystem<sup>122</sup> meaning that the supplier (or manufacturer) can supply, process, and/or install the delivery in the building or nested into other deliveries. Deliveries, as used in this thesis, become physical subsystems and their related processes as they are delivered and nested (inserted) into a building or a subsystem of a building. Deliveries nested into other deliveries can generally speaking – and with reference again to supply chains – be characterised as *upstream deliveries* while if inserted into the building itself they are *downstream deliveries*. The notions of upstream and downstream are also used as relative to a certain viewpoint and will be more consistently elaborated in the description of the model in part IV – ‘Model’.

120 See *Industrial production theory*, II.3

121 The integration of process and product is, as earlier pointed out, substantiated by Bertalanffy. See *General systems theory*, II.4 p5/6. Also advanced DSM-techniques tends towards juxtaposing processes, products and operators (organisational DSM's) See *Industrial production theory*, II.3

122 On *dimension*, See system definition above



FIGURE II.5.2  
THE DASHBOARD OF A CAR IS TODAY  
DELIVERED TO THE CAR ASSEMBLY LINE  
AS A FINISHED INTEGRATED PRODUCT  
DELIVERY COMPRISING SEVERAL SUB-  
SYSTEMS IN ITSELF.

- 123 Authors own translation from Danish. See Vibæk (2009) – the last part of the definition points towards the service dimension of the system structure model – See *Model presentation*, IV.1
- 124 See *General systems theory*, II.4
- 125 See Baldwin & Clark's distinction explained in *Industrial product theory*, II.3

### *Integrated product delivery*

Being concerned with the possibilities of knowledge transfer about systems and systems application from other fields into the fields of architecture and construction makes *integrated product deliveries* a central concept and a type of delivery to be dedicated special attention in this thesis. Integrated product deliveries, as used in the product industry, are complex systems in their own right and represent an efficient means of reducing complexity in focus for a given design task – in particular if these integrated product deliveries are well established as commoditised products. While (building) materials and (building) components are perhaps easy to understand as deliveries, the integrated product delivery as a subsystem requires a little more introduction. Following Mikkelsen et al., an integrated product (in construction) can be defined as ‘*a multi-technological complex part of a building*’ that can ‘*be configured and customised*’ to a specific construction project. It is furthermore ‘*developed in a separate product development process based on the principles in integrated product development*’. In its actually produced and specifically customised state and when delivered to a customer this *building assembly* becomes an integrated product delivery (IPD) that – as a kind of supra level – also can include ‘*marketing, shipment and servicing*’ (Mikkelsen et al 2005:3)<sup>123</sup>. The definition of an IPD as (sub)system goes clearly beyond the division between product and process – between physical and non-physical – thus again acknowledging the difficulty of a consistent distinction between what, as Bertalanffy suggested, ‘*may be the very same thing*’.<sup>124</sup> As an example a service can be seen as a system but whether it is mostly a product or a process depends on the specific service in question and on how you look at it. Following the definitions of *system* and *delivery* above, this thesis concentrates on IPD’s containing several kinds of physical substance that become nested into the final building. Although configurable for specific building projects, IPD’s exceed as systems the project and context specific purpose. IPD’s exist with different degrees of complexity and together with materials and components they can be integrated – or *nested* – into each other so that a more complex and integrated system contains one or several less complex systems. A prefabricated bathroom pod as a subsystem to a building contains several nested subsystems as electrical wiring, plumbing and structure that themselves can be seen as systems. Whether these are relevant in a given system structure depends on the focus of attention. *Integration* and *nesting* are almost aligned in present definition and become conceptually the opposite of *modularisation*.<sup>125</sup> However, to integrate or nest a delivery

does not exclude a subsequent disintegration or *disassembly* for replacement or conversion purposes. Modularisation and integration/nesting are like opposite sides of the same coin. Whereas integrated products and their separate production and delivery are common within other larger designed and engineered products such as cars, ships and aeroplanes, it is still a relatively new system entity in construction.<sup>126</sup> (See figure II.5.2)

Present thesis works with two main types of IPD's in construction that are both of them upstream in relation to the final building that they are nested into and downstream in relation to the simpler building materials and components that they are integrations of. In some cases IPD's can also be nested into each other.<sup>127</sup> The two main types are *chunks* that are volumetric (spatial) units that can integrate a wide range of sub-systems (or parts of these if these subsystems are distributed in the building) and *assemblies* that are defined as system based deliveries by having a narrower more specific scope often encompassing fewer systems but in their entirety. Where chunks in this definition are concerned more with overall spatial performance, the assemblies are rather concerned with system performance of one or few specific systems. This distinction is in other contexts referred to as '*by zone*' and '*by system*'. Chunks are deliveries 'by-zone' whereas assemblies are deliveries 'by system'. Assemblies or parts of these (modular assemblies) can be nested into chunks, and in some cases chunks can be nested into other chunks (e.g. a bathpod into a large volumetric element). Both main types are predominantly off-site produced before final delivery. A final special type of IPD is onsite processing and delivery of a clearly delimited and finished integrated solution that can have touch of both assembly and chunk. This type, although delivered on-site with low preparation still works as integrated through the high degree of service that lies in the finished installation.<sup>128</sup>

### System structure

The notion and the underlying concept of *system structure* is central to and a main contribution of the present thesis. Conceptually, system structure fusions the closely related concepts of *product architecture* and *supply chain*. While within the product industry a product architecture indicates a static (actual or thought) physical structure (organisation) of the constituent elements of a product, a supply chain is concerned with the structure of the flow of processes, materials and operators in order to reach this final physical structure. Another way to put this distinction could be a *product breakdown structure*

- 126 The sections of Part III – 'Product' introduce and discuss several different kinds of these integrated product deliveries in construction.
- 127 This primarily illustrates the difficulty in making a completely consistent hierarchical graduation of complexity and integration of different deliveries in construction.
- 128 In the case studies of Part IV – 'Model' this kind of integrated product delivery is referred to as parallel deliveries as opposed to serial nesting. A discussion of this distinction and the different kinds of integrated product deliveries can furthermore be found in *Findings*, V.1

- 129 See e.g. Armistead et al (1996)
- 130 Ulrich & Eppinger uses the term system level design for products as e.g. printers, photocopiers and scooters. 'The system-level design phase includes the definition of the product architecture and the decomposition of the product into subsystems and components.' (Ulrich & Eppinger 2008:15). See also *Industrial production theory*, II.3
- 131 As described in *Systems in architectural theory*, II.1, Gottfried Semper in the mid-nineteenth century anticipates montage as an architectural and tectonic strategy.

as opposed to a *work breakdown structure*.<sup>129</sup> The system structure seeks to encompass both these aspects of structure thus, as mentioned earlier, overcoming the dichotomy of process and product. The system structure in present definition is exclusively concerned with architectural design and construction of buildings as complex systems assembled by a number of subsystems. The adaptation of the term from the more production related 'predecessors' reflects this fact. Leaving out the notion of architecture as in product *architecture* furthermore avoids confusion of this term within the context of architectural design as a distinct profession and discipline.<sup>130</sup>

Corresponding to the definition of *model* above, a system structure is not an ontological entity – it is so to say not inherent in any building seen as a complex system. A system structure is an epistemological (artificial, immaterial) entity that makes it possible to articulate and interpret certain characteristics of buildings related to the way they are produced and constructed. Particularly concerned with the ways in which a building can be divided into constituent elements that matches the way buildings are actually produced, the *overall purpose* of a system structure is to bring closer on the one hand architectural ideation and on the other hand contemporary processes of construction and building production. The distance between architectural ideation and the way buildings come into being is the main problem set out to be treated in this thesis. The idea of a system structure is the main contribution in this regard.

The introduction of the notion of system structure should not only be understood as a 'technical' tool to look at a building. Inherent in this particular view is also a certain *architectural interpretation* of buildings in general – and industrially produced buildings in particular. The definition above of buildings as complex systems of subsystems points towards an epistemological split of the architectural (art)work into on the one hand the whole as an indivisible entity that is more than its constituent elements and, other the other hand, the work as an *assemblage* of relatively independent elements created outside the work that together form a coherent whole – that is equally more than its constituent elements. Technically, assemblage means the (simple) act or result of assembling elements. However, assemblage within the arts also refers to three dimensional (sculptural) compositions or 'collages' of miscellaneous objects or materials or as defined in Webster's: '*an artistic composition made from scraps, junk and odds and ends [i.e. miscellaneous articles, ed.]*'. The assemblage has connections to the artistic technique of *montage*.<sup>131</sup> In such works of arts the

constituent elements both point inwards towards the internal composition but also outwards towards their origin outside the work. The architectural and artistic implication of the notion of system structure as applied in this thesis tends towards the notion of the architectural whole seen as an assemblage of its relatively independent subsystems.<sup>132</sup> The assemblage is the entire system – the building as whole – as both physical object and architectural work.

The system structure is modelled by use of a visually perceivable model (see above) and displays a given structure (actual, thought or simplified theoretical) of deliveries of different complexity and their interrelation as they become nested into each other and/or ultimately into a finished building. In other words: It expresses a certain *configuration* of the constituent elements (deliveries) of the system (the building).<sup>133</sup> The delimitation of each delivery is not clear-cut and universal but project specific and depends furthermore on the specific focus and purpose of modelling the system structure. Where each delivery – apart from comprising some kind of physical substance – often additionally would imply a contractual relation (between a supplier and a receiver), this is not a definite criteria. Company internal or partly company internal system structures can in some cases make sense – particularly if the company is a manufacturer producing highly complex integrated product deliveries or perhaps even all encompassing building solutions either as prefabrication or as on-site construction or combinations hereof.<sup>134</sup> On the other hand, a delivery can also comprise various nested subcontracts that are opaque (not visible) in the system structure, if this detailed subdivision is considered irrelevant for the specific purpose of the modelling. Such opaque subsystems are actually one of the means to reduce unnecessary complexity of the design process. Apart from aiming at a consistent subdivision according to the complexity and integration of each delivery, the system structure promotes the distinction between offsite and on-site deliveries in regard to where/when the delivery is produced and to what degree it is prepared for nesting on-site or into other off-site deliveries. Apart from the point that the model through this *flexible structuration* is project and purpose specific, one of the major arguments for its utility is that the balance between off-site production and on-site construction always is project specific. Through use of the coded model the system structure can act as analytical tool (retrospectively and potentially proactively) that gives an overview over different system structure scenarios, read: different ways to produce a given system (i.e. a specific building).<sup>135</sup> Important here is to note that offsite production or prefabrication is not necessarily the same as industrialisation in the sense of

132 For an elaborated discussion of the *assemblage* as a three dimensional version of the montage or collage in art and architecture) see (Bundgaard 2006:39-47)

133 Configuration is here used in a sense similar to the way it is used in Space Syntax as explained in II.4

134 Most if not all building solutions are a mix of different degrees of off-site production and on-site construction.

135 This resembles the notion of *equifinality* as described in II.4

136 See *Industrial production theory*, II.3

automation. Often off-site production is merely construction under roof. Still, the choice of a certain off-site production (or prefabrication) can have other justifications – economy- or quality-wise.

Equal to the capacity of, through the model, facilitating a visual display of possible production and assembly structures, and inspired by Nagurneys definition of supply chains,<sup>136</sup> system structures can also be used to indicate a possible afterlife of the different sub-systems due to the quality of integrating process and product. By displaying possible disintegration or *disassembly* scenarios the system structure extend, its utility to facility management for modelling scenarios for after the end of a building's useful life. This will be further elaborated in part IV, 'model'. The system structure underlines a building's quality of being an open system with partly interchangeable constituent parts that can be put together in different configurations.

## INTEGRATION TAXONOMY

Based on the notion of *dimensions* and the definition above of the three different dimensions of a given delivery or subsystem (being integrated or not), this paragraph seeks to draw up a taxonomy that can be used for classification of the different deliveries in a system structure. The overall purpose of the system structure in the first place is to handle complexity by focussing (the limited capacity of) design attention where it is most needed during the architectural design process while simultaneously better integrating issues about how the architectural idea is transformed into physical matter in the final building. Reducing the complexity of the design process does, as pointed out, not necessarily reduce the actual complexity of the final outcome (i.e. the building – or main system). Through the coded model of the system structure a chosen abstraction level is established according to the specific purpose in question while less relevant detail are left out of focus.

The three dimensions of *preparation*, *standardisation*, and *service* can all be seen as expressing different aspects of complexity concerning a delivery (subsystem) in a building. Each of the three dimensions is here detailed as divided into four levels that generally can be said to span from low to high integration of complexity. Integration of complexity (in a delivery) means that the complexity is handled by the supplier e.g. through production system or delivery



FIGURE II.5.3  
EXAMPLES OF THE DIFFERENT PREPARATION LEVELS

service. Potentially, *integrated complexity* reduces the complexity to be handled by the (architectural) designer/client or whoever is receiving a given delivery.

Due to the qualitative character of the subject (of complexity), the graduation of each dimension into four levels is arbitrary in the way that the categories seek to theoretically cover the possible range within each dimension while the specific subdivision is fixed to four intuitively meaningful categories. The categories attempt to avoid too much overlap and at the same time provide a comparable graduation between the dimensions that makes it easier to understand and use. Below, the three different dimensions and their corresponding values or levels are listed.

### Preparation level

The preparation dimension describes the level of preparation of the delivery when it leaves one (production) location in order to be inserted into another, being a building or subsystem of a building. This *in between* state of a delivery is independent of the processes needed to install the delivery at its destination point in the system structure. The following four levels are defined corresponding to the definition of deliveries and integrated product deliveries above:

0. MAT = Building material (manufactured raw material as one single or a composite material).<sup>137</sup>
1. COM = Building component (assembled component as a simple custom made component of one or few materials or a standard (industrial) technical device.)
2. ASM = Assembly (integrated assembly of materials and/or components often encompassing one or few subsystems in their entirety – an assembly by system)
3. CHK = Chunk (large volumetric element that can integrate a wide range of subsystems or parts of them if these subsystems are integrated in the building as a whole)

Some deliveries leaves one location as kit-of-parts (earlier KOP-category) of prepared materials, components and or assemblies that when installed at the destination point constitute assemblies (ASM) or chunks (CHK). Whether these are coded as assemblies, chunks or as their constituent components and materials is defined by the primary place of processing. If a considerable amount of

137 Raw materials are seldom if ever used in a non-processed manner in a *building* as e.g. directly from the mine. The category refers to building materials – materials on a level that is relevant in architectural construction. In another context with another focus, materials could even be treated on the molecular or atom-level. It is the focus on buildings and architectural constructions that defines the relevant range.



FIGURE II.5.4  
EXAMPLES OF THE DIFFERENT STANDARDISATION LEVELS

FIGURE II.5.5  
EXAMPLES OF THE DIFFERENT SERVICE LEVELS

138 Earlier iterations of the taxonomy had a kit-of-parts category (KOP) that however showed difficult for consistent coding and has been omitted.

processing and adaptation is needed at the destination point, the delivery is classified as its constituent (upstream) sub-elements. If only simple assembly or a minor amount of processing and adaptation is needed then the delivery is classified as the assembly or chunk.<sup>138</sup>

### Standardisation level

The standardisation dimension describes the level of standardisation of the delivery when it leaves one (production) location in order to be inserted into another, being a building or subsystem of a building. The following four levels are defined:

0. BSP = Bespoke (custom product/custom delivery – non-standard solution made specifically for a project)
1. M2O = Made-to-order (custom product/standard delivery – customised product version within existing system – often called mass customisation.
2. C2F = Cut-to-fit (standard product/custom delivery – cut and delivered in customized dimensions for known customers)
3. OTS = Off-the-shelf (standard product/standard delivery – delivered in standard dimensions produced for unknown customers)

### Service level

The service dimension describes the supplier's level of direct involvement in the handover of the delivery to the point of destination. The following four levels are defined:

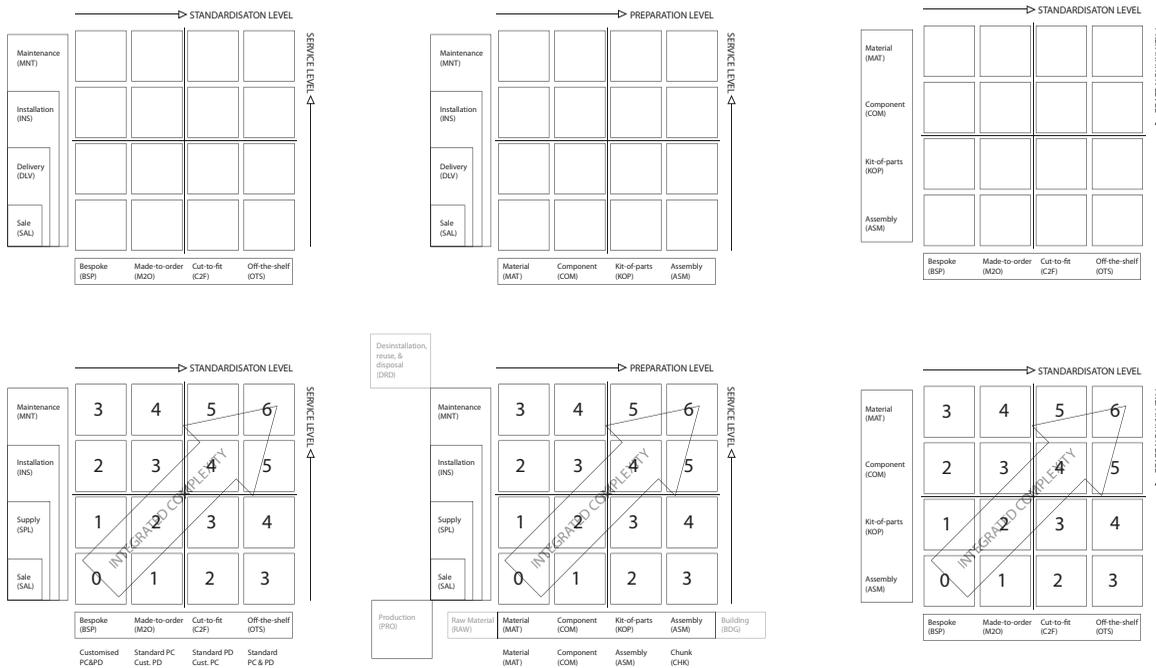


FIGURE II.5.6  
2D-GRAPHS WITHOUT VALUES

FIGURE II.5.7  
2D-GRAPHS OF DIMENSION PAIRS  
WITH THEIR RESPECTIVE VALUES

0. SAL = Sale (delivery pick-up arranged by purchaser/receiver)
1. SPL = Supply (supplier delivers to purchaser/receiver at point of destination (integration location i.e. factory or building site))
2. INS = Installation (supplier installs at point of destination (integration location i.e. factory or building site))
3. MNT = Maintenance (supplier maintains delivery after delivery and installation)

Remark that the levels of the service dimension are inclusive in the way that a higher service level automatically also includes the lower levels (e.g. delivery (SPL) always includes sale (SAL)). Likewise maintenance (MNT) always includes sale, delivery and installation (INS). Although maintenance can perfectly be (and often is) a separate (service) delivery applied to a building after its construction, the focus of the system structure (cf. above) is exclusively delimited to deliveries that contain physical matter to be inserted in the building up until its completion. Such deliveries that include maintenance after completion will consequently automatically encompass the other service levels.

**Integrated Complexity Value**

Theoretically, every delivery can be classified along each of the three dimensions defined above. The different dimension values of each delivery can then be crossed and plotted into simple diagrams showing the relations between pairs of dimensions. Figure II.5.6 shows how such diagrams could look. Intuitively it can be understood that deliveries located in the lower left corner of the graph will have a low integrated complexity whereas, on the contrary, deliveries located in the upper right corner will have high integrated complexity.<sup>139</sup> By moving rightwards or upwards, integrated complexity of deliveries increases while moving leftward or downward means that integrated complexity decreases. It is thus argued that also high standardisation values point towards some kind of integrated complexity of the delivery. Although standards perhaps are defined completely outside a product through e.g. legislation or public regula-

139 As mentioned above all three aspects and their related levels express something about the complexity integrated in a delivery or product. Integrated complexity means complexity handled by the supplier and thus – at least theoretically – is beyond the attention of the purchaser/receiver of the delivery – representing the next link in the ‘supply chain’.

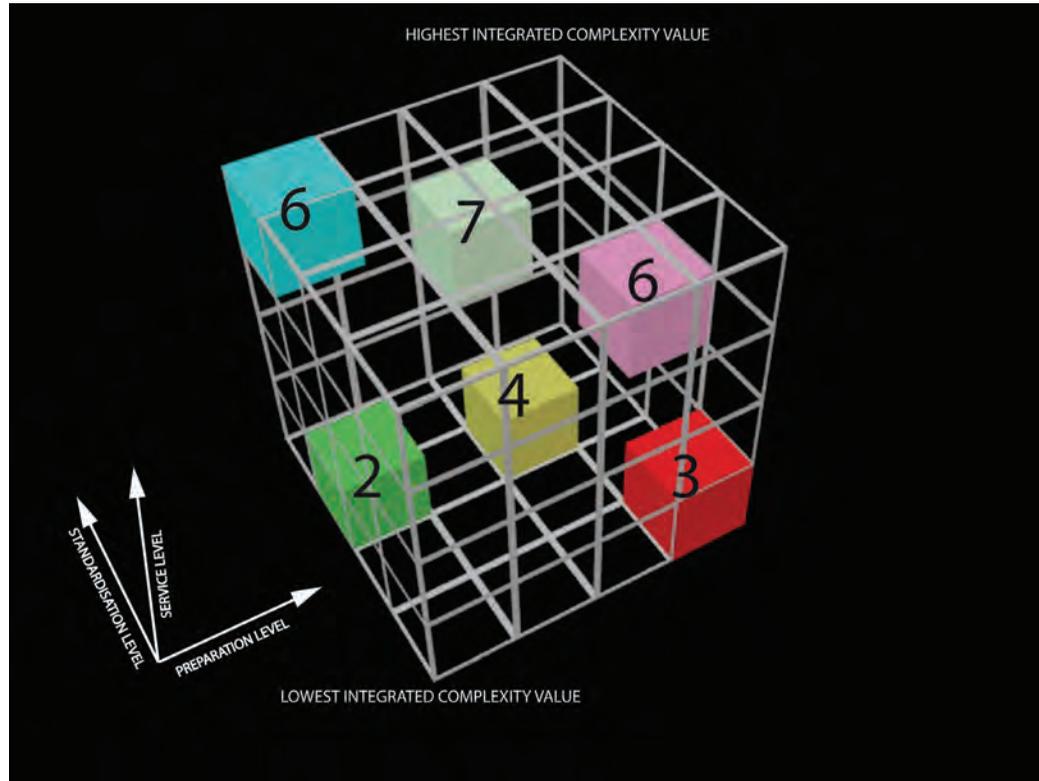


FIGURE II.5.8  
EXAMPLES OF DIFFERENT TOTAL  
INTEGRATED COMPLEXITY VALUES AS  
COLOUR CODED CUBES IN A THREE-  
DIMENSIONAL GRAPH

140 Conceptually a *relative integrated complexity value* could be calculated by adding all total values of the deliveries in a system and dividing it by the number of deliveries. A relative integrated complexity value would – at least theoretically – be comparable between systems (different buildings or different system structures for the same building)

tion, these exteriorly defined standards make it possible to deliver a ‘simpler’ product by constraining the solution space. The complexity integration lies in this case prior to the product itself that subsequently can draw on it as an established standard.

By applying numerical values to the levels of the different dimensions it is tentatively sought to arrive at a simple (and simplified) mathematical expression of the integrated complexity seen as combinations of the different dimensions. By using values between zero (0) and three (3) for each of the dimensions of a given delivery the values can subsequently be added to a sum. Figure II.5.7 shows how values of two dimensions are added.

If the values of all three dimensions of a given delivery are added it gives what is here defined as a *total value of integrated complexity*. In order to express this in a diagram one needs three dimensions. In figure II.5.8 this is expressed like a three dimensional graph. In the first case such a value is only a local measure in the sense that it can (theoretically) be used to compare different versions of the same physical element in a building. By having three dimensions it can, again intuitively, be understood that if one dimension value goes one down and another one up or if one dimension value goes two down and each of the two other goes one up each, then the total value of integrated complexity will stay constant. Working with numerical values of qualitative parameters (as the dimension) is of course not correct in a strictly mathematical sense and the values are – at least not at the current stage of research – meant to be taken as exact. It does however give an impression of different levers that can be used to adjust the amount of integrated complexity in a delivery – and perhaps of the total amount of deliveries that constitutes a building (seen as a complex system).<sup>140</sup>

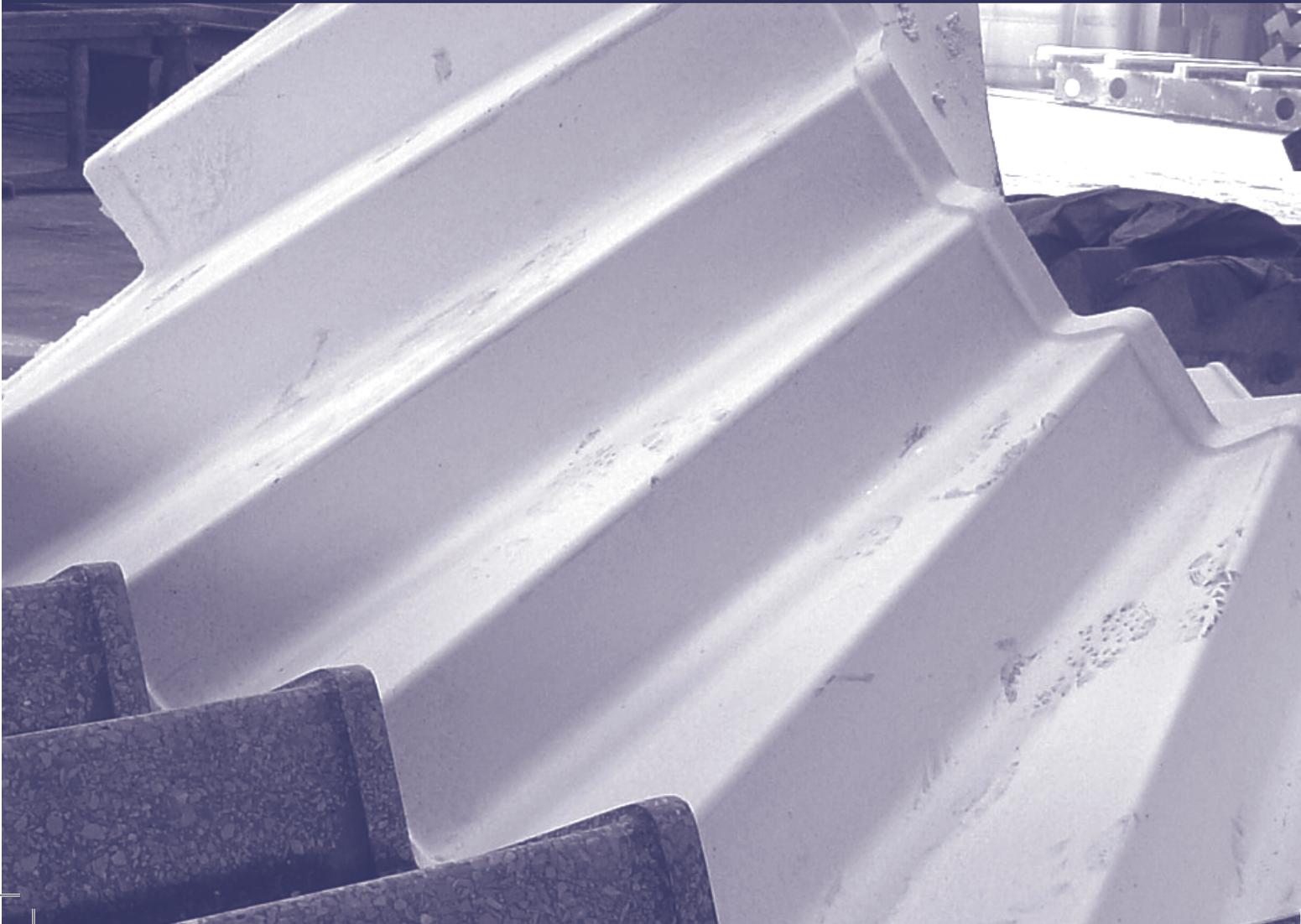
Such levers could be including installation (INS) to a supply (SPL) or using an off-the-shelf (OTS) product instead of a bespoke (BSP) solution.

### **Examples**

The highest possible value of integrated complexity would be a completely standardised (OTS) chunk (CHK) that is delivered, installed, and subsequently maintained (MNT) by one single supplier or at least with this single supplier as responsible for the entire service.<sup>141</sup> On the contrary, the lowest possible integration of complexity would be the – perhaps slightly unusual – situation where a completely bespoke (BSP) material (MAT) would be sold for pick-up (SAL) to be arranged separately by the receiver (manufacturer, client, or main contractor) who would also be in charge of its later installation in the building or as nested into another delivery. However, most deliveries would be located in between these two extremes as e.g. a standardised (OTS) ventilation device (COM) delivered (DLV) for subsequent installation by a plumber or a cut-to-fit (C2F) delivery of simple façade cladding panels (MAT) installed onsite by supplier (INS).

The above examples do, as general (theoretical) examples, perhaps seem evident. However, applied in a design process with specific deliveries or as an overall design strategy they can potentially contribute to a more conscious selection of where design effort is located (read: where complexity is kept open) and where the effort is rather ‘outsourced’ to other (upstream) suppliers (read: where complexity is integrated). The following part III - ‘Product’ looks into specific examples of what integrated product deliveries are and can be and how they can be described using the terminology as defined in this part.

141 Whether the actual installation and/or maintenance is done by a sub-supplier has little importance as long as the contractual relation is between supplier and manufacturer, client, main contractor or whoever is receiving.



# PART III

# PRODUCT

- III.1 COMMODITISATION IN  
ARCHITECTURAL CONSTRUCTION
- III.2 CUSTOMISABLE ARCHITECTURAL SUBSYSTEMS
- III.3 DEVELOPMENT AND CLASSIFICATION  
OF INTEGRATED PRODUCT DELIVERIES



### PART III – PRODUCT

As opposed to the previous part II – ‘System’ being a theoretical exploration, the present part III – ‘Product’ represents a practical exploration and discussion of the building industry and its products as they are available on the market today – or perhaps will become available through discernable tendencies or development initiatives. A particular focus is the integrated product delivery as a new or emerging kind of building product. Through three chapters different aspects of products and integrated product deliveries in construction are examined. In *Commoditisation in architectural construction*, commoditisation is proposed as a useful concept for understanding integrated product deliveries as a qualitatively different kind of products compared to other kinds of delivery in construction. The notion of industrial ecology is also introduced as having special parallels to this kind of building products. In *Customisable architectural subsystems*, the delimitation and definition of integrated product deliveries as an entity are challenged through specific examples or types. Finally, *Development and classification of integrated product deliveries* starts with short historical intro to product development in construction leading to the description of a specific recent initiative. In the last part of the section the elaborated taxonomy of integrated complexity from the *Systems terminology* section is tentatively applied to different building products in a short catalogue-like format.

## III.1 COMMODITISATION IN ARCHITECTURAL CONSTRUCTION

- from construction of projects to production in projects

### INTRODUCTION

The current section and part examines the *product* as an entity and its relation to what is normally called a *project* in construction and architectural creation. The formal definition of a product is simply 'something produced'. To produce can have several meanings as e.g. 'to give birth or rise to – yield', 'to give being, form, or shape to – make or manufacture' or 'to bear, accrue or cause to accrue' (Mish et al. 1989). Common to the definitions is that they do not hint to the exact nature of *what* is produced – the nature of the product. In general economic theory what is produced and sold like products on the market is divided into three main types of industries – Primary, secondary and tertiary industries concerned respectively with a) extraction or exploitation of raw materials as found in nature, b) conversion of raw materials into goods, and c) services as transportation, finance and a wide range of other more immaterial products. Lately it has furthermore become popular to talk about a fourth type – *experience industry* – providing (immaterial) products as e.g. entertainment, event, and tourism services. Whereas (tertiary) services often serve basic human or societal needs and support the primary and secondary industries, experiences are more disconnected from the 'material base' of production. Pine and Gilmore adds a fifth on top termed the *transformation economy* (Pine & Gilmore 2000) as a new emerging industry concerned not only with providing experiences but customised experiences that transform the beneficiary mentally or physically i.e. psychotherapy, meditation, transplantations or plastic surgery. Products in the transformation industry are life changing experiences. Consequently, products and their delivery can not simply be delimited to the material realm. Most contemporary products are intermingled wholes of raw materials, goods, services – and perhaps even of experiences and transformations. This is not different when it comes to *architectural products*. Although the architect traditionally is considered to create physical wholes and as such directly related to secondary industries, the ideation and design – the act of giving form or shape to something – is in itself rather a *service*, that in the end also provides a spatial *experience* that potentially *transforms* our way of living

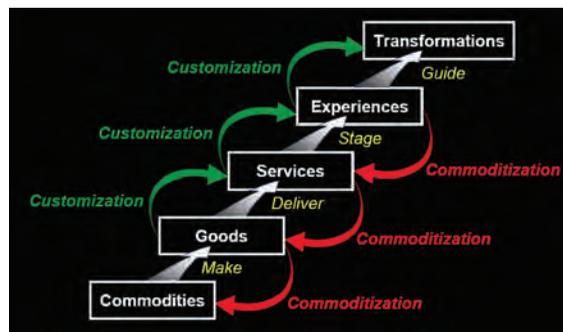


FIGURE III.1.1  
PINE & GILMORE'S FIVE INDUSTRIES  
(OR ECONOMIES) AND THEIR RELATION.

### Knowledge Transfer and Business Model

When architects work with the development of physical systems in projects they often tend towards forgetting or (even explicitly) giving low priority to the simultaneous need for the development of an integrated and economically sustainable business model that can bring the system 'beyond the prototype'. Even though thinking in systems by nature does seem related to architectural thought and conception, the architect works distinctively project oriented. Every new project is a new start. This means that the general potential – or product character – of a specific architectural project only seldom is transferred to subsequent projects. One explanation among other possible could be that the architect has no particular training – at least not traditionally – in seeing *the general in the specific*. Rather, she seeks *the specific in the general*. Architectural projects aim at providing context sensitive solutions for design problems that however often also contain a considerable amount of elements of general human needs. Sometimes it is even considered as negative that architectural ideation and design work draw directly on earlier experience that supposedly contaminates a context sensitive and artistic answer to a specific design problem. The direct knowledge transfer between projects in the conceptual design phase is normally low and non explicit (e.g. in the form of tacit knowledge). Within industrial design this is a little different. Specific industrial designs often form part of a product family and several designs can be based on the same knowledge of a material technique and the resulting form. The general aspect – or system level – becomes like a signature of the designer. Industrial design is also – as opposed to architectural design – often characterised by large batches of mass produced items. Although the unique and original idea is praised, industrial designers are generally much more oriented towards a product perspective than the architect. Perhaps one of the explanations is that the architect works with the space as primary material whereas the industrial designer rather works with the object. Although both work with the shaping of physical material into form, the designer is more directly engaged with the material as object whereas the architect works with the material as forming and enclosing space – a phenomenon that seems more difficult to commoditise as general solutions due to a much higher complexity of influencing contextual factors. The task of integrating this context simply is more complex. The resulting enclosed space and the surroundings are both a part of and separate from the architectural object and the 'product' is consequently more difficult to delimit in a clear and non-ambiguous way.

- 1 *'Although ideally a form should reflect all the known facts relevant to its design [...] the technical difficulties of grasping all the information needed for the construction of such a form are out of hand – and well beyond the fingers of a single individual'* (Alexander 1964:4)
- 2 'The heuristics methodology is based on "common sense" – that is, on what is sensible in a given context. Contextual sense comes from collective experience stated in as simple and concise a manner as possible. These statements are called heuristics [...]' (Maier & Rechtling 2009)
- 3 For a definition of *integrated complexity* see *Systems terminology*, II.5
- 4 This distinction is e.g. introduced by (Mikkelsen et al. 2005)
- 5 See *Systems Terminology* – II.5

### Complexity

Increased complexity of contemporary buildings as well as the processes of producing them challenge the integrative capacity of architectural practice as e.g. pointed out by Alexander (Alexander 1964:4).<sup>1</sup> Bachman states that *'architecture is perhaps the ultimate profession of integration'* (Bachman 2003:6). This seems to call for new and different means to reduce complexity of the architectural design and construction process without impairing the capacity of the final result to integrate culturally well-founded high architectural quality with the complex requirements of modern life, technical performance and legislative regulations. It is thus not primarily about reducing the complexity of the outcome but rather about handling this complexity through new products, tools or heuristics<sup>2</sup> that do not force architectural creation into the straitjacket of traditional industrialised mass production. While all construction today is industrialised to some extent, industrialisation can be approached in different ways that express varying degrees of *integrated complexity* and flexibility.<sup>3</sup> An assertion here is that the choice of integrating complexity and where and how this is done in the system structure (or supply chain) of a building has significance for the degree of flexibility of the architectural solution space, i.e. the available design choices within a given context with a given set of conditions. This correlation, it will be argued, is not necessarily linear in the way that higher integration of complexity necessarily gives lower (architectural) freedom or flexibility. Architectural creation is not a free standing art like e.g. painting or sculpture. It is highly dependent on the way it can be produced and/or constructed in a given society on a certain technological stage and with a specific market structure. The general specialisation and industrialisation of our society has enhanced the dependency on industrial production processes and products produced outside the context of each particular building project. The art of building is moving from manually dominated *construction of projects* towards industrially dominated *production in projects*.<sup>4</sup> A key theme here becomes the degree of commoditisation of each of the constituent elements (the subsystems) as well as of the whole architectural work – or *assemblage* as present thesis tentatively term the industrialised architectural work.<sup>5</sup> Commoditisation here refers to the establishment and consolidation of such constituent elements on a market as discrete marketed *products*. Commoditisation integrates complexity through e.g. enhanced standardisation, preparation and service – the dimensions introduced in the previous section.

## INDUSTRIAL STRATEGIES FOR HANDLING COMPLEXITY IN CONSTRUCTION

Together with Beim & Nielsen, the author has earlier argued for a theoretical division of industrialisation in the construction industry into three different main strategies for supplying deliveries for a building. The three strategies express different degrees of integrated complexity – or commoditisation – of the deliveries (Beim, Nielsen & Vibæk 2010):<sup>6</sup>

- A. Traditional Product Delivery – Supplying simple building materials or smaller components around the remaining, but faint (craft founded) interfaces, which still exist in the industry. Focus in building projects becomes the coordination of (craft based) processes on-site.
- B. Integrated Product Delivery – Organizing, developing, and supplying products as integrated subsystems like building assemblies and chunks with clear interfaces to other subsystems. Focus in building projects becomes the coordination of products.
- C. Turnkey Delivery – Taking control of the entire value and supply chain, process and value chain by developing and supplying all-encompassing building systems. Focus in building projects becomes possibilities vs. production efficiency of the (closed) building system.

The strategies are explained more in detail below:

### *Traditional product delivery - building by pieces*

This first strategy refers to building systems relating to traditional crafts and construction processes. Although the strategy is called *traditional*, product examples of this first strategy can actually represent highly industrialised processes during production. Building materials as e.g. gypsum boards, bricks, flooring and even different kinds of mortar and filler are produced in factories with a high degree of automation, specific quality standards and efficient supply systems (= industrialised). Industrially produced building materials and smaller components can evidently be sub-deliveries of larger more integrated elements but, as an isolated strategy, construction with materials and smaller components is mainly project oriented and primarily restricted to on-site processes. For further elaboration on this strategy as a form of industrialised con-

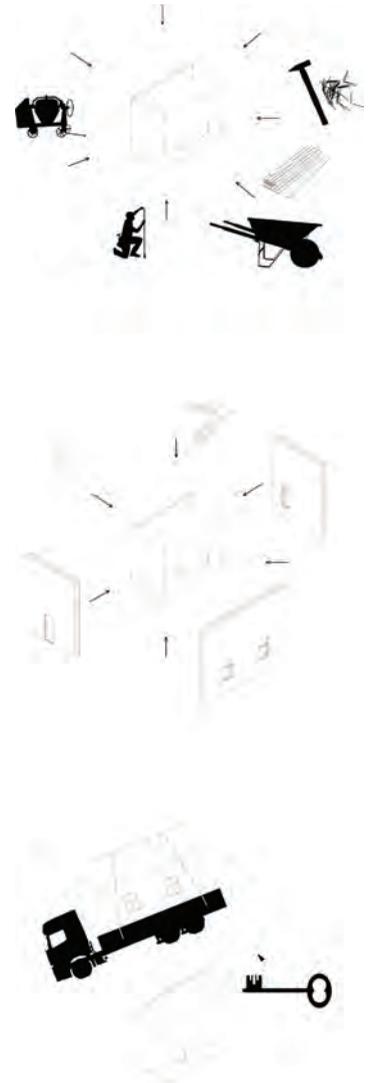


FIGURE III.1.2  
THREE DIFFERENT STRATEGIES FOR SUPPLYING DELIVERIES FOR A BUILDING, BY BEIM, NIELSEN & VIBÆK

6 Current paragraph is partly re-used from (Beim, Nielsen & Vibæk 2010:79-83)

- 7 Lean Construction Institute, <http://www.leanconstruction.org> accessed on July 29, 2011
- 8 See definition of integrated product delivery in *Systems Terminology*, Part II – ‘System’

struction, the concept and the theories of *lean construction* follow this track. They concentrate on ‘*project based production management in the design, engineering, and construction of capital facilities*’.<sup>7</sup> Rather focusing on building products and their degree commoditisation, this section and the thesis do not leave space for a more detailed unfolding of this field of products.

#### ***Integrated product delivery - building with assemblies and chunks***

Within the strategy of integrated product delivery, the building as a whole is conceived as a total of sub-supplied industrialised building assemblies and chunks. Each manufacturer provides a clearly delimited but integrated product, which ideally has well defined interfaces with other adjoining products or fits into some kind of general standardized frame. The integrated product deliveries are systems in their own right and their production can be highly industrialised although in practice this is seldom the case due to the combination of relatively high complexity and low sales volume compared to the traditional deliveries above.<sup>8</sup> The focus of product development within this strategy is the performance of the final assembly or chunk according to technical demands as well as its capacity to adapt to specific conditions set by the different contexts. A determining competitive factor will be the manufacturers’ ability to sustain and maybe enhance these subsystems until they become best practice and eventually industry standards in order to consolidate them as established products on the market. Today several examples of building assemblies can be found with different scale and different degrees of physical and spatial integration with other assemblies, chunks or with the building as a whole. However, the idea – this strategy in its clear form – of putting together a building based completely on assemblies and/or chunks is so far not realisable – and perhaps not desirable at least from an architectural point of view! By segregating certain parts of a building into integrated factory produced elements – the integrated product deliveries – it is possible to make use of both the technical and the economical advantages of a controlled production environment (prefabrication). This again opens new perspectives along the service dimension like e.g. product guarantee, servicing and liability that are difficult to obtain for project based assembly of materials and components on the building site.

#### ***Turnkey delivery - all-encompassing building systems***

Within the strategy of turnkey delivery, it is usually a single company or a consortium which is in charge of a total solution comprising the whole process from sale over production to final delivery. In this sense it could look like a



FIGURE III.1.3  
NCC KOMPLETT WAS A MULTI STOREY  
TURNKEY DELIVERY SYSTEM: 'JUST  
A MOMENT, PLEASE – ASSEMBLY IN  
PROCESS.'

conventional turnkey contract, but as industrialised strategy the main focus is a standardised product and its entire value chain – not the single project, which is rather seen as a way to learn in order to improve later versions of the *product*. The turnkey delivery is usually – but not necessarily – characterised by a high degree of prefabrication. A concept or a brand is created around the product which can have its own name different from the supplying company itself. Questions of interface between constituent elements or modules are solved internally within the product solution and internally in the company. Although outsourced integrated product deliveries (as above) could be used as part of the solution, it is seldom the case. Due to the complexity of the final delivered solution a determining competitive factor will – despite the product focus – be the manufacturer's ability to create and sustain the brand through excellence, highly esteemed references and credibility on project level. Most turnkey deliveries are based on a single base building system. Some concepts are highly standardised consisting of only one or few types and low (project) adaptation based on a specific physical appearance. Other concepts are more neutral and open based on certain standardised structural principles and details, but are adaptable concerning the layout and appearance. As with the chunks and assemblies, the high degree of control obtained through prefabrication facilitates quality check and product guarantee. Almost all all-encompassing systems are directed towards the single family house market. More large scale and multi storey concepts are however beginning to appear.

## ENHANCED COMMODITISATION

Currently, the strategy of traditional delivery and to some extent the strategy of turnkey delivery dominate the building industry. Both strategies share some of the same problems architecturally as well as businesswise the latter often 'just' being traditional product deliveries (materials and components) put together under a roof as one-of-a-kind projects. Either complexity is high, difficult to control and make profitable or choice is low with heavily standardised solu-

9 Although standardisation of the individual building material or building component can – and often is – high, these materials and components often need considerable adaptation on-site thus losing this ‘quality’ of standard.

tions leading to poor architectural possibilities (small solution space) and too narrow market opportunities. If buildings are to be composed as (unique) projects and directly by materials and components – as they mainly are within both these strategies – it is almost impossible to control all interfaces and thus the final outcome in any industrialised way. The increasing amount of different building materials and the endless possibilities of combinations have eliminated the craftsman’s default solution and blurred the link between craft and modularisation of the building by lack of embedment in an established (vernacular) building tradition. This makes the establishment of clear interfaces (almost) impossible on this level of detail. Automation of off-site processes within the strategy of turnkey delivery is in most cases only loosely implemented – partly due to low batch size and (too) many project specific variations. From a point of view of integrated complexity and commoditisation, the strategy of integrated product deliveries is different. The traditional delivery by nature has a low level of integration in all dimensions (preparation, standardisation and service).<sup>9</sup> The turnkey delivery is considerably more commoditised with a usually high preparation level (prefabrication) and a high service level (turnkey). Standardisation varies but is mostly low in order to sustain sufficient sales volume. A consistent use of the strategy of integrated product delivery opens up for high integration of complexity in all (three) dimensions by moving the focus of this integration into discrete deliveries further upstream while these products represent performance based entities (of the final result) rather than material and craft based entities. Complexity for each of these is less than for the whole and the complexity of controlling the whole is partly distributed over and integrated into these subsystems. The design of integrated product deliveries introduces a product level between industrial and architectural design that might require central skills from both disciplines: On the one hand enhanced knowledge about general and specific material properties and the production techniques to manipulate these into (integrated) objects – as the industrial designer, as well as on the other hand the training in the relational or compositional techniques of creating spaces and forms through the combination of integrated systems and materials as the architect.

### *Organisational integration*

In traditional product delivery the organisational setup delivering a building is created ad hoc around the specific project (each building) and thus project specific. Such an (ad hoc) organisation has no integration but dissolves at the end of each project. It is so flexible, that it hardly exists! Revenue (for each of the

stakeholders) in such an organisation can only be based on economies of scope – the ability to make profit on product diversification (because each project is a unique product!). In turnkey delivery on the other hand, the organisation is an inherent part of the all-encompassing product solution and exceeds the project level. This organisation includes marketing, sale and perhaps even servicing after delivery within one centrally controlled entity. This type of organisation corresponds in supply chain terms ultimately to a vertically integrated conglomerate and tends to be tuned toward economies of scale (standardised mass-production). Due to little organisational flexibility (as e.g. expensive investment in specific production facilities) the responsiveness in terms of the product is low. For buildings based primarily on the strategy of integrated product delivery the organisational setup delivering the building is fragmented over a number of different organisations each one specialising in the delivery of an integrated subsystem of a building delivered as a *product* rather than as a project. By focussing on a subsystem instead of the entire system (of a building) complexity is reduced while the commercial potential is enhanced through the product's possible integration in many different buildings. This represents – on building level – rather *virtual integration* where ‘*companies [...] partner with other companies to create [responsive, ed.] supply chains for fast moving markets*’ (Hugos 2006:21). Instead of constructing projects as within the strategy of traditional delivery or producing (all-encompassing) products as with the turnkey strategy, the entities of an organisational setup based on the strategy of integrated product delivery *produce in projects*.<sup>10</sup> This strategy combines economies of scale with economies of scope by splitting the building and the process of bringing it into being into two parts – a product level of integrated product deliveries (economies of scale) and a project level where these are assembled into a building (economies of scope).<sup>11</sup>

- 10 See description of vertically vs. virtually integrated supply chains in II.3 and (Hugos 2006)
- 11 This is different from splitting idea from its execution as pointed out as the main problem to be treated in present thesis.

## INDUSTRIAL ECOLOGY – A STRATEGY FOR DISCRETE CONTROLLED PRODUCTS

The increasing demand for environmentally sustainable solutions that takes better into account the human ecological footprint and use of non- or slowly renewable resources will undoubtedly heavily impact the construction industry in the years to come. Being the most resource intensive industry material-wise and among most the energy consuming counting both construction and operation the built environment constitutes a major field for resource optimisation.



FIGURE II.1.4  
OAT-SHOES AIM AT MAKING THEIR  
PRODUCTS 100 PERCENT BIO-DEGRA-  
DABLE – CRADLE TO CRADLE

This calls for technically more advanced solutions but also for a more systematic use of *simple* and context sensitive solutions based on knowledge that already exists in an often tacit form embedded in traditional cultural behaviour or vernacular building styles. Entities as climate, created physical environment, and the life span and use of it (behaviour) must be considered in their interaction in order to evaluate on a building's impact on our ecosystem.

#### **Commoditisation as eco-friendly**

*Industrial ecology* covers the idea of closed material loops of production where waste and recycling are used as input for new production in a continuously closed cycle thus virtually leaving no ecological footprint. However, grasping material cycles of all components and materials of an entire building and its use is an immense task and outside the information processing capacity of a single designer or even a design team working on project basis. Actually *controlling* these cycles is even more unrealistic and can never be the task of architectural design alone. This does however not mean that architectural design should not be concerned with such issues. A further commoditisation of the construction industry by the development of integrated product deliveries, as defined above, can move some of this need for information and knowledge processing into a (non project specific) system level (i.e. the product) with possible workload and economic amortisation over many individual building projects. Such *products* can still be mass customisable (made-to-order) in order to fit certain project specific requirements that are kept open or held within a certain predefined range of flexibility as in parametric design.

#### **Cradle to cradle**

Under the slogan of *waste equals food*, McDonough and Braungart (McDonough & Braungart 2002) theoretically eliminate the concept of waste and divide materials into biological and technical nutrients thus leaving open the possibility of closed material cycles without excluding the use of artificial and potentially environmentally harmful materials (technical nutrients) as long as they are kept strictly separate from biological nutrients and their cycles. Biological nutrients return to the biological cycles and are ultimately always biodegradable whereas

technical nutrients return to technical cycles in a kind of industrial metabolism controlled by human activity (Ibid:103ff). Technical nutrients do not have the same general decomposability as biological nutrients (composting) and need often be kept separate material by material. Systems integrating both kinds of nutrients hence should be easily separable into these two general systems of material flow.

#### *Nested systems and embodied energy*

As pointed out by Meadows, systems can be nested within systems (Meadows 2008:15). In the case of products, this means that material flows can be considered on various levels of integration. Materials do not need to be brought all the way back to its raw material state in order to be recycled in new products – it can in some cases be used directly on a higher integration level as e.g. a component or a complete integrated product delivery (assembly or chunk). Even entire buildings are reused for other purposes with smaller or larger amounts of retrofitting needed. This perspective on reuse makes good sense when it comes to the question of embodied energy – or *emergy* as it has been termed (Odum, 1996) – meaning the total amount of energy applied to bring a product into its present state. Decomposition or disassembly also requires energy hence second-hand use is not just a question of saving money! However, the amount of embodied energy must be weighed against the actual reusability of a certain subsystem (constituting a certain amount of integrated complexity). Aluminium for example takes a lot of energy to produce but is then as material highly remouldable through various techniques not necessarily requiring intensive use of energy. Thus using aluminium for very project specific components that can then be remoulded for new use makes sense. Other materials perhaps requiring more energy for later conversion could be designed for reuse on higher integration levels. The integration level of reuse (i.e. material, component, assembly, chunk, or building) is important to consider in design seen from an environmental point of view.

#### *Design for disassembly*

As explained in the section on *general systems theory*, Meadows introduces hierarchy and hierarchical organisation as a common characteristic of complex systems including natural systems as ecosystems or living organisms:

“A cell in your liver is a subsystem of an organ which is a subsystem of you as an organism, and you are a subsystem of a family, an athletic team, a musical group, and so forth’

(Meadows 2008:82)

- 12 See *General systems theory*, II.4
- 13 See *Industrial production theory*, II.3
- 14 *Flexibility* can have different connotations in construction. For authors own discussion of the notion of flexibility in architectural systems distinguishing between *design flexibility*, *conversion flexibility* and *flexibility of use* see (Beim, Nielsen & Vibæk 2010:26ff) – cf. note in *Industrial production theory*, II.3
- 15 As shortly introduced in *industrial production theory*, II.3 px?, Steward Brand works with the concept of several layers in a building, each with their life span and argues for the necessity of designing for replacement of parts according to these life spans and layers. (Brand 1994)
- 16 The introduction of deliveries on different tiers in a supply chain will be elaborated in *Model presentation*, IV.1

For Laszlo these hierarchically organised subsystems being systems in their own right became *holons* of a *holarchic structuration*.<sup>12</sup> Buildings as complex systems are equally hierarchically organised. This however, does not entail that buildings are also *designed* as such hierarchical systems – even less that they are subsequently physically decomposable or dismountable into their subsystems (or holons) and the subsystems of these subsystems. *Design for disassembly* as one of the design for x-strategies defined in the section of *Industrial production theory*<sup>13</sup> is preparing buildings for salvageability and reuse on various integration levels already in initial design stages. By designing hierarchies or (supply) chains of nested systems on various integration levels, ideally leading through integrated product deliveries (assemblies and chunks) to be inserted in a building, the complexity needed to be handled on each level is considerably reduced – it is integrated upstream in the nested deliveries. This equally concerns the integrative design work to be performed by the architect – it is partly embedded further upstream. *Vola*-fixtures are popular components that are often specified by the architect. These fixtures, as others, use standardised connections and washers that are nested into the product this obviating the need for designing or choosing these parts each time. *Vola*-fixtures can equally be standard fixtures in e.g. a bathpod product thus obviating the choice of fixtures when you choose this integrated product. Both connections, washers, fixtures and potentially the entire bathpod can (later) be replaced as discrete elements. This phenomenon here tentatively termed '*nested commoditisation*' could potentially enable closed material loops (of technical and biological nutrients) that interface materially and procedurally in a building as discrete products forming a whole. If nested systems can be independently replaced on various integration levels (e.g. according to life span or changed requirements) the result will be a very robust architectural design led by equal flexibility of design, conversion and maintenance.<sup>14 + 15</sup>

The integrated product deliveries in construction introduce a possible way to handle the complex material cycles in the construction, use and disposal of buildings after the end of their useful lives through the use of industrialised products on various levels of integration that potentially can be nested into each other through various tiers.<sup>16</sup> A construction industry of products based on the principles of industrial ecology and design for disassembly would however require new infrastructures for dealing and trading with salvaged materials, components, and systems with different degrees of integration –

understood as integrated complexity. Although some industry within the field already exists, salvageability and the establishment of material *cycles* instead of one-way streams from raw material to waste are still in embryo.<sup>17</sup>

However, products and systems can, as pointed out, not simply be reduced to the materials they comprise. Elements of process and thought – or knowledge – also have to be considered when trying to close the material streams into loops. Processes are equally resource consuming – and even embedded design work constitutes a considerable part of the investment in a product and should perhaps not just be ‘thrown away’.

17 For an elaborated discussion of the topic see (Nordby, 2009) *Salvageability of building materials*

## III.2 CUSTOMISABLE ARCHITECTURAL SUBSYSTEMS

- emerging types of integrated product deliveries in architecture

### INTRODUCTION

This section explores and discusses the emergence of *integrated product deliveries* in architecture and construction as new different *types* of systems. Integrated product deliveries are proposed as a means for handling design complexity by integrating design decisions into discrete products of matter, process, and thought thus facilitating a more strategically focussed design attention. Inspired by the concept of *industrial ecology*, a new architectural ‘tectonic’ strategy is proposed: A future industrialised architecture seen as temporary ‘*assemblages*’ or *configurations* of (relatively) independent and already established subsystems – integrated products – of (ideally) closed material loops that interface materially and procedurally to form a coherent building. Challenging the initial definition given in the section on *systems terminology*, specific examples are used to clarify different borderline aspects concerning deliveries as integrated products.

### SYSTEM STRUCTURE AND INTEGRATED PRODUCT DELIVERIES

In the product industry, complex engineered industrially produced design objects as cars, ships and airplanes have gradually been decomposed into supply chains of strictly defined modules and subsystems. These constituent elements are then through various tiers joined into larger complex assemblies and chunks that are subsequently put together into final end user products. Complex products are often produced and delivered in mass customised versions enabled by controlled variations in the subsystems. The same has to some extent become the case in our built environment as a plausible though still complementary approach within industrialised construction.



FIGURE III.2.1  
PARTS OF A CAR – MODERN CARS ARE  
NOT ASSEMBLED PIECE BY PIECE OF  
RAW MATERIALS

- 18 For a more elaborated definition of the notion of *system structure* see *Systems terminology*, II.5

Within the product industry, the organisation of subsystems into a product is normally termed the *product architecture* – using the term *architecture* in a slightly different way than architects do referring to the structural properties or *system hierarchies* of the product. In order not to confuse concepts these system hierarchies in a building will – as stated earlier – rather be termed the *system structure*.<sup>18</sup> A system structure thus designates the physical and organisational subdivision of a product or building into several – and sometimes nested (hierarchical) subsystems.

### **Contracts as subsystems**

Any building and its coming into being can be seen as a structural and hierarchical organisation of a number of subsystems of various levels of complexity – any building has a specific *system structure*. In traditional construction, these subsystems would normally correspond directly to the established crafts involved. Hence, the bricklayer would together with bricks and mortar constitute a subsystem as well as would the carpenter and the woodwork or historically later specialisations as the plumber and the plumbing or the electrician and the wiring. In complex modern industrialised products, however, the subsystems of a product architecture tend towards division along lines not necessarily corresponding to any craft. Rather the subsystems here represent multi-technological parts defined by their performance – e.g. the motion of a motor, the lighting properties of a fixture, or the information provision of a display. Equally, in building projects, complexity has raised and specialisation and division of labour has considerably enhanced the number of stakeholders involved in a project. As a consequence, the task of controlling these subsystems of trades and crafts and their interactions in a specific building project on a trade-by-trade basis has become increasingly difficult. The appearance of turnkey contractors as an intermediate actor specialised in providing the client with a singular contract based on an estimate and coordination of all subcontractors seems both to lock the traditional craft-based division and to leave the control with this division out of the hands of the client and, perhaps more important, out of the hands of the architect who is supposed to specify it. This ‘black-box’ tender process almost inevitably produces expensive solutions. With supplementary consultants often being paid a percentage of the total contract sum, incentives for most stakeholders are small to change established structures and work actively with the design of a more adequate system structure of a building project seen from a project point of view. A system structure (the product architecture of construction) and the resulting constituent elements seem inevitably to be

- 19 See definition for present thesis in *System Terminology*
- 20 The concept of *flexible solution space* is introduced in Vibæk (2007) *Flexible Solution Space – Architecture by means of industrialised structural building systems*

bound to contractual relationships between the stakeholders. It is not just a matter of physical and formal design – it is equally a question of organisational design based on contracts. Stakeholders, processes and physical deliveries are bound together. If the physical structure of subsystems is to be changed, the structure of processes and stakeholders performing them must equally change. Today, only by specifying to an ever greater extent can the architect try to control the subcontracting of the turnkey contractor. This can, however, easily result in over specification where the focus becomes specific solutions instead of their performance. The result can again be that now the contractor is locked in an inappropriate system structure – this time forced by the architect who does not have direct access to the suppliers (manufacturers and subcontractors) on the market thus specifying on the basis of deficient knowledge.

#### *Integrated product deliveries as subsystems*

Integrated product deliveries (IPDs) represent, as defined earlier, a bridging of a *product perspective* and a *process perspective* in construction. They are normally considered as physical systems that can be configured and customised as a specific delivery and form part of a unique construction project. The deployment of IPDs in architectural design and construction can help to reduce the complexity of the design and construction process.<sup>19</sup> Such assemblages of discrete subsystems rather than simple materials and components can theoretically form complete buildings and seem in many ways as an intriguing alternative architecturally, businesswise, and even seen from an environmental point of view exactly through their quality of integrating complexity around a certain function or performance instead of around a craft. However, IPDs are not limited to the physical realm alone. Process systems or perhaps even systems supporting the ways architecture is conceived – *systems of thought* – can, it will be argued, be seen as equally relevant types for development of customisable IPDs in construction. Processes and knowledge can also be integrated into deliveries that do not necessarily comprise physical elements. As these latter system types focus on standardisation and mass customisation of the design and building process rather than physical systems they point out other tracks towards a more systemised yet still flexible architectural solution space.<sup>20</sup>

The notion of IPDs introduces a more nuanced picture of the system structure of a building which is no longer limited to building materials and components handled by corresponding crafts. As well as a building conceptually can be decomposed into its spaces – i.e. living space, kitchen, entrance – or its archi-

tectural elements – as wall, opening, roof, floor etc – it can also be decomposed into its systems as actually delivered and/or installed. This division has the advantage of better matching the industrialised means of production behind that is based on product delivery. The IPDs reduce design complexity in focus through nesting of building materials, components and subsystems into performance based entities that can be inserted into the building as discrete integrated or distributed systems.<sup>21</sup> Design work is embedded in the subsystems before they, as specific deliveries, become part of the entire system – the building project. Using configurable industrialised IPDs in architectural design moves the architect's attention towards the interfaces *between* subsystems rather than the design of subsystems themselves. The subsystems are commoditised whereas their combination remains central to architectural design.<sup>22</sup> If the subsystems are flexible enough this facilitates the integrative task of the architect thus potentially increasing the possibility of architectural coherence of the end result. The architects Kieran Timberlake call this 'the architecture of the joint' (Kieran & Timberlake 2004:93) pointing towards a new role of the architect – a new architectural discipline. I will return to a discussion of this role in the concluding section, *Findings* in Part V – 'Reflection'.<sup>23</sup>

### ***Assemblages as product combinations***

As pointed out earlier, the system structure of a building will *always* to some extent be project specific. There is no generic or ideal decomposition – or breakdown structure – of constituent elements of a building and there is no clear distinction between on-site construction and off-site fabrication. Every building is in varying degrees both, depending on subsystems available, economy, infrastructural issues, project brief, design intentions and a myriad of other factors. Every offsite produced physical element (delivery) in the end requires onsite work in order to be integrated or nested into the final building. This challenges the more commonly used notion of prefabrication and perhaps also the common rejection of seeing a building as a product – or at least an assemblage of products. Despite the impossibility of setting up universally valid system structures, there can however be *isomorphisms* between patterns of different systems structures.<sup>24</sup> Such isomorphisms rather represent a product view than a project view – a view that can inform *across* projects. The concept of system structure gives a way to look at different scenarios for the structural, processual *and* contractual breakdown structure of a building project into constituent elements that matches the way the buildings are actually produced, delivered, installed and maintained (cf. the service aspect)<sup>25</sup>. Combining the sys-

- 21 Whereas a bathroom pod would have a relatively clear physical delimitation from surrounding elements, an interior climate solution would normally be distributed.
- 22 See also the described split between product and project level in *Commoditisation in architectural construction*, III.1.
- 23 See *Findings*, V.1
- 24 A systems approach would look into such similarities and seek to explain them as system properties having a more general character than each system structure seen isolated.
- 25 See *Taxonomy in Systems terminology*, II.5

26 Parts of this paragraph earlier published in Beim, Nielsen & Vibæk (2009) p 90

tem structure with the entity of delivery and its related dimensions of integrated complexity (preparation, standardisation and service), gives a way to discuss how entire buildings are or can be more or less commoditised. First, however, it is useful to have a closer look at the deliveries themselves – the subsystems of the assemblage – and the perspectives of their commoditisation.

## EXAMPLES OF INTEGRATED PRODUCT DELIVERIES IN CONSTRUCTION

In order to put more specific pictures on what *integrated product deliveries* (IPDs) in construction are and to illustrate the broadness of the term encompassing both aspects of product, process and thought, this section gives a non exhaustive overview of some of the different types of IPDs already on the market or on their way. The introduction will furthermore try to relate the examples to the different dimensions and their levels of integration. Starting with one of the most well established ones – the bathroom pod – this presentation includes a façade renovation system, a lighting control system, a partition wall concept, a user involvement software program, as well as a discussion of *systems of thought* as a possible field for complexity integration through development of concept IPDs or supportive functions for concept generation. As mentioned in the introduction, this section challenges the boundaries of the initial definition by introducing different types. In the subsequent section, *Classification of integrated product deliveries*, more examples focussing on the physical type will follow.

### **Bathroom pod<sup>26</sup>**

One of the ‘classical’ and thus more well established integrated products in construction is the bathroom pod with several manufacturers and systems in different materials on the market in many countries. The bathroom of a dwelling gathers a collection of activities that usually call for certain privacy thus resulting in a shielded or closed area mostly of a rather limited size. Moreover, the bathroom requires conveying of a considerable amount of installations such as hot and cold water, sewer for toilet, wash basin and bathtub/shower, ventilation, electricity and heating. This makes the bathroom a functionally and spatially well defined space or utility, while at the same time it represents some of the most expensive square metres of the dwelling. The combination of the limited size and the many crafts involved in completion often results in long



construction time, difficult coordination and a following high risk of errors and deficiencies. All the facts mentioned above make the bathroom an obvious target for industrialisation understood as separate prefabrication (of a pod), controlled production process and quality combined with optimised use of materials and manpower.

Although savings are considerable in larger batches of identical or almost identical bathrooms, factory produced single deliveries are still seldom found. Part of the explanation is to be found in the fact that market standards never have been established for the bathroom pod as a *product*. Manufacturers generally have only few and loosely defined types (product lines) and e.g. no standard measures. In pursuit of flexibly meeting *any* customer's demand, most pods are still mainly delivered as *projects* designed specifically for each building project. They are not configured based on design parameters embedded in the system and each delivery thus still requires considerable design effort. Using the taxonomy presented in the *systems terminology* section of this thesis, one could say that although the level of the preparation aspect is high (CHK), the level of the standardisation aspect is low (CM or M2O).<sup>27</sup> The service aspect varies. Some examples of specific national type approvals exist, but it is rather an exception than a rule.<sup>28</sup> This also means that only little automation has been applied – many procedures are rather (traditional) construction under roof than true industrialised production.

The bathroom pod in some cases integrates an installation shaft, which in other cases is separate and actually also exists as a configurable IPD on the market.<sup>29</sup> Due to possible sharing of installations kitchens will often have spatial proximity to bathroom and installation shaft and examples exist of completely integrated solutions. In some cases the entire bathroom pod could be planned for later disassembly and replacement – an idea that has so far only been seen and tear on conceptual level for hotel and hospitality environments with heavy wear and differentiated deterioration rates combined with a strong economical incentive for short shutdown periods.<sup>30</sup>

FIGURE III.2.2  
BATHROOM POD MANUFACTURED BY  
KULLMANN, NEW JERSEY, USA

- 27 See *Taxonomies* in II.5
- 28 The former Danish manufacturer EJ Badekabiner had type approvals on the Norwegian market.
- 29 NCC-Denmark offers such a product. See Beim, Nielsen & Vibæk (2009) p 100
- 30 The American New Jersey based building manufacturer Kullman has been involved in some of these ideas. NNE Pharmaplan – a consulting and engineering company in the field of pharma and biotech – is developing a concept for hospitals as a system of structural ‘racks’ (an infrastructure) where installations and spatial units such as cleanrooms, operating rooms, bed rooms can be plugged in and out in a reconfigurable organisation. The concept was presented at a conference about ‘Hospitals built with integrated product deliveries’ held by the Danish Technological Institute, February 2011



FIGURE III.2.3  
FAÇADE RENOVATION IN PROCESS

- 31 Elements of this paragraph including citation is authors own translation from a ‘Guide to façade renovation’: ‘*Rundt om facaden*’ RBE (2009)
- 32 The restructuring of the company has been supported economically by the foundation Realdania as part of the initiative *Buildinglab.dk* directed towards innovation in the construction industry.

Further commoditisation (consolidation as a product) of the bathroom pod seems straight forward – as e.g. establishing market standards for interfaces and rising the standardisation level through parametric configuration – but despite that many positive aspects can be pointed out development is slow. It seems that the manufacturers of bathpods so far have prioritised responsiveness rather than efficiency thus resembling the organisation of traditional product delivery – construction of projects dominates the true approach for the integrated product delivery strategy, of production in projects. The main obstacle for IPDs in the construction industry is still cultural: Buildings and their constituent subsystems are constructed – not assembled.

#### *System for façade renovation*<sup>31</sup>

An integrated product delivery within the definition applied in this section does not necessarily need to be a factory produced transportable clearly physically delimited product. As the following example illustrates it can also be a product mainly defined by a sequence of well defined material processes or procedures that can be put together in different ways to form a complete delivery – in this case of a façade renovation solution.

With an annual percentage of new building stock constituting less than 1% of the total stock and only an insignificant part being demolished in a country like Denmark, retrofitting of the existing building stock – like in most western countries – constitutes a major part of the construction industry. Façade renovation of the existing building stock is an important part of this field. Although cladded versions of concrete construction are prevalent in modern Danish (large scale) construction, most of the building stock is still dominated by the traditional masonry.

RBE – a mid-sized Danish builder – has specialised in façade renovation of traditional masonry buildings and has engaged in a restructuring of the company and its activities towards a more focused and systematic approach<sup>32</sup>:

“*One of the goals has been to decompose a façade renovation into clear and meaningful constituent elements and then to join these again in a whole. A new system for façade renovation!*”

(RBE, 2009:32)

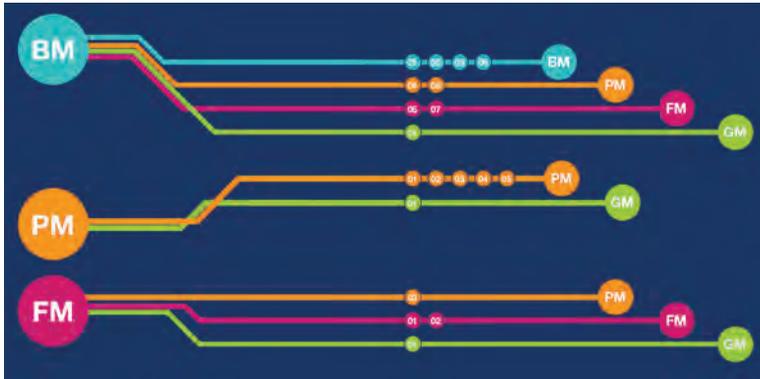


FIG III.2.4  
DIAGRAM OF RBE'S DIFFERENT FAÇADE  
CONVERSION TYPES

However, a system for façade renovation that makes a difference for the company as well as for the customer cannot be confined to a mere systematic description of technical methods and techniques. A complete system requires equally focus on 'efficiency, discipline and better communication' (ibid). Although combinations of fixed material procedures are actually applied each renovation is individual and specific.

The system works with four general types of masonry façades: exposed masonry (BM), smooth finished wall (FM), plastered wall (PM) or green wall (GM).<sup>33</sup> The different work processes used on the façades are divided into three main blocks: cleaning, masonry work and finish. By application of 19 (meaningful) combinations of processes from these main blocks the result is either renovation of the existing wall type or conversion into one of the other types. Although the system reduces complexity of the process for both customer and internally in the company, it is still considerable due to dependency on the project specific outset – a specific façade to be renovated. The level of the preparation aspect is low (MAT and COM) due to the fact that most processes are performed directly on the existing building façade. Standardisation aspect is equally relatively low but still based on the limited number of types (M2O) whereas the service level is high (INS): The façade renovation is handed over to the client as a finished solution.

An important aspect of any system definition is its boundaries to surroundings (system boundary definition) which means what is covered by the system and what falls outside. The 19 established methods are directed towards and estimated to cover the need for façade renovation of approximately 80% of Danish multi-storey apartment blocks built between 1850 and 1950. In this sense the system elaboration has supported the definition of a primary business target for the company. This does not necessarily make it the *only* business target. Another interesting IPD delivered by RBE is the *Easyvator* – a complete mini-elevator solution for the existing building stock – a both physically and functionally clearly delimited delivery perhaps even clearer than the bathroom pod used as example above. A short introduction can be found in the following section.<sup>34</sup>

### Lighting control system

Both the bathroom pod and the façade renovation represent integrated products that are physically located in specific areas or parts of a building – one *by zone* and one *by system*.<sup>35</sup> The following describes an example being

33 The codes – as used in the diagram below – represent the Danish abbreviations for the corresponding: *blank mur, filtset mur, pudset mur og grøn mur*

34 See *Development and classification of integrated product deliveries*, III.3

35 This distinction is explained under *integrated product deliveries in Systems terminology*, II.5



FIGURE III.2.5 A+B  
LUTRONS QUANTUM MANAGER  
INTEGRATES THE ENTIRE LIGHTING  
CONTROL IN ONE SINGLE SYSTEM

- 36 See *Commoditisation in architectural construction*, III.1
- 37 <http://www.lutron.com/> - accessed on August 18, 2010

physically widely distributed (i.e. integrated in the building as a whole) and furthermore making use of different technical systems while at the same time being delivered integrated as one single system around a specific environmental parameter: the lighting conditions of a room, a dwelling or an entire block or office building.<sup>36</sup>

Artificial lighting makes up a considerable amount of the energy use in modern live and work environments. Furthermore solar heating from daylight – in particular in modern widely glazed indoor environments – constitutes an important energy issue in many parts (climates) of the world due to the need for ventilation and cooling. These factors interact in many ways – one of the most obvious perhaps being that bigger openings for daylight means more heat gain while smaller openings enhances need for artificial lighting during daytime. Mostly daylight and artificial lighting are however industry-wise treated as separate systems with separate suppliers leaving the architect as the only ‘integrator’ of the final solution (cf. Bachman).

Lutron Electronics has specialised in delivery of complete lighting control systems. With offset in light dimmers the company today delivers a range of different lighting solutions for both residential and commercial settings spanning over – and at the same time integrating – dimmers, fixtures, lighting control systems, sensors, window systems and shading devices<sup>37</sup>. A short description of one of their product lines exemplifies:

“*Quantum total light management maximizes the efficient use of light to improve comfort and productivity, simplify operations, and save energy. This powerful and efficient system dims or switches all electric lighting, and simultaneously controls daylight using automated shades. Quantum easily integrates with building management systems. A solution for new construction and retrofits, Quantum is ideal for office buildings, hospitals, universities, and more.*”

(www.lutron.com)

Partly due to the distributed character of the system it is widely modularised and easily reconfigurable or extendable making use of existing standard wiring and being compatible with most lighting fixtures and window framings. By connecting all devices to a centralised control system different lighting conditions can be pre programmed to support a variety of different activities, scheduled

	Silver	Gold	Platinum
Annual Scheduled Maintenance (includes preventative maintenance, on-site training, and minor reprogramming)		●	●
24-Hour Response Time			●
72-Hour Response Time		●	
100% Parts and 100% Labor	●	●	●
Unlimited Technical Hotline Support	●	●	●
Remote Programming (up to 4 hours, for applicable systems)	●	●	●
Remote Diagnostics (for applicable systems)	●	●	●

work cycles or changing exterior light and weather conditions. The preparation level is in this case medium (COM and ASM) and limited by the distributed character of the system. Standardisation is high (OTS and M2O) in the ways that all components are off the shelf while joined into a mass customised solution. Finally, the service level is very high (MNT): Although installation is outsourced to an electrical contractor, liability issues are kept within the company and *‘[m]any Lutron products and systems include warranty to cover parts and labour’*<sup>38</sup>. Procurement involves client decisions about future maintenance, service and upgrades included in so-called service plans that come as part of the delivery. Figure III.2.6 shows an overview of Lutron’s three service plans.

Another interesting thing about Lutron’s system boundary definition is that it bridges and integrates two considerably different technical realms into one integrated product delivery located around their basic expertise in light dimming and control. Often well established product categories and interfaces seem to fix the industry on closed separate markets that perhaps even become increasingly specialised. In this case, the specialisation in lighting controls has oppositely led to an integration of two different fields of technical expertise that share a common parameter – the lighting conditions in built environment. As Lutron also delivers fan control systems, a possible future path could be to deliver complete interior environmental control solutions. However, it is always a business challenge to find the right balance between ‘we-can-solve-it-all’ and expertise within a delimited field.

### Partition wall space

The present example is so far only a design proposal.<sup>39</sup> It does however share the above mentioned attempt to integrate separate fields of the building industry into one new product-like integrated product delivery. The assignment was to develop a space divider allowing for flexible and changeable boundaries in both live, work and mixed environments.

A scan of existing products on the market showed on the one hand the smooth looking drywall preferred in residential settings that however has a considerably on-site intensive installation and subsequently only little flexibility of both conversion and use. On the other hand a wide range of more or less modular wall systems primarily aimed at office environments was found. These systems tend to have a temporary look and the modularised character seems little appealing for live environments. Furthermore, these systems showed a trend or

FIGURE III.2.6  
A QUICK COMPARISON OF THE THREE  
STANDARD LUTRON SERVICE PLANS

- 38 <http://www.lutron.com/Service-Support/Service/Pages/Overview.aspx> - accessed on July 30, 2011
- 39 Conceptual design was carried out during the course ‘Building Product Design’ at University of Pennsylvania, Spring 2010. Design team: TBK-Thabo Lenneiy, Benjamin Callam & Kasper Sánchez Vibæk. Instructor: Jordan Goldstein. For further presentation see Appendix VI.7.B, Building Product Workshop - Transwall

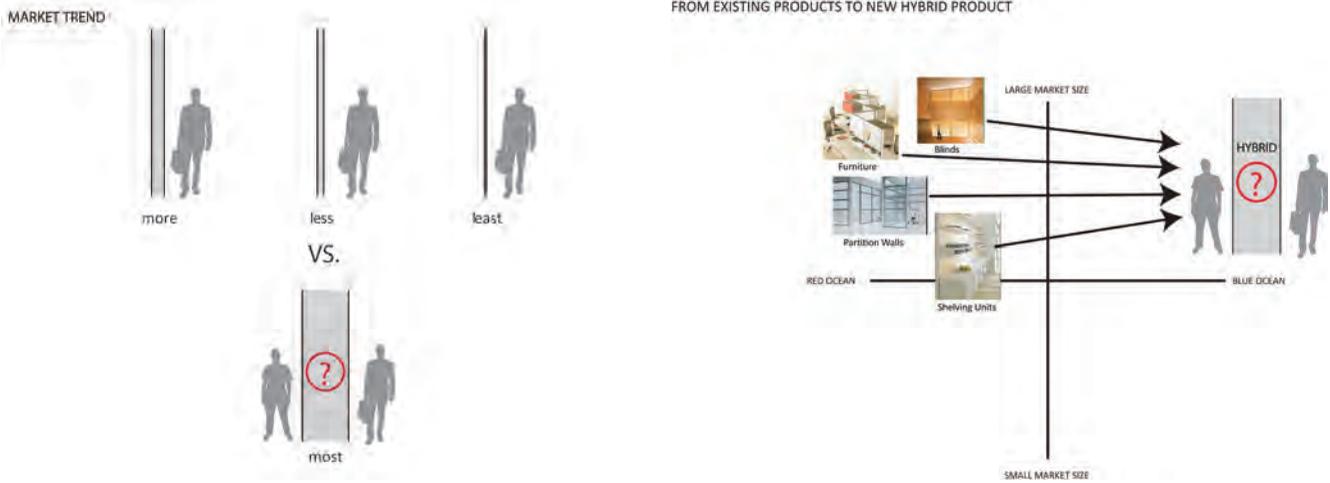


FIGURE III.2.7 A+B  
MARKET TREND AND NEW OPPOR-  
TUNITY

40 Terms and concepts borrowed from concept presentation of 'wall.space', June 2010: 'Define you own wall.space' See pdf-presentation in Part VI - 'Appendix' VI.7.B (NB: On CD)

movement towards smallest possible profiles conceptually and literally mini- mising the footprint of the partition. (See figure III.2.7)

The design proposal took a different approach and located an opportunity to engage in a more tangible presence combined with a permanent look. The wall concept introduces the third Cartesian dimension of depth as a value creating factor rather than one to be virtually eliminated. By potentially merging the tra- ditional concept of a wall with existing related niche markets as shelving units, furniture, cell units, blinds and shutters, installation routes etc. the third dimen- sion makes the wall into useful space in itself – a 'wallspace'. This new hybrid inherently gets additional attributes as flexible buffer (spatially, functionally and acoustically), possibility of a multifaceted look using the third dimension, and integration of fixed functions normally occupying space thus cleared for more flexible use. The 'wallspace' is simultaneously wall, space and infill.

Built up on a neutral (existing) frame system and concentrating design effort on critical details as a self stabilizing nailless and screwless attachment and off- module attachment ability, the concept adopts an opposite 're-inventing-the- wheel'-strategy by combining, refining, supplementing and further developing existing system solutions thus creating a new system product – or integrated product delivery – that potentially can become a base for further niche markets in the form of an infinite number of possible infill solutions along parameters like panel geometry, material or fill and openings.<sup>40</sup>

FIG III.2.8 A+B  
WALL.SPACe SCENARIOS BY TBK



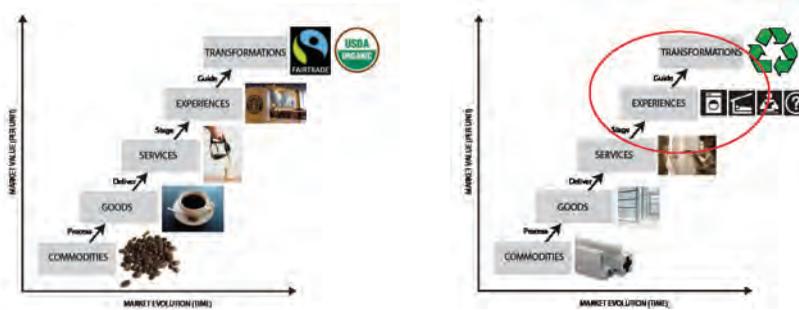


FIGURE III.2.9 A+B  
TOWARDS HIGHER VALUE PRODUCTS –  
STARBUCK'S COFFEE AND WALLSPACE

41 Parts of this paragraph is taken from (Vibæk 2007) *User Involvement as a Configurable Integrated Product Delivery*

An integrated product as sketched with *wall.space* above responds to a change in market trends as pointed out by Pine & Gilmore (Pine & Gilmore, 2000). Markets and products have moved from traditional delivery of commodities over goods and services towards provision of experience and even transformation. Higher value products as experience and transformation encompass lower value levels but add value by ‘staging’ experiences and ‘guiding’ towards transformation – personal as well as societal. The flexible infill option of *wall.space* become a major ‘staging’-attribute and the potential use points towards a transformation of how we define and delimit designed space (see figure III.2.9). The *wall.space* system is conceived as having a high preparation level arriving as a finished assembly partly in the form of a kit-of-parts (ASM). The standardisation level of adapted components assembled from the factory is medium (C2F and M20) whereas the service level can vary according to the applied business model. If the idea of outsourced infill solutions is accomplished the service level would probably be low (SAL) as the integrated solutions implies various deliveries.

The development of integrated product deliveries as *wall.space* potentially challenge the established interfaces between traditional building products and components and the crafts involved in their manufacturing and delivery. As pointed out by Alexander & Chermayeff, the interfaces between components, elements and systems in a physical structure should always be problem specific as

“*the joints between successive and adjacent domains [read elements, ed.], the extent of their separation, the precise way they are attached to one another, the kind of transition that needs to occur between them, are all matters of vital importance*’

(Alexander & Chermayeff 1965:141)

#### *User involvement through a process software tool*<sup>41</sup>

This paragraph briefly presents a specific software tool – *U\_build* – recently developed for user involvement in construction processes as an example of the process focus as an equally relevant field for development of customisable integrated product deliveries in construction. *U\_build* is an attempt to make a tool covering parts of a new need for knowledge sharing between more and new players in the process of construction.



FIGURE III.2.10  
U\_BUILD SOFTWARE BOX

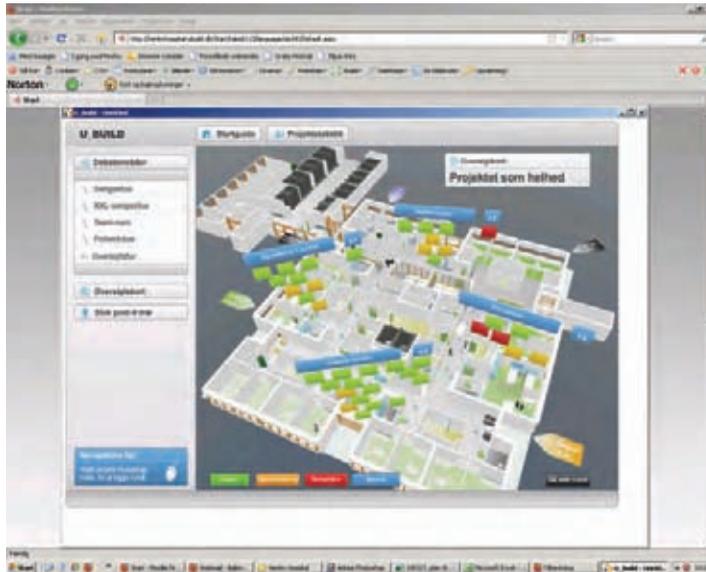
- 42 The project has – as the RBE façade renovation system – been supported economically by the foundation Realdania under the initiative of Buildinglab DK, that will be described shortly in the end of following section, *Development and classification of integrated product deliveries*, III.3
- 43 The latter part of user generated content matches the definition of the so-called web 2.0 applications. As pointed out by Vibæk, U\_build in this sense could be characterised as an integrated product delivery 2.0 (Vibæk 2009:9).

The tool has been developed from an idea initially conceived by the young Danish architectural office *Mutopia*<sup>42</sup> and enables a controlled user involvement and dialogue applicable for the development of building projects and urban planning. The development started from the idea of creating ‘[...] *an interactive software tool that systemises dialogue and knowledge sharing throughout a building process*’ (Mutopia, 2008:6). A first version was launched and marketed as a software product for *dialogue management* in 2009.

U\_build has been used e.g. in a process of user involvement and participatory planning for a new heart disease department at Herlev Hospital in Copenhagen. Staff, patients and their relatives could via the internet use the U\_build application to take a virtual walk in a 3D-model of the new department provided by the architect. Comments could be posted as general or within and concerning the specific spaces as the bed rooms, the waiting rooms, operating rooms etc. (See figures III.2.11 & III.2.12)

A specific focus is the gathering and ordering of user data in order to facilitate a semi automated dialogue between owner/developer and end users (defined broadly) and clarify ideas, aspirations and desires concerning a specific construction or planning project. The data achieved through the use of U\_build can subsequently be applied for qualification of the basis for decision making by owner/developer or consultants through the programming and early design phases.

U\_build has by the developers themselves been characterised as an ‘*integrated product delivery spanning across the [traditional] value chain in construction*’ (Mutopia, 2008:7). However in the physical sense it is not a building assembly or chunk and hence does not fit the conventional definition of such integrated product delivery. It has the process as the core whereas the physical outcome itself is not predefined in any way. However, if we simply call it a part of construction it does match quite well the definition and the characteristics of an integrated product delivery: A system supplier delivers a (software) product that is ‘*configured and customised*’ for user involvement in a specific construction or planning project. Specific project content as e.g. a 3D-model, project material and information and a prepared structure for dialogue and comments is customised for each delivery. The application can be seen as a kind of configurator based on a combination of a mass customised integrated product delivery (the application adapted for use in a specific project) and the systematically ordered input from a group of users that are given access to this solution.<sup>43</sup>



Within this thesis and concerning the present version of the system structure model that will be presented in part IV – ‘Model’, U\_build falls outside the definition of an integrated product delivery that ‘concentrates on IPD’s containing several kinds of physical substance that become nested into the final building’.<sup>44</sup> This choice of system boundary definition has, as a start, been made for simplifying reasons. U\_build as example however points out a potential need for integrating pure systems of process into the system structure – or perhaps even systems of information or thought as the following paragraph gives examples of. This issue will be discussed further in the concluding parts of this thesis. It can – from an architectural point of view – seem intriguing to work with integrated product deliveries within this broader perspective where the system type is more about systematic tools and processes than about actual physical building systems. Perhaps this does not to the same degree force the creative process of conception into a too narrow solution space as well defined physical systems tend to do? For further presentation and a critical discussion of perspectives see (Vibæk, 2009).<sup>45</sup>

### Systems of thought

The above ‘dematerialisation’ of the concept of integrated product deliveries into elements of process or combinations of process and product can be further enhanced through ‘products’ that focus on the systematisation of thought in design. What I here term as *systems of thought* – though still being on a speculative stage – are systems that similar to the physical systems or process systems above are aimed at reducing the complexity in focus (not the complexity itself!) – in this case particularly concerning the conceptual phase of architectural design. To distinguish this genre of systems from systems of process they are not dictating a particular process but facilitate or support the design process through use of symbols. They provide a structure for thinking and for ‘storing’ these thoughts in a systematic way.

A very basic system of thought – although still providing expression of immense complexity – is a language and its physical manifestation as e.g. letters, words, sentences, texts and its grammatical rules. Another system of thought widely applied in architectural design is the drawing including a number of

FIGURE III.2.11  
A SCREENSHOT OVERVIEW OF A  
CUSTOMISED VERSION OF THE  
U\_BUILD APPLICATION FOR HERLEV  
HOSPITAL

FIGURE III.2.12  
POSTED USER COMMENTS IN U\_BUILD  
FOR A FUTURE BED ROOM AT HERLEV  
HOSPITAL

44 See *Systems terminology*, II.5

45 The article can be found in *Appendix VI.5.A*

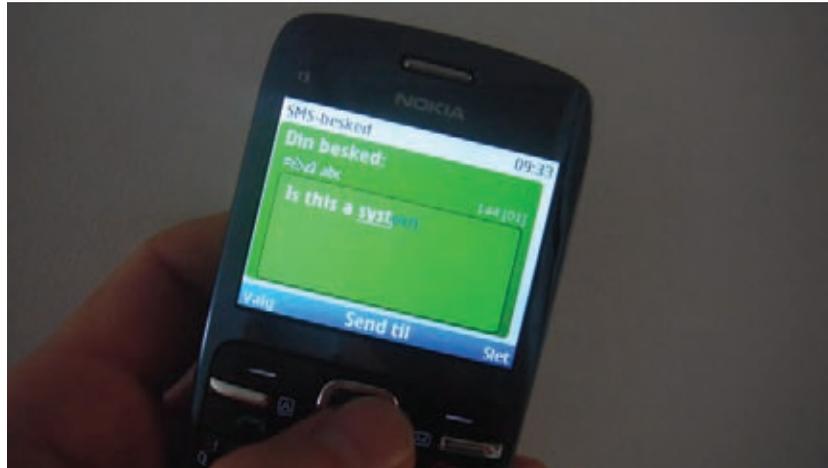


FIGURE III.2.13  
EVEN CHEAP MOBILE PHONES TODAY  
SUGGEST AND EVEN LEARN TO SUG-  
GEST WORDS FOR TEXT MESSAGING.

- 46 As an equivalent, digital word processors can both have pre programmed spell-check and be able to ‘learn’ new words or even phrases through its use.

conventions for the interpretation its elements – lines, curves, hatches, line weights, colours etc.

Herbert Simon (Simon, 1996) introduces what he terms the *sciences of the artificial* as a way of systemising design thought as opposed to the analytic thought applied in the natural sciences. Whereas knowledge in natural sciences are characterised by being ‘intellectually tough, analytic, formalizable, and teachable’ design knowledge is rather ‘intuitive, informal and cook-booky’ (ibid :112). Where natural sciences in the cartesian or mechanistic tradition *explains* complex phenomena by splitting it up into smaller components, design thought aims at removing differences between desired and present states by synthesising incommensurable parameters into a satisfactory solution thus *changing* or *creating* new complex phenomena. Simon calls this a process of ‘satisficing’ as opposed to optimising (ibid:119).

Whereas the first CAD-systems were simply digitalised drawing tables imitating their analogue equivalent new object based and parametric design tools are more ‘intelligent’ and integrate and in some cases actively accumulates experience based knowledge through use.<sup>46</sup> This accumulated knowledge can without dictating a specific process or procedure support decision making in design by proposing patterns or solutions already embedded in or ‘learned’ by the system (See figure III.2.13). The processing power and memory capacity of computers make them highly adequate for developing supportive systems of thought. However, important to underpin is that design – of e.g. physical form – although often attempted throughout history can never be a direct result of rule application. As Alexander states (Alexander, 1964)

“It is not possible to set up premises, trace through a series of deductions, and arrive at a form which is logically determined by the premises, unless the premises already have the seed of a particular plastic emphasis built into them. There is no legitimate sense in which deductive logic can prescribe physical form for us’

(ibid:7f)

Alexander does however claim that the computer and other techniques may be a way to magnify man’s intellectual and inventive capability and even compares it to man’s magnified physical capacity facilitated by the machines invented in the 19th century (ibid:11) – the first industrialisation. Advanced systems of

thought – perhaps even marketed as products – seem to touch upon the ‘last resort of architectural intuition’ and challenge the conception of the architect as a singular ‘auteur’ in architectural creation. A further discussion of new roles of the architect when or if architecture becomes *assemblages* of discrete more or less configurable systems – or integrated product deliverables can be found in the concluding section of *Findings*.<sup>47</sup>

47 See *Findings*, V.1

## FUTURE PERSPECTIVES OF INTEGRATED PRODUCT DELIVERIES

What are the consequences of an enhanced use of integrated product deliveries in construction? This paragraph discusses some of the perspectives, risks, advantages, and drawbacks of the outlined development – a development that to some extent is already a fact but also is a tendency that can be followed more or less actively – or maybe be rejected.

### *The contextuality of the built environment*

A question could be whether a new industrialised product-by-product structure of the built environment can be drawn to replace the fainting traditional trade-by-trade structure of the crafts involved in construction? While a product-by-product structure is predominantly serial with products nested into each other in a supply chain ending onsite, the trade-by-trade structure is rather parallel with materials brought to site for processing by separate crafts. Earlier we took the standpoint that there is no ideal general system structure for the built environment. Any building project has its specific system structure. This is due to the fact that a building will always have to meet a wide range of contextual factors (physical, organisational, cultural, economical etc.) that will never meet a ‘one-fits-all’ system structure. Seen from the point of view of the industry the most rational would seem to have fixed conventions on interfaces between clearly defined integrated building products. This would create the basis for well structured markets of subsystems as assemblies and chunks. An analogy would be the car industry where almost every car consists of the same basic structure (product architecture) of main components as e.g. chassis, body, motor, doors, 4 wheels, windshield etc. Specific versions of these components can even be produced by one manufacturer and be used across many different car brands. This makes it somehow easier to design and produce a new car as it does not really question what a car *is!* This is different in architectural creation.

48 Generally speaking, economies of scale is about the benefits gained by the production of large volume of a product, while economies of scope is linked to benefits gained by producing a wide variety of products by efficiently utilising the same operations. ([http://www.articlealley.com/article\\_38647\\_15.html](http://www.articlealley.com/article_38647_15.html)) accessed on August 15, 2010 – see also II.3

Although architects do not necessarily have to ‘reinvent the wheel’ in every project there are inherently considerable differences due to the much larger web of contextual interactions and dependencies compared to products as cars or even extremely complex engineered products as large ships or aeroplanes. Although technically complex, e.g. the car basically deals with the problem of moving you from a to b. This can be done slow or fast, comfortably or not, cheap or expensive etc. However behavioural, cultural, environmental, and material issues are either universal or relatively simple when compared with the built environment. The tendency is not clear: The case analyses in Part IV – ‘Model’ will show examples of both parallel (trade based) and serial (product based) system structures that diverge more or less from the divisions along the traditional crafts.

### *Industrialised architecture*

The integrated product deliveries, as the types sketched above, can as nested subsystems potentially contribute both to the creation of industrial ecologies as well as to the integration of complexity on different integration levels in order to reduce complexity of the overall architectural design process. The gain could be a more environmentally responsible construction industry combined with better chances of achieving integrated architectural wholes. Some of these new subsystems span across markets and trades and can integrate elements of both matter, process and thought. These emerging customisable architectural (sub)systems can be seen as what Kieran Timberlake terms the elements of a new architecture (Kieran & Timberlake, 2008) that perhaps also introduce a new architectural tectonic strategy that here tentatively is termed *industrialised architecture* based on architectural *assemblage* of these discrete subsystems.

In order to make this new *architecture* possible it is however necessary that these new nested and integrated product deliveries are flexible in their internal (system) structure and function, as well as in their interfaces with the surroundings and other adjacent product deliveries on varying integration levels. There is a risk that these industrially produced systems will tend towards a limited solution space of standardised products in order to attain economies of scale rather than the architecturally far more appealing economies of scope<sup>48</sup> that rather draw on standardised operations or processes. The first industrialisation wave of construction in the 1960’s and 1970’s is the result of such inflexible systems. Although the present computer technology with its superior processing and information storing capacity does constitute a considerably different

basis for production based on economies of scope it is so far difficult to see whether the economical incentive is present in the building industry. Many legislative, contractual and organisational issues still seem constraining. If subsystems are inflexible most probably so will the solution space of the assemblage – the industrialised building.

#### *Cohesion vs. fragmentation*

While conceptualised as focusing on wholes and interfaces or interaction between subsystems, a new tectonic strategy of industrialised architecture paradoxically runs the risk of resulting in a fragmented expression. The focus on the wholes loses sight of the detail. A major task of the architect as integrator becomes to insure coherence across subsystems that he is not in control of in detail. Again sufficient flexibility of the integrated product deliveries is crucial. A design strategy could also be to find an adequate mix of distributed and non-distributed (discrete) system products where the former type enhances visual coherence as constituting network or web-like structures that binds the whole together. Another design strategy is to actively choose and use deliveries from lower integration levels – that tend to be more ‘fine-grained’ – together with the often larger integrated product deliveries of higher integration levels. Our first assertion was that integrated complexity has significance for the degree of design flexibility of the architectural solution space. In an ‘ideal’ world with infinite resources and time, this would mean that ‘building by pieces - the traditional delivery strategy’ would minimise integrated complexity and maximise design flexibility. Oppositely, the all-encompassing turnkey delivery would maximise integrated complexity but seriously constrain the architectural solution space. However, faced with real world conditions, the combination of economies of scale in the integrated product deliveries and the economies of scope in their assembly into buildings points towards the assumption that customisable integrated product deliveries will enhance design flexibility compared to both the ‘building-by-pieces’ and the ‘turnkey solution’ strategies.<sup>49</sup> The design flexibility of the total system structure – the final building solution – again depends on the project specific and context dependant structure. Integrated product deliveries seem to provide a new balance between integrated complexity and architectural solution space.

Whether integrated product deliveries will become the primary ‘elements of a new architecture’ only time will show. Many obstacles are in the way and it can also be discussed whether it is a desirable scenario seen from an architec-

49 For an introduction to the three industrialised strategies of construction, see *Commoditisation in architectural construction*, III.1

tural point of view. Can architectural works as assemblages create coherent wholes? Certain is, that producing architecture in a predominantly intuitive way has become ever more problematic as design issues today are far more complex and the number of stakeholders involved in the creation of a building is ever increasing. This has in itself created increasing problems with lack of coherence in our built environment. More systematic approaches seem indispensable at least as supplementary or design supportive activities. In the light of this development, the emergence of integrated product deliveries serving as industrialised customisable architectural subsystems does seem to present solutions for some of the present problems in the construction industry. Enhanced use of integrated product deliveries represents a strategy that cannot just be discarded. Further conceptualisation, investigation and development of new proactive supportive tools will however be necessary to explore and exploit their potential. The model presented in the following part, Part IV – ‘Model’ is a proposal under development for such a tool.

## III.3 DEVELOPMENT AND CLASSIFICATION OF INTEGRATED PRODUCT DELIVERIES

- Tentative application of the taxonomy on building products

### GENERAL PRODUCT DEVELOPMENT WITHIN CONSTRUCTION

Since the end of World War II a range of different initiatives have had the aim to change the construction industry from a traditional craft based on-site construction activity towards a more product based industrialised industry in line with the development in the rest of the product industry. In the USA the means of production left from the war industry was directly converted into facilities for e.g. providing mass produced housing – although in individual units – for a new emerging middle class of Americans partly supported by an exploding production for the general post-war reconstruction of Western Europe.<sup>50</sup> In Europe, housing needs were enormous due to the war damages as well as an equally rising middle class and the general population growth. Here the industrialisation of construction mostly led to large multi-storey developments – often based on national standards meant to support standardised industrial production of building components. However, within construction and architecture, standardised solutions and monotonous mass production of e.g. dwellings and urban environments only had a short period of glory in the 1960'ies and 1970'ies. Architecture has, as opposed to the product industry and except from this relatively short although fairly visible (!) intermezzo, always been concerned with the unique and the industrialised means of construction of that time was primarily geared towards solving the urgent housing need and could not meet the later demand of enhanced adaptability, once this urgency has disappeared. The result is, as pointed out elsewhere, that most building production today still is executed on-site and organisationally mainly (again) follows the divisions along the traditional crafts rather than a product-by-product structure.<sup>51</sup> However, today other factors as increasing labour cost, and enhanced (technical) complexity of contemporary construction increasingly call for more industrialisation in order to speed up the construction processes

50 See e.g. (Bergdoll & Christensen 2008)

51 See *Customisable architectural subsystems*, III.2

- 52 See *Industrial production theory*, II.3
- 53 See *Classification systems in construction*, II.2
- 54 See <http://www.realdania.dk/English.aspx> accessed on August 10, 2011

and make them more cost efficient. In a Danish context, initiatives have mostly been concerned with the process whereas the product focus has been limited to the relatively simple (preparation) level of building materials and smaller components – probably due to the monotonous references from the peak of mass-produced housing solutions in the early 1970'ies. Construction has been considered fundamentally different from the general production industry.

However with the general spread and use of information technology in industrialised production from the mid-1990'ies and on, this clear division seems to change. Gradually the production industry has been able provide so-called *mass-customised* products that – as pointed out in the section of *Industrial production theory* – to some extent bridge the division between the one-of-a-kind logic of the construction sector and the economies of scale logic of the product industry.<sup>52</sup> Several public initiatives within the construction sector in Denmark – including *Det Digitale Byggeri* (Digital Construction) as described earlier – try to establish standard processes and consistent classification systems through use of the new ability to handle complexity provided by the information technology.<sup>53</sup> Few however, take into consideration and question the actual trades and contractual divisions of the sector. Recognising the improbability of meeting broad markets of clients within all-encompassing industrialised building concepts, this thesis – and earlier research in the field – points out the strategy of focussing on the development of more integrated product deliveries as a plausible alternative to on the one hand handling the complexity of building by pieces with industrialised building materials and on the other hand the all-encompassing solutions. The integrated product deliveries introduce a new intermediate product level that by making use of new information technology based production combines the process and the product focus of development in the construction sector. This strategy inherently requires an interdisciplinary approach that crosses established trade based divisions. However, in a sector based on projects rather than products and the systematic development of these, the incentives for moving outside your field of expertise are usually small due to high risk and poor prospects of return on investment over several projects. Commoditisation through reuse of ideas as more integrated products is unusual within construction. The following paragraph shortly introduces a recent initiative trying to head in this direction.

***Building Lab DK – a product development initiative for construction***

Building Lab DK (in Danish, Byggeriets Innovation) was initiated by the major private Danish building foundation Realdania<sup>54</sup> and worked from 2006-2008

as a secretariat and facilitator for innovation projects in the building sector thus providing considerable funding in a 50/50 financial solution with engaged companies or consortia. The overall aim was to '*initiate, inspire and facilitate innovative concepts and consortiums within construction*'.<sup>55</sup> From 2008 the secretariat belonged organisationally under DAC – the Danish Architectural Centre.<sup>56</sup> Perhaps new this time – compared to earlier publicly funded initiatives – was that Building Lab DK had a specific focus on the development of and transition from innovative ideas within the construction sector into commercially sustainable products that from the start were to be deeply rooted in the companies or consortia that were later to produce and market them. This meant that specific knowledge developed within the supported development projects were not necessarily to be shared and freely accessible for others but could on the contrary be used directly as market advantages for the involved companies. Through (hopefully) successful product development, these new products, their business models, and the consortia behind were supposed to lead the way and serve as inspiration – or urge by necessity - for others to go similar ways thus seeking to drive development directly through the market and creating new industrialised market niches for construction.

During the approximately 4 years of service, the secretariat facilitated 21 different product development processes - ideally divided into five phases: 1) a *trawl* phase where potential collaborators and focus areas are located 2) a *frame* phase where stakeholders get together around a development idea 3) a *preject* phase where the stakeholders are challenged to expand the idea 4) a *proof of concept* phase where the idea is documented and the right stakeholders engage in the project and 5) a *project* phase where the idea is executed with the selected and engaged stakeholders. A final phase is the *anchoring* of the resulting product and its business model after development. (Vind & Thomassen 2009). Where the first phases seek to develop an initial idea in a non-linear interaction between non-systematic scanning, brainstorming and evaluation and goals and means are held as open as possible, the later project phases are meant for qualification, implementation, and anchoring of the idea as a marketable product.

The RBE-façade renovation system and the U\_Build user involvement tool mentioned in the previous section are both examples of such development projects within the framework of Buildinglab-DK that have led to finished products although the latter not as an integrated product delivery in the physical sense. Others like a balcony solution (Altan.dk) and an offsite fab-

55 <http://www.buildinglab.dk> accessed on October 21, 2008 – website has been closed down

56 <http://www.dac.dk> accessed on August 10, 2011

- 57 For a short introduction to modular clusters as introduced by Baldwin and Clark see *Industrial production theory*, II.3,
- 58 See *Systems terminology*, II.5
- 59 The case analyses can be found in Part IV – 'Model'

ricated installation shaft are now well known brands and have become fairly established products on the market. To which extent RBE use their established façade types and processes in present marketing is not confirmed. It should be said though that neither the initial ideas nor the products themselves were developed by Building Lab DK that simply provided co-funding and facilitation of the process. Without the initial ideas and the dedication of the companies, no development would have taken place.

Among the other projects within the framework can be mentioned a trade based configuration system for wooden housing construction, a prefabricated modularised integrated façade system, and a modular structural building system in high strength concrete. Being a recent and relatively short initiative only time will show whether some of the projects will last as integrated product deliveries used widely in construction and – even more relevant – whether such integrated products possibly are able to establish new market niches, or modular clusters as they are termed in the product industry, with several suppliers of similar products thus increasing incentives for continuous product development.<sup>57</sup>

## PRODUCT CATALOGUE

The final paragraph of this section gives short catalogue like introductions to a collection of different products currently available from the building industry that can be characterised as integrated product deliveries in the definition provided in the section on *Systems terminology*.<sup>58</sup> The examples have all been collected during the course of the PhD-project and do not form an intention to provide a representative selection. A few of the examples are not yet marketed products (commoditised) in the true sense. They are still under development or at ideation stage but point towards potential market possibilities. Some of the examples from the previous section that discussed the different types and their borderlines (systems of matter, process and thought) as well as some of the deliveries presented in the later case analyses are included in order to give a better overview by using one common format or template.<sup>59</sup> Within the framework of the present thesis, the 'ideal' integrated product delivery has a high level of integrated complexity (read: it reduces through its application the design complexity in focus) while still being sufficiently flexible to cover a market segment big enough to support efficient industrialised production based on mass customisation and in some cases also elements of automation.

If integrated product deliveries, as here, are considered to meet more than just technical demands, they should – particularly if including exposed/visible parts in the final building – also be visually appealing and be able to adapt to different spatial settings. Using the dimensions from the integration taxonomy as introduced in the section of *Systems terminology*<sup>60</sup>, such integrated product deliveries will normally present a high preparation level (assembly or chunk), a high service level (installation or maintenance), while the standardisation level is kept sufficiently low to offer an adequate range of different configurations. The latter point means that integrated product deliveries most often will present standardisation levels like made-to-order (M2O) or even bespoke (BSP). However, bespoke integrated product deliveries should perhaps rather be termed integrated *project* deliveries as the product or system level of these (the thing that different versions of the delivery have in common) are limited. The issue of product delivery vs. project delivery will be discussed further in the concluding part of this thesis.

Examples below are tentatively classified along the integration taxonomy and its dimensions of *preparation*, *standardisation* and *service*. However, sufficient information for each product is not always available. In such cases the total integrated complexity values, as suggested in the integration taxonomy, are based on estimates.<sup>61</sup> Although being expressed in a quantitative manner, the total integrated complexity values can at present conceptual stage of development not be considered a hard fact coefficient of integration. However, the assertion is that it still gives an idea of how different dimensions contribute of the in terms of integration. The point is that integration – or reduction of design complexity in focus through the use of products that embed design knowledge and product complexity - cannot just be reduced to a question of prefabrication. Prefabrication – here expressed primarily through the preparation dimension - is just one among other dimensions that define the total level of integration of a product. Using different dimensions, as suggested, nuance the picture so that e.g. a highly serviced and standardised solution is considered to have a relatively high integrated complexity value even if it is delivered and assembled on-site as materials and components thus having a low preparation level.

The examples below are ordered alphabetically by the system owner.

60 See *Systems terminology*, II.5

61 The values should rather be understood as qualitative estimates or classification (as e.g. *made-to-order*, or *bespoke*) The numerical values are not exact values. See also *Taxonomy in Systems terminology*, II.5



FIGURES III.3.1 A-F  
EXAMPLES OF ALTAN.DK-PRODUCTS

- 62 Information partly retrieved from (Beim, Nielsen & Vibæk 2010:96f)
- 63 [http://www.altan.dk/media/Altan\\_droemme\\_2010.pdf](http://www.altan.dk/media/Altan_droemme_2010.pdf) - page 36 (accessed on August 9, 2011) – author's translation from Danish

## INTEGRATED PRODUCT DELIVERIES – ARCHITECTURAL SUBSYSTEMS

### PRODUCT 1<sup>62</sup>

System name: Altan.dk  
System owner: Altan.dk

#### *Short description*

Balcony systems for installation on existing buildings as a new project or as replacement of old balconies. Each balcony is based on standard types and basically delivered as a kit-of-parts in three parts from different factories: Base, fixture and railing. The base is finished according to standardised principles as e.g. varied but standardised depth. The aluminium type covers 70% of the sale.



*'Altan.dk is not exclusively about the balcony itself but equally the process. Vi take care of everything from A to Z during the course from the first inspection to the finished assembled and installed balcony ready for use. We are not just a balcony contractor but equally a service provider that handle project design, static calculations, processing by the authorities etc.'*<sup>63</sup>

#### *Market and opportunities*

Altan.dk provides 30 years of warranty which is quite unusual on assembly level in construction. Most balcony solutions are practically maintenance free for the user. The typical client is non-professional/private clients and typically in groups represented by smaller housing associations.

From 2006 and forward, Altan.dk have established balconies in more than 500 different locations. The total average price is approximately 100.000 DKK (13.500 euro)

#### *Integration levels*

Preparation level: ASM (2)  
Standardisation level: M2O/C2F (2.5)  
Service level: MNT (3)  
Total integrated complexity value: (7.5/9) - HIGH

Further information: <http://www.altan.dk>



FIGURES III.3.2 A-D  
THE X-TENSION CONCEPT: EXTERIOR,  
INTERIOR, PLAN AND SECTION

64 (Karsten Pålsons Tegnestue  
2003:8)

## PRODUCT 2

System name: X-tension  
System owner(s): City of Frederiksberg, Karsten Pålsons Tegnestue,  
Falcon Rådgivende Ingeniører, Skanska et.al.

### Short description

System for renovation of multi-storey masonry apartment blocks constructed before 1945 through insertion/addition of an integrated solution with new bathroom and kitchen installations based on prefabricated components like concrete structure (tier 2-slabs and panels), (tier 1-) bathroom pods and a light (tier 2-) building envelope of glass and aluminium.

“The main principle in the X-tension renovation system is to remove the vulnerable wet room areas in the old building and replace them with a completely new self supporting core comprising prefabricated bathroom, kitchen and façade elements.”<sup>64</sup>

### Market and opportunities

The system clearly focuses on a specific part of the Danish building stock typically located in larger Danish cities and solves a common problem of modernisation of these older buildings. The system both has roots in earlier experience as well as provides reference for future projects – particularly for the architectural office involved.

Only few specific projects based on the system have been carried out. It is rather meant a principle for renovation of this specific type of building than a marketed product solution. While specific manufactures have gained general knowhow through the projects, *X-tension* has (so far) not been turned into a unified business concept with a specific supply chain.

### Integration levels

Preparation level: COM/ASM/CHK (2)  
Standardisation level: BSP/M2O (0.5)  
Service level: INS (2)  
Total integrated complexity value: (4.5/9) - MEDIUM

Further information: [http://www.paalsson.dk/pix/pdf/Udv\\_Byggesystem.pdf](http://www.paalsson.dk/pix/pdf/Udv_Byggesystem.pdf)  
and (Karsten Pålsons Tegnestue 2003)



FIGURES III.3.3 A-D  
DEBA CONCEPT EXAMPLES

65 <http://www.deba.de/index.php?id=33&L=1> accessed on August 8, 2011

## PRODUCT 3

System name: DEBA Module

System owner: DEBA Badsysteme GmbH, Germany

### *Short description*

Complete flexible made-to-order (M2O) bathroom solutions delivered installed and ready to use based on a standard self supporting modular metal sandwich construction system where fully fitted off-site produced planar (tier 2-) assemblies are put together (nested) – usually onsite but volumetric (tier 1-) chunks are also an option.

*[...] at DEBA finished means that: floor and wall coverings, all installations as well as the horizontal piping to the sewage area are all included. No additional work is needed. The bathroom is ready for immediate use.<sup>65</sup>*

### *Market stage and opportunities*

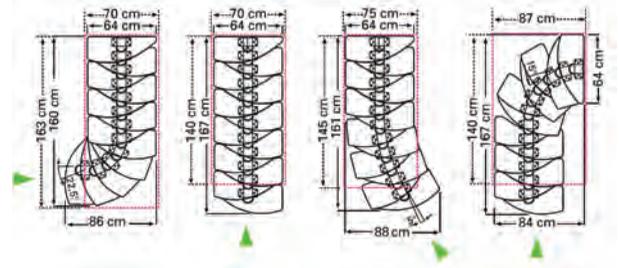
Although the system is marketed towards both new buildings and refurbishment, its real advantage when delivered as a planar tier 2-system is within refurbishment where access is often difficult and installation of volumetric tier 1-systems is not an option. The DEBA-system has been used widely in five star hotels, liners (ships) as well as in residential refurbishment.

DEBA has 190 employees and produces approximately 5000 bathpods per year

### *Integration levels:*

Preparation level:	CHK (3)
Standardisation level:	M2O (1)
Service level:	INS (2)
Total integrated complexity value:	(6/9) - MEDIUM

Further information: <http://www.deba.de/>



## PRODUCT 4

System name: Dolle Modular Staircase  
(Graz, Rome, Copenhagen, Chicago etc.)  
System owner: Dolle A/S, Denmark

### Short description

Modular staircase delivered as a finished kit-of-parts where the number of treads and the rise can be adjusted within certain margins to fit the specific context and floor-to-floor height where the stairs are to be inserted. The modular staircase product line comprises several models that have different materials, finish and tread design. Most models can be assembled with a straight flight or a quarter turn, some also with a half turn. Different banister solutions are optional.

*“We CE mark our modular and spiral staircases [...] which means they comply with EU’s essential requirements on health, safety and environmental protection. CE marking guarantees clients that our products, as a minimum, meet the common European minimum requirements; although in many cases we set the bar higher with even more stringent requirements.”<sup>66</sup>*

### Market and opportunities

Dolle has specialised in smaller interior staircase solutions mainly for private customers. Apart from the modular products they also do attic stairs (flagship product), spiral stairs, special space saving staircases and banister systems. A staircase configurator available on the webpage lets you specify all relevant parameters of a model for placing an order which can then be executed directly online.

Dolle is one of the world’s largest manufacturers of staircases selling in 40 countries with over 90% of sales as export.

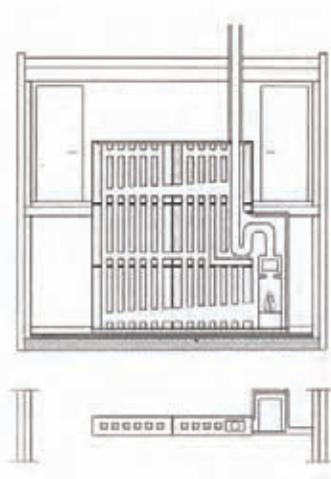
### Integration levels:

Preparation level: ASM (kit-of-parts) (2)  
Standardisation level: M2O/OTS (2)  
Service level: SPL (1)  
Total integrated complexity value: (5/9) – MEDIUM

Further information: <http://www.dolle.dk/en-us/dolle.aspx>

FIGURES III.3.4 A-D  
DOLLE LAYOUTS AND PRODUCT  
EXAMPLES

66 <http://www.dolle.dk/en-us/dolle/quality.aspx> accessed on August 9, 2011



FIGURES III.3.5 A-D  
HEATED EARTH WALL: PLAN, SECTION,  
AND PRODUCT EXAMPLES

67 See <http://www.lehmo.at/lehmo/index.html> (accessed on August 9, 2011)



## PRODUCT 5

System name: Heated earth walls

System owner: Lehm Ton Erde (Martin Rauch), Ernst Waibel, Austria

### Short description

A stove combined with a room divider with integrated heating all made of offsite fabricated rammed earth modules. While the stove is made as one tile or block in standard shape and size, the room divider is modularised and assembled on-site where the joints of the flexible earth material then can be smoothed out to form one monolithic heated wall.

*“This type of stove is generally used, in combination with integrated hot water heating and solar collectors, in low energy houses, where it supplies all necessary heating. It can be mass produced, although individual variations in the material can make each stove unique”<sup>67</sup>*

### Market and opportunities

Although the particular solution or production method might be patented the whole idea of constructing in earth is that it is found (almost) everywhere as a local material. The offsite fabrication enables standardisation and facilitates quality check. The oven itself is marketed as a product. It is not known (to author) whether the room divider solution is equally commoditised.

### Integration levels

Preparation level:	ASM (2)
Standardisation level:	M2O/OTS (2)
Service level:	INS (2)
Total integrated complexity value:	(6/9) – MEDIUM/HIGH

Further information: (Kapfinger 2001), <http://www.lehmtonerde.at/> & <http://www.lehmo.at/>



## PRODUCT 6

System name: Quantum

System owner: Lutron Electronics Company, Inc.

### Short description

Lighting control solutions comprising lighting fixtures, switches, sensors, dimmers, and shading devices delivered in modules and assembled as one integrated lighting solution including installation and later servicing.

“*Quantum total light management maximizes the efficient use of light to improve comfort and productivity, simplify operations, and save energy. This powerful and efficient system dims or switches all electric lighting, and simultaneously controls daylight using automated shades.*”<sup>68</sup>

### Market and opportunities

Although the installation is outsourced to (local) subcontractors, one of the great advantages of Quantum and other Lutron systems is the service packages that remove the burden of maintenance of the finished solution. Another is the modularity and openness of the system that makes it flexible both concerning reuse of existing installations as well as reconfiguration and extension of an installation. Yet another one is the green aspects of energy optimisation based on combination of several technical realms.

### Integration levels

Preparation level	COM/ASM (1,5)
Standardisation level:	OTS/M2O (2)
Service level:	MNT (3)
Total integrated complexity value:	(6,5/9) – MEDIUM/HIGH

Further information: <http://www.lutron.com><sup>69</sup>

FIGURES III.3.6 A-D  
LUTON CONTROL SYSTEM AND INTERIOR SOLUTIONS

68 <http://www.lutron.com/Products/WholeBuildingSystems/Quantum/Pages/Overview.aspx> accessed on August 8, 2011

69 For an extended description within this thesis see also *Customisable architectural subsystems* III.2



FIGURES III.3.7 A-D  
THE NCC SHAFT CONCEPT, PRODUCT  
AND INSTALLATION

70 <http://www.ncc.dk/skakt> accessed on September 4, 2011 (author's translation from Danish)

## PRODUCT 7

System name: Installation shaft

System owner: NCC Construction Denmark

### Short description

Offsite factory produced installation shaft system for multi-storey housing projects. The shaft is produced in one-storey high modules and comprises a finished plug-and-play installation of all vertical risers and technical systems within one volumetric T1-chunk. The chunks are stacked on-site in sequence with the erection of the structural building system – in Denmark mostly prefabricated slab-systems.

“The prefabricated installation shaft is one of NCC’s innovative suggestions for how the industrialisation of construction processes can lead to reduced construction periods, lower construction costs and a more uniform quality – an optimisation of the construction process”<sup>70</sup>

### Market and opportunities

Equal to products as the bathpod, an installation shaft is one of the places in a building with the highest concentration of and level of coordination between different of the traditional trades that all have to install a minor part of the overall solution. A strictly planned factory production considerably reduces risk of faults. An idea has been to develop a user interface integrated with a bathpod solution. Other development areas are similar products for the office and laboratory developments.

### Integration levels:

Preparation level	CHK (3)
Standardisation level:	OTS/M2O (1,5)
Service level:	INS (2)
Total integrated complexity value:	(6.5/9) – MEDIUM/HIGH

Further information: <http://www.ncc.dk/skakt> and [http://www.dac.dk/db/filarkiv/13563/skakten-rapport\\_19-korrektur.pdf](http://www.dac.dk/db/filarkiv/13563/skakten-rapport_19-korrektur.pdf)



## PRODUCT 8

System name: Stavne blocks

System owner: NTNU (Anne Sigrid Nordby) and Stavne Rebygg, Norway

### Short description

Wall blocks of massive reused timber that can be joined into self supporting wall panels. Initially the blocks have been used as interior partitions but an exterior version is on the way. The blocks are supposed to be produced close to the construction site where they will be deployed and by use of locally available reclaimed timber. A set of standard solutions for joining and other details have been developed as part of the system.

“The wall has a strong expressive character and stands like a piece of installation art in the space. The project for a further development of the Stavne block into an exterior wall and the establishment of a production line is now in the pipeline<sup>71</sup>

### Market and opportunities

The system represents an attempt to establish a new construction material based on the principles of reuse and a specific construction method. No nails are used. Dimensions and weight make them manageable by hand. With roots in academic research it has so far only been produced for test purposes and is not an established product or brand.

### Integration levels:

Preparation level: COM (1)  
 Standardisation level: OTS (3)  
 Service level: SAL (0)  
 Total integrated complexity value: (4/9) – LOW/MEDIUM

Further information: <http://stavneblokka.blogspot.com>

FIGURES III.3.8 A-D  
 PRODUCT PROTOTYPES AND TEST OF  
 THE STAVNE BLOCKS

71 <http://stavneblokka.blogspot.com> accessed on August 9, 2011 (author's translation from Norwegian)



FIGURES III.3.9 A-B  
THE RBE-FACADETYPES AND ONSITE  
PROCESS

- 72 Author's translation from Danish
- 73 For an extended description within this thesis see also *Customisable architectural systems* III.2

## PRODUCT 9

System name: Façade renovation system

System owner: RBE, Denmark

### *Short description*

RBE delivers façade renovation of traditional masonry buildings. Based on a classification into four main façade types, 19 combinations of cleaning, masonry work, and finish are offered as 'standard solutions' supposedly covering the needs for 80% of Danish multi-storey apartment blocks built between 1850 and 1950.

“One of the goals has been to decompose a façade renovation into clear and meaningful constituent elements and then to join these again in a whole. A new system for façade renovation!”

(RBE, 2009:32)<sup>72</sup>

### *Market and opportunities (advantages)*

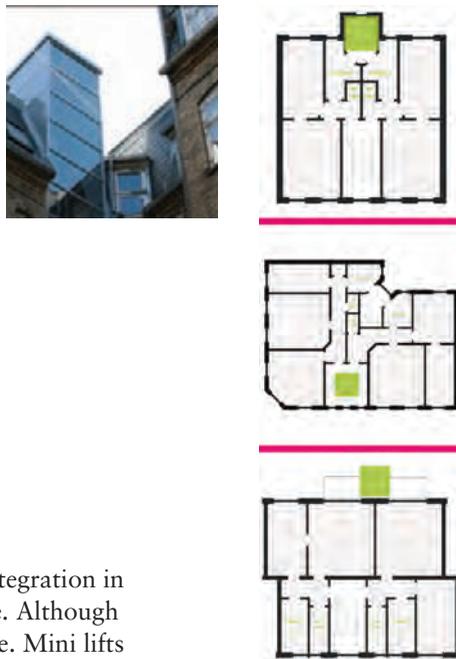
The façade renovation system is particularly directed towards minor private housing associations that by choosing RBE get both consultancy and delivery as an integrated and lucid solution that potentially obviate the need for costly external building consultants.

RBE has 100+ employees

### *Integration levels*

Preparation level:	MAT (0)
Standardisation level	M2O (1)
Service level	INS (2)
Total integrated complexity value:	(3/9) - LOW

Further information: <http://www.rbe.dk/Facader.182.aspx><sup>73</sup>



FIGURES III.3.10 A-B  
EASYVATOR ARE INSTALLED IN  
EXISTING BUILDING STOCK FOLLO-  
WING THREE MAIN STRATEGIES

## PRODUCT 10

System name: Easyvator

System owner: RBE, Denmark

### Short description

Easyvator solutions are complete mini lift solutions designed for integration in existing (older) building stock not originally planned for lift service. Although small, the lifts still comply with the requirements for wheelchair use. Mini lifts are typically installed in the middle of an older stairway, as replacing the backstairs, or as an extension to the backstairs.

“On Blågårds Plads [in Copenhagen] it became a compromise between the elder residents’ wish to be able come up and down combined with the younger residents’ desire to have direct access to the common roof terrace”<sup>74</sup>

### Market and opportunities

The Easyvator concept focuses attention on a limited and difficult part of the market thus seeking away from the ‘red ocean’ with most competition into a ‘blue ocean’.<sup>75</sup> Many of the target dwellings were originally constructed for the emerging class of industrial workers moving in from the country side. Today these dwellings are centrally located in inner city areas which has made them attractive for higher income groups with financial capital and incentive for improvements.

Easyvator is a subsidiary of RBE with approximately 100 employees and specialised in general improvement of the existing building stock

### Integration levels

Preparation level: ASM (2)  
Standardisation level: M2O (1)  
Service level: MNT (3)  
Total integrated complexity value: (6/9) – MEDIUM/HIGH

Further information: <http://www.easyvator.dk/>

74 <http://www.easyvator.dk/inspiration.139.aspx> accessed on August 8, 2011

75 The distinction red ocean/blue ocean was introduced by Kim & Mauborgne in the book *Blue Ocean Strategy*. (Kim & Mauborgne 2005)



FIGURES III.3.11 A-B  
UCON FINISHED ATTIC PRODUCT ARE  
INSTALLED BY CRANE

76 <http://www.rucon.dk/færdigkviste/> accessed on August 9, 2011

## PRODUCT 11

System name: Rucon færdigkvist (Rucon finished attic)

System owner: Rucon

### Short description

Finished off-site produced attics like the Rucon solution have become an increasingly used way to produce high quality solutions in a protected and controlled environment before final installation on-site. Several manufacturers offer more or less bespoke solutions – some of the more standardised versions have online configurators where the customer can design his own mass customised solution

“Easy installation and adaptation mean shorter time with a hole in the roof, Quick installation due to high degree of completion from the factory, affordable solution with lower scaffolding and labour cost”<sup>76</sup>

### Market and opportunities

Heavy technical and legislative demands connected to the physical resolution of the roof in a rainy and humid climate like e.g. in Denmark, make roof openings a complex part of buildings. This makes integrated building assemblies comprising parts of this area an obvious target for offsite produced solutions manufactured in controlled workshop or semi industrialised factory environments. However, larger truly industrialised manufacturers are so far not found.

Rucon is – as many of the other manufacturers in this field – a smaller company with 20+ employees and roots in carpentry.

### Integration levels

Preparation level:	ASM (2)
Standardisation level:	M2O (1)
Service level:	INS (2)
Total integrated complexity value:	(5/9) – MEDIUM

Further information: <http://www.rucon.dk/færdigkviste/>



## PRODUCT 12

System name: Podwall  
System owner: Swift Horsman, UK

### Short description

Podwall is a modular system of clad steel frames forming wall assemblies with integrated installations and appliances mounted from the factory. The modules arrive fully fitted and can literally plug together on-site to form entire bathroom environments, reception areas, acoustic walling, office fronts etc.

*“Podwall is a fully prefabricated modular walling system incorporating finishes and services all of which are manufactured completely offsite in a dedicated controlled environment”<sup>77</sup>*

### Market and opportunities

As a modularised tier 2-assembly but with appliances and other accessories mounted from the factory, the Podwall seeks to combine the advantages of the high degree of completion of the (tier 1-) chunks with the more flexible dimensions of panelised systems in a kind of semi-volumetric solution. The highly customised solutions address primarily a high end market.

Swift Horsman has several product lines within offsite manufactured fit-out solutions. Operates mainly in the UK

### Integration levels

Preparation level: ASM (2)  
Standardisation level: BSP/M2O (0.5)  
Service level: INS (2)  
Total integrated complexity value: (4.5/9) - MEDIUM

Further information: <http://www.swifthorsman.co.uk/companies/swift-horsman/products/podwall>

FIGURES III.3.12 A-C  
PODWALL PRODUCT SOLUTIONS

77 <http://www.swifthorsman.co.uk/companies/swift-horsman/products/podwall> accessed on April 1, 2011



FIGURES III.3.13 A-C  
THE COREFAST PRODUCT

78 [www.corusconstruction.com/bi-steel](http://www.corusconstruction.com/bi-steel) accessed on October 15, 2011 and [http://www.tatasteeleurope.com/en/products/construction\\_products\\_and\\_services/structural\\_steelwork/corefast/](http://www.tatasteeleurope.com/en/products/construction_products_and_services/structural_steelwork/corefast/) accessed on August 8, 2011

## PRODUCT 13

System name: Corefast

System owner: Tata Steel Europe (former Corus), UK and Netherlands

### Short description

Modular construction system for creating structural lift and stair cores in multi-storey buildings made of Corus's Bi-Steel™ – a steel/concrete composite material that combines high strength and structural rigidity with low tolerances. The *Corefast* system is manufactured as off-site fabricated tier 2-assemblies joined into one storey high complete tier 1-modules (chunks) before they are stacked into a finished multi-storey core on-site. The system is suitable for cores from eight to over a hundred storeys.

“*Corefast is a superior construction system to traditional reinforced concrete cores - it is faster, easier to construct, more accurately engineered and can offer reduced structural thickness.*”<sup>78</sup>

### Market and opportunities

The main advantages of the *Corefast* system is the low tolerances that makes it easier to combine with other high precision off-site manufactured building components and assemblies. Furthermore the construction time on-site is reduced with up to six times as compared with in-situ reinforced concrete cores.

Tata Steel Europe is Europe's second largest steel producer and a subsidiary of Tata Steel Group with over 80.000 employees worldwide.

### Integration levels

Preparation level: CHK (3)  
Standardisation level: M2O (1)  
Service level: INS (2)  
Total integrated complexity value: (6/9) – MEDIUM/HIGH

Further information: [http://www.tatasteeleurope.com/en/products/construction\\_products\\_and\\_services/structural\\_steelwork/corefast/](http://www.tatasteeleurope.com/en/products/construction_products_and_services/structural_steelwork/corefast/)



## PRODUCT 14

System name(s): ONE by Transwall, Z-WALL,  
CorporateWALL, and REASONS  
System owner: Transwall, USA

### Short description

Transwall manufactures, sells, and delivers made-to-order movable floor-to-ceiling and architectural wall systems for office environments. The company markets four product lines addressing different partition wall needs. The wall systems are delivered and installed by Transwall as finished tier 2-assemblies and are both highly configurable and re-configurable.

“The marketplace interests were just starting to come together around green architecture through use of modular walls and construction, addressing flexible architecture, and growing desires for increased daylight in office spaces through the use of glass. Transwall’s products were, and continue to be positioned at the intersection of these forces”<sup>79</sup>

### Market and opportunities

The advantage of partitions like Transwall’s systems is the double flexibility of both initial configuration and later conversion that makes the systems highly adequate for office environments with frequent need for reconfiguration. The residential market requires a more permanent look that has so far not been addressed by Transwall.<sup>80</sup>

Transwall has 60 employees and an average order is in the 200.000-400.000 \$ range

### Integration levels

Preparation level: ASM (2)  
Standardisation level: M2O (1)  
Service level: MNT (3)  
Total integrated complexity value: (6/9) – MEDIUM-HIGH

Further information: <http://www.transwall.com/>

FIGURES III.3.14 A-D  
TRANSWALL PRODUCTS: ONE BY  
TRANSWALL®, ZWALL, CORPORATE-  
WALL AND REASONS

79 <http://www.transwall.com/index.php/profile/about> accessed on August 8, 2011

80 This assumption is partly based on author’s own market research. See *Customisable architectural subsystems*, III.2



FIGURES III.3.15 A-D  
EXAMPLE FROM THE WINDOWMASTER USER INTERFACE AND REFERENCES FROM SWITZERLAND, DENMARK AND UK

81 <http://www.windowmaster.dk/regado.jsp?type=page&id=122> accessed on August 8, 2011 (author's translation from Danish)

## PRODUCT 15

System name: NV Comfort™ and NV Advance™  
System owner: WindowMaster

### Short description

Indoor climate solution and control system based on natural ventilation through controlled openings in façade and roof. Openings in the building envelope are automatically opened and closed based on pre-programmed values for room temperature, CO<sub>2</sub>-levels, outdoor temperature, rain, and wind speed.

“The setting of a desired room temperature and CO<sub>2</sub>-level can be adjusted for each single room from a central location in the building on a NV Comfort™ touch screen. Additionally, the user can always use the system to directly open or close a window if more or less fresh air is desired.”<sup>81</sup>

### Market and opportunities

The system combines a sophisticated pre-programmed environmental solution based on several measurable parameters with the possibility of direct user interaction based on personal here-and-now sensory perception of an interior space. It thus seeks to overcome the alienation often produced by completely automated solutions.

### Integration levels

Preparation level	COM/ASM (1.5)
Standardisation level:	OTS/M2O (2)
Service level:	INS (2)
Total integrated complexity value:	(5.5/9) - MEDIUM

Further information: <http://www.windowmaster.dk/>





# PART IV

## MODEL

- IV.1 MODEL PRESENTATION
- IV.2 SYSTEM STRUCTURE ANALYSES
- IV.3 KIERANTIMBERLAKE
- IV.4 SCANDIBYG
- IV.5 NCC
- IV.6 ARUP ASSOCIATES



## PART IV – MODEL

The two former parts II and III have mainly constituted explorations of theoretical and practical fields in order obtain a better understanding of the problem area and the main problem formulated as the scope of the thesis as well as establishing a terminology for the latter parts and – hopefully – for the field of knowledge in general. The present Part IV – 'Model' introduces the system structure model and the system structural view it provides as the primary outcome or product of the thesis. As described in the section of *Method and scientific approach*, the model has been developed iteratively with initial inspiration in the mentioned explorations and a primary case study conducted at KieranTimberlake. Subsequently, the first model draft has, as a hypothesis of a generally applicable model, been tested back on the primary case material as well as on three other secondary case studies as an analytical tool. This has worked partly as a discussion of the explanative power of the model partly as four separate analyses and discussions of the four different cases. The case-studies – particularly the primary – are fairly detailed and should consequently be seen as relevant in themselves as a way of further folding out aspects of the field of contemporary industrialised construction as well as giving valuable feedback for the evaluation and modification of the model.

- 1 See *General systems theory*, II.4
- 2 Ibid

## IV.1 MODEL PRESENTATION

The present section presents the model that has been elaborated in order to describe and support the use of the concept of *system structure* in architectural design. The model and its application to a number of case studies is considered one of the main contributions of the present PhD-thesis. Perspectives in the conscious use of this system structure model could be architectural, ecological, economical, legislative and technical by introducing a new way of handling the complexity of architectural design and of focussing design attention. As an inherently integrative discipline architectural design is perhaps the most obvious place in construction for the application of such a systems approach.

Inspired by the notion from general systems theory of *equifinality*, an assumption is that two fundamentally equal buildings can constitute significantly different system structures. Equally, using the notion of *isomorphism*, widely different buildings can have similarities on a system structural level. A goal is that the proposed model should be able to clearly express these situations.<sup>1</sup> The model should thus contribute to the understanding and in a simple way facilitate the discussion of *different* production scenarios for *specific* building projects as well as *similar* production scenarios for *different* buildings. A given system structure will always be influenced by the context it forms part of regarding culture, geographical location (geology, climate etc), technological stage of the society, socioeconomic factors, special local building techniques, available (local) production facilities and a range of other factors. In a present day context where the realisation of architecture and construction is subject to heavy changes that are partly driven by new technological possibilities (pull) and partly affected by external factors, cf. above (push), the model is to be seen as a descriptive and potentially proactive tool for understanding buildings on a system level that lies beyond their direct appearance. This requires, as argued earlier, a *soft system* approach of *levelled complexity* and *flexible structuration* where the model can be used to produce and look at system structures from different viewpoints, expressing different level of detail according to the specific purpose of using it.<sup>2</sup>

## PURPOSE OF THE MODEL

The concept and the model address an increasing need for tools to handle the complexity of architectural design from idea via construction to the final physical result. The initial outset is an apparently growing distance between how architecture is conceived and how it can be produced. The industrialisation of the construction sector has considerably accentuated this tendency. With point of departure in the idea of an integrated systems approach, the suggested model is supposed to help bridging the gap between architectural ideation and contemporary industrialised construction by enabling a more active use or integration of products from the building industry already from early design phases. This can potentially reduce the need for resource intensive and time consuming translation of architectural concepts into physical matter and form as well as limiting an otherwise infinite number of design choices and enabling a more strategically focussed design attention. The *system structure of architectural design*, as accessible through the use of the model, gives a system-structural view on buildings and how they are put together and the model should be seen as a tool to help understand and qualify the choice and combination of different more or less industrialised systems of varying complexity into a coherent modern industrialised architecture – buildings as assemblages of both high artistic and technical quality. The system structure brings in issues of supply chain management and product architecture into the architect's toolbox as supplementary design parameters that are however meant to simplify rather than complicate the overall design process.

The ambition has been to develop a model that can visualise the use of systems, their integration level – understood as their degree of (integrated) complexity – and their combinations, interrelations and nesting into a complete building seen as a complex system. The model is a visual tool that, apart from being relatively easy to code, moreover, through its graphical qualities, is able to communicate various levels of information in an easily perceivable way. The primary target group is the architect – working in practice, education, and/or research. Other potential users are construction engineers, other consultants and contractors as well as manufacturers of building products of more or less integrated and industrialised nature. The visualisation provided by the model serves in the first place scientifically as an analytical tool for understanding the system structure of already built projects. In a more developed form the model can potentially become a proactive design tool used both in architectural

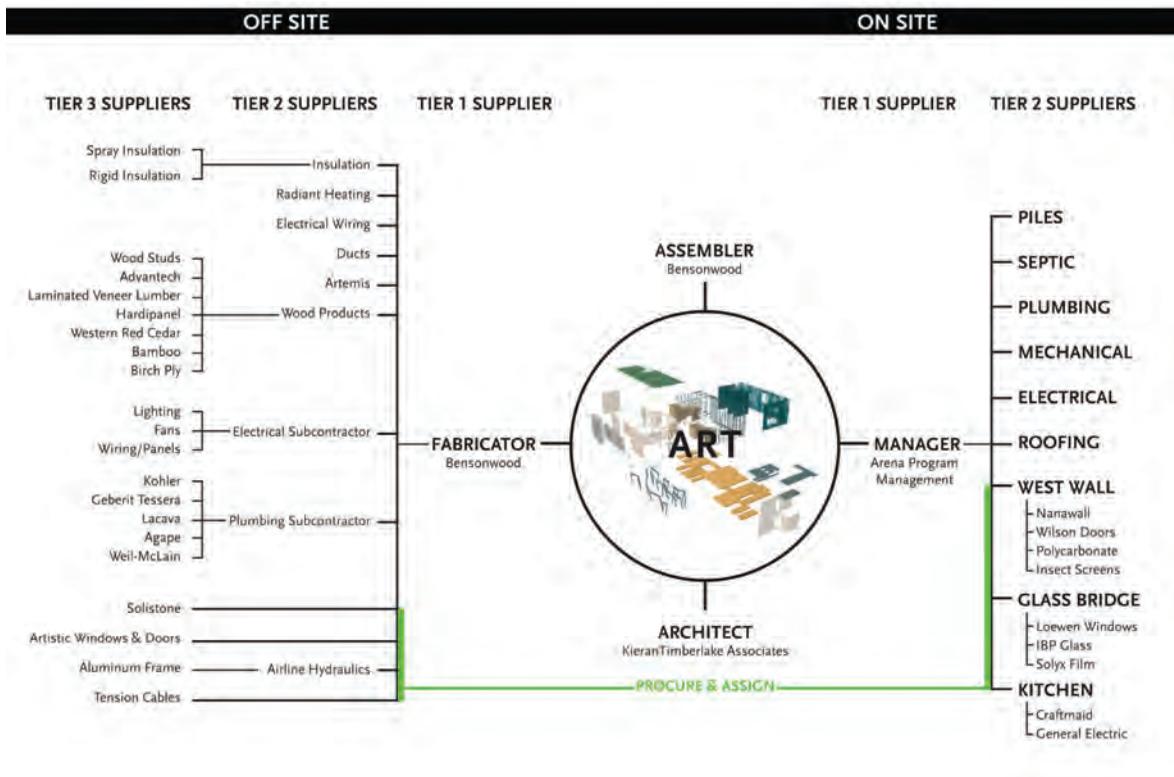


FIGURE IV.1.1  
SUPPLY CHAIN FOR LOBLOLLY HOUSE  
BY KIERANTIMBERLAKE

3 To talk about a final building is intuitively easy to understand. It can however be problematic to conceptualise a building as something stable over time. In the current context we will not go further into this discussion and, at least provisionally, accept that such finished state of a building will exist for an amount of time.

conceptual and design development phases for a more conscious decision making concerning the combinations of systems into specific building projects. This aspect is much in line with Christopher Alexander when he states that:

“Scientists try to identify the components of existing structures. Designers try to shape the components of new structures. The search for the right components and the right way to build the form up from these components, is the greatest physical challenge faced by the designer. I believe that if the hierarchical program is intelligently used, it offers the key to this very basic problem – and will actually point to the major physical components of which the form should consist”

(Alexander 1964:130)

Alexander’s use of ‘patterns’ are however concerned with the *functional* organisation whereas the proposed system structure model is rather focusing on *physical deliveries* thus integrating the genesis of the physical structure into the model. The focus – with roots in the theoretical exploration in part II – ‘System’ – is how buildings can be divided into constituent sub-elements or systems in different ways, how these systems in some cases are nested into larger assemblies or chunks (= more complex systems) and, finally, how they interface with adjacent systems in the finished building. This points towards a definition of the system entity for the model being physical systems and their related processes as they are delivered and inserted into a building. Systems in this definition of *delivery* will, cf. the definition provided earlier in the thesis, always contain physical elements that become a part of the final building.<sup>3</sup>



## TIER MODEL AND SUPPLY CHAINS

KieranTimberlake – an architectural office in Philadelphia, USA – has worked with a way of describing applied systems in building projects through the use of supply chain models. These models are inspired by industrial management and production systems.

KieranTimberlake’s version of the supply chain model is not to be understood as complete supply chains showing the absolute flow of materials from ‘*natural resources, raw materials and components into a finished product*’ (Nagurney 2006). Rather these ‘chains’ are limited to the focus of the architect in a particular architectural project. The model is split into two separate chains – of off-site and on-site processes ending respectively with a fabricator delivering off-site production *to* and a manager controlling on-site processes *on* the building site (see figure IV.1.1). Each of the chains is divided into a number of tiers – three off-site and two on-site tiers.

Interesting about this model is the capacity of displaying how the architect is working with systems and their interfaces. To some extent it also shows the nesting and combinations of these systems (or deliveries) from simple sub-systems over more integrated ones to the final building. Although working with the concept of different tiers in sequence, the model does not include the integration level – the integrated complexity of each delivery – as a consistent parameter of the different systems found in the diagrams. The integration level will here be more specifically defined as *the integrated complexity of a subsystem at the moment of its delivery*.<sup>4</sup> To use KieranTimberlake’s tier model for this aspect is further complicated by the distinction between off-site and on-site suppliers in separate supply chains.

### *New tiers and the dimensions*

Strongly inspired by KieranTimberlake’s supply chain model and applying the concept of system structure and the elaborated taxonomy of dimensions,<sup>5</sup> a revised version is proposed that combines off-site and on-site deliveries into one single tier hierarchy that integrates a graduation of integration levels with a slightly enhanced number of tiers (T1-5). Lower tier numbers express a higher system complexity *downstream* in (see figure IV.1.2) the supply chain while higher tier numbers represent simpler systems *upstream*. The sequence of the tiers is: Raw materials (T5), Building materials and standard components (T4),

FIGURE IV.1.2  
NEW TIERS EXPRESSING THE SYSTEM  
LEVELS OF THE SYSTEM STRUCTURE  
MODEL

- 4 See also the definition of *delivery in Systems terminology* II.5  
5 See II.5

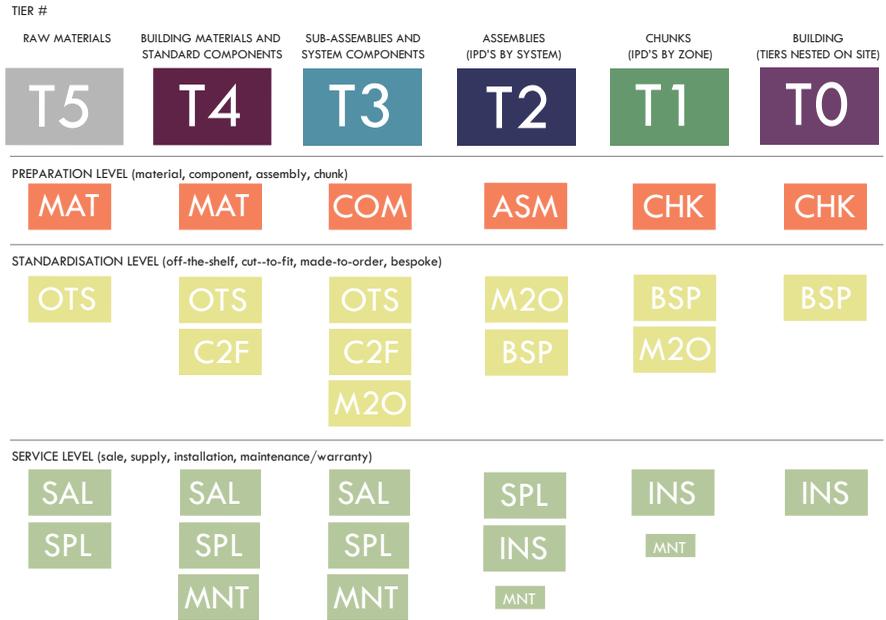
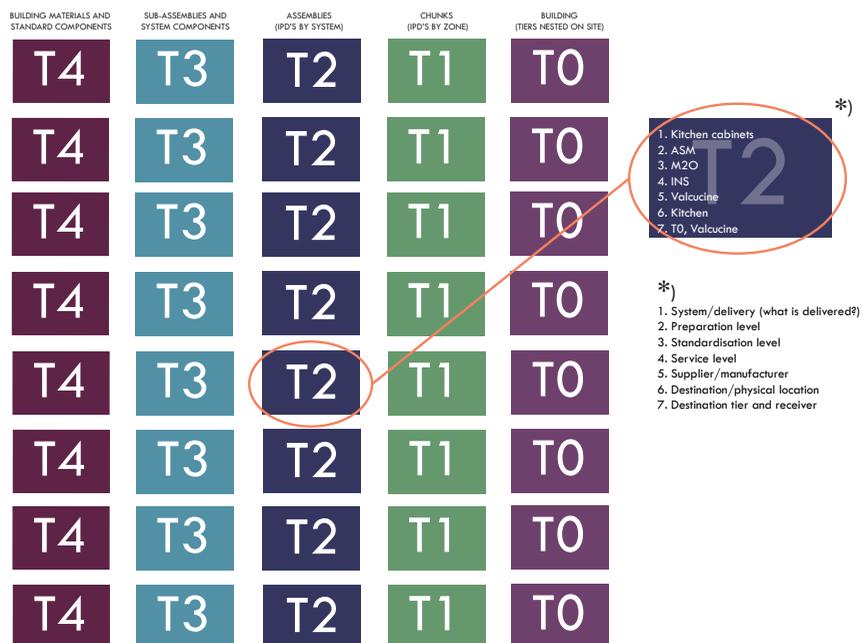


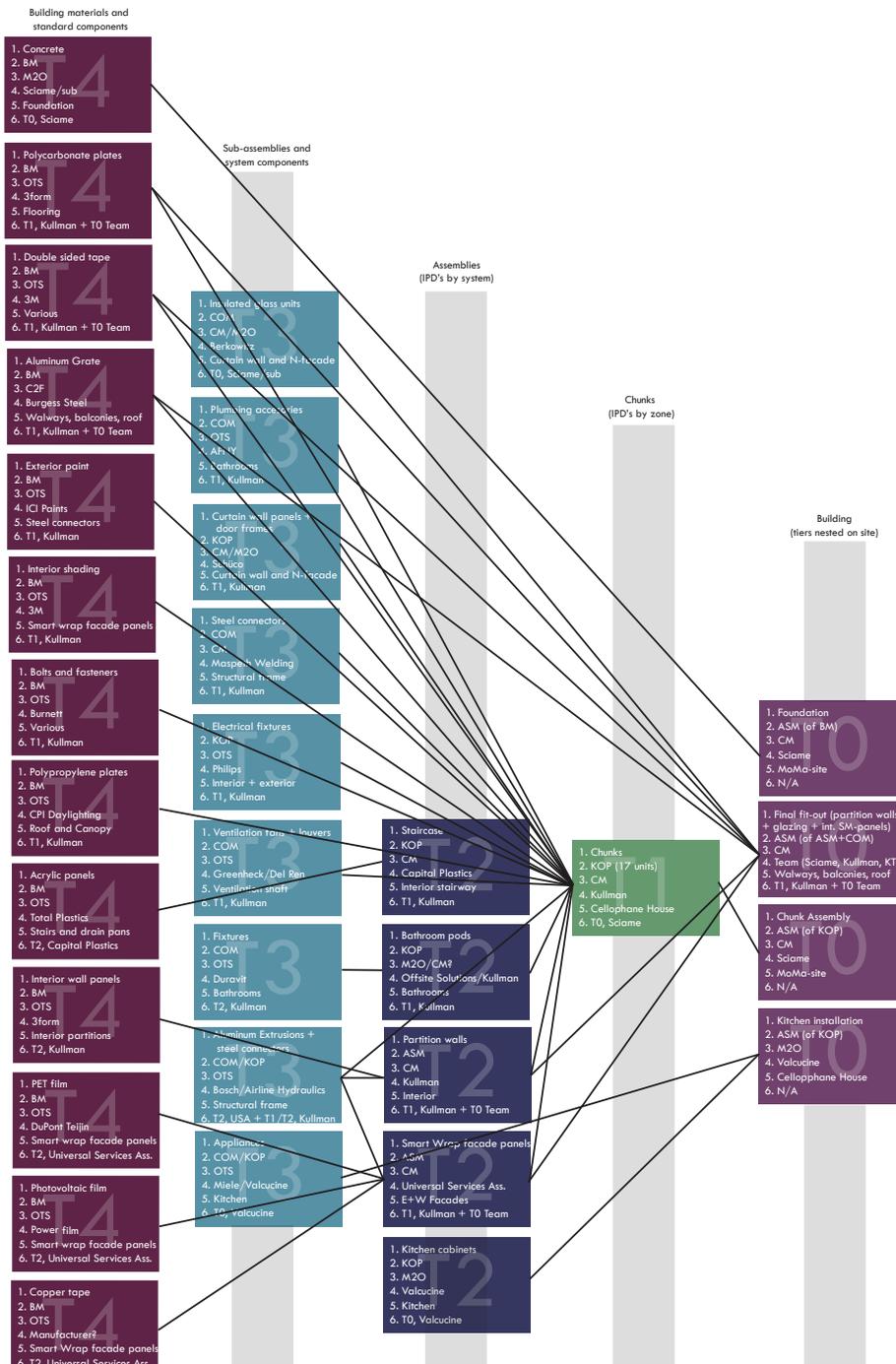
FIGURE IV.1.3  
RELATIONS BETWEEN TIERS AND DIMENSIONS

Subassemblies and system components (T3) Assemblies (by system) (T2) and Volumetric chunks (by zone) (T1). A last 'Tier 0' (T0) is the finished building onsite where all systems independently of their complexity are integrated. Theoretically there could be additional 'upstream' levels in the hierarchy (higher tier numbers) e.g. a next level (T6) focussed on molecular properties of materials. However, the included levels express the range of what would normally be the focus of the *architect* within normal building projects.

The integration level (expressed by tier #) is parallel to the values of the dimension of *preparation* as it is explained in the taxonomy and is, for each delivery, supplemented by the two other dimensions of *standardisation* and *service*. Figure IV.1.3 shows the relation between tiers and dimensions. While the prepara-

FIGURE IV.1.4  
GENERIC SYSTEM STRUCTURE MODEL AND AN EXAMPLE OF A SPECIFIC DELIVERY CODING (A BOX)

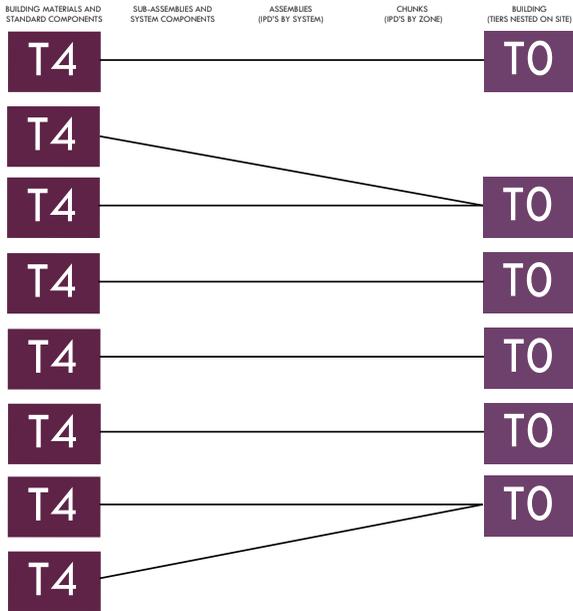




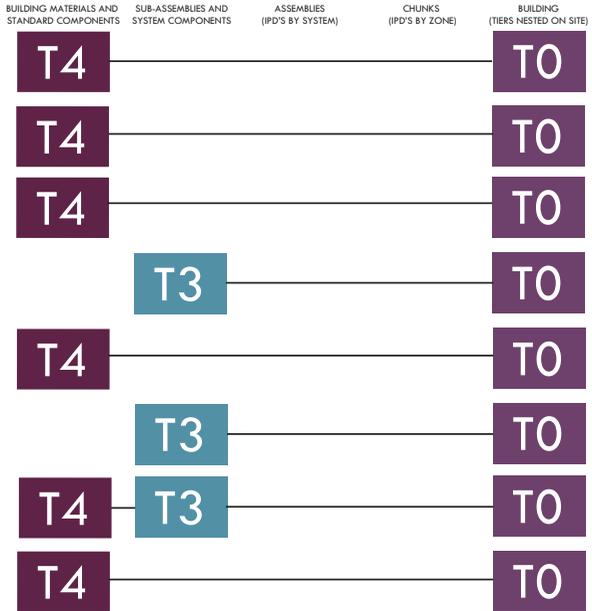
tion level is consistent with the tiers (tier 4-1), standardisation and service level can vary relatively independently. A high standardisation level, however, is most common on upstream tiers of simple materials, components. The service level has to do with additional delivery aspects of immaterial quality around the actual physical system. It expresses something about e.g. warranty, liability and responsibility issues connected to a building product and its delivery. The purpose of these supplementary dimensions for each delivery is to introduce a second layer in the model that makes it more robust in terms of capacity for consistent classification of *any* system or delivery applied in a building project – particularly regarding what has earlier been termed integrated complexity.

FIGURE IV.1.5  
SYSTEM STRUCTURE ANALYSIS OF  
CELLOPHANE HOUSE™ BY KIERANTIM-  
BERLAKE (EARLY DRAFT)

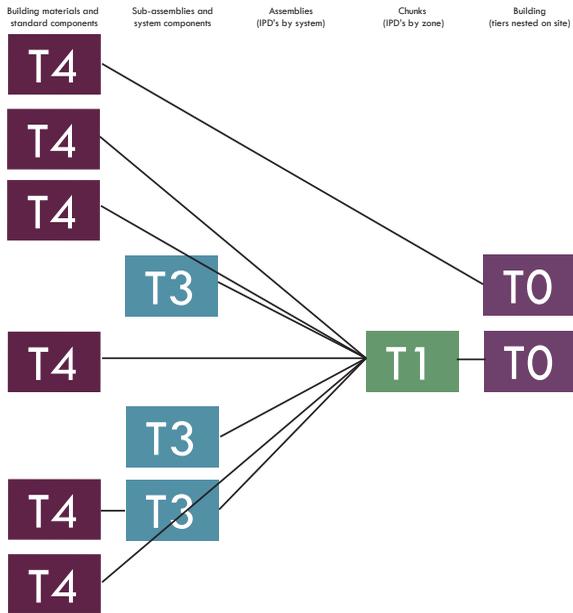
SCENARIO A - TRADITIONAL ONSITE CONSTRUCTION



SCENARIO B - CONTEMPORARY ONSITE CONSTRUCTION



SCENARIO C - CONVENTIONAL PREFABRICATION



SCENARIO D - CONVENTIONAL BESPOKE PREFAB

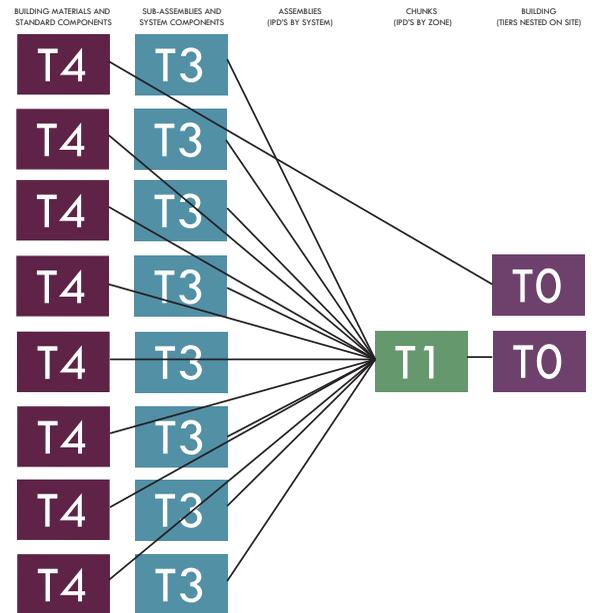
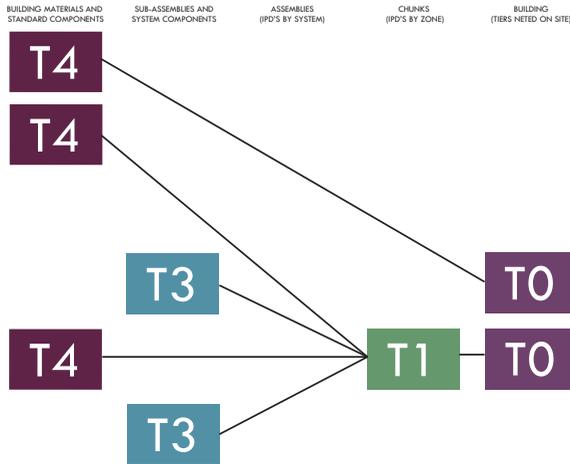


FIGURE IV.1.6 A-F  
DIFFERENT THEORETICAL CONSTRUCTION SCENARIOS EXPRESSED AS SIMPLE SYSTEM STRUCTURES

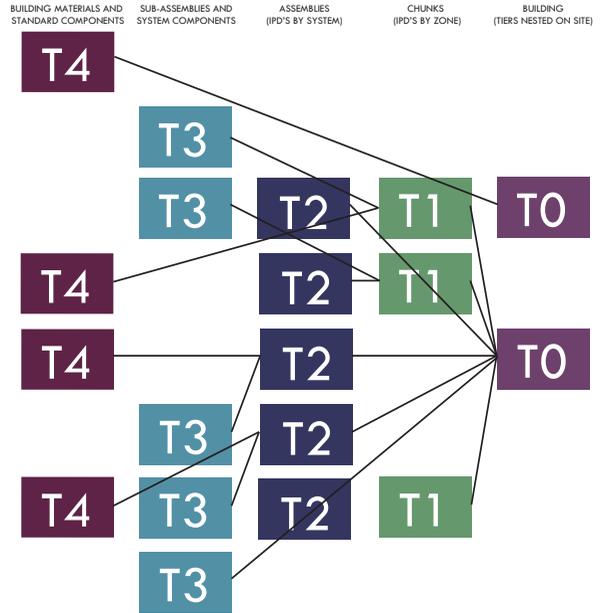
6 Ibid

The total *integrated complexity value* expresses to what extent the architect (or other ‘customer’) can draw on knowledge and processes already embedded and nested into the delivery further upstream. It could also be explained as the degree of commoditisation of a delivery.<sup>6</sup> The dimensions nuance the coding of the deliveries that each of them is graphically represented by a simple box in the system structure model.

SCENARIO E - CONVENTIONAL STANDARDISED PREFAB



SCENARIO F - FUTURE INDUSTRIALISED ARCHITECTURE



**System structure scenarios**

The system structure model has a generic character that potentially can be applied to any building project – industrialised or not – as a way of analysing and visualising the system structure in question.

As mentioned earlier, it expresses a *focussed* view representing a specific viewpoint i.e. the architect’s, the contractor’s, the manufacturer’s etc. In each case the details or scale relevant for this view can be expressed in the system structure. Some of the deliveries (in focus) will appear nested as chains of subsystems, systems and supra-systems (from upstream to downstream tiers) with the building itself as the final integration point (T0). Others will be directly nested into the final building. A characteristic of the model is that it combines the idea, the process, and the product into one single system entity circumscribed by the concept of delivery and visually expressed like a box (See figures IV.1.4 and IV.1.5). A way to illustrate where a delivery of a certain integration level is nested into another delivery or into the final building is through the use of simple lines between the boxes. These lines are always directional downstream meaning that simpler deliveries (always) are nested into more complex ones with the building itself (T0) being the most complex of all.<sup>7</sup>

Simplified theoretical scenarios have been put into the generic model for showing (and testing) its explanative power in a simple way (see figure IV.1.6 A-F). Different ways of defining and organising deliveries in construction projects will be reflected differently in the model – read: result in different system structures. As an example traditional and contemporary onsite construction scenarios will have a large amount of the simple T4 and some T3 deliveries that are integrated directly at T0 – the building site. On the contrary standardised and customised prefab scenarios can have virtually the same T4 and T3 deliveries but with the

7 An exception to this directional rule is if the model, as it will be introduced later, is used to look at disassembly scenarios. In some cases lines can be found between deliveries on the same tier. This is a question of the ‘granulation’ of the model rather than an expression of inconsistency

- 8 For an introduction to *levelled complexity*, see *General systems theory*, II.4
- 9 See *General systems theory*, II.4

principal integration point at the T1 level – in volumetric chunks (by zone). Finally a more tentative ‘future industrialised construction’ scenario will have longer supply chains of serially nested deliveries on various integration levels. While some deliveries are nested into others upstream, others on various levels are integrated directly at T0 – the building. Future industrialised construction, it is asserted here, will tend towards a larger amount of mid-level deliveries as T2 and T1 – assemblies (by system) and volumetric chunks (by zone).

The different theoretical scenarios do present different – visually easily distinguishable – system structures. These differences provide a first basis for a discussion about the concept of system structure when applied to real architectural projects as well as it suggests an incipient language for characterising this ‘system-structural’ aspect of any architectural design. It is the author’s belief that such a language and the corresponding model is useful in the discussion and further application of increasingly more industrialised and more complex products and deliveries in architectural design and construction. Being able to discuss the system structure of a building project – in the first place analytically and retrospectively – enhances the researcher’s and the designer’s capacity to understand and handle a complex structure or organisation through a kind of *levelled complexity* where the relevant focus or level of detail is chosen for the analysis in question.<sup>8</sup> As an intermediate system layer the model introduces different integration levels (the tiers) and can in a more developed state enable a dynamic management of the focus of attention while keeping the overall structure – the system structure – easily visually perceivable and editable.

## MODEL TEST, FURTHER DEVELOPMENT AND PERSPECTIVES

So what are the perspectives of applying a more systemic approach to architectural design and facilitate a better understanding of the integration of systems in construction projects as they move towards the application of more industrialised and complex integrated product deliveries? An easy answer could be that there is no way back to traditional construction exclusively based on the use of simple building materials and components brought directly to and processed on the building site (T0). As Alexander points out there is no way the current and increasing complexity in architectural design can be grasped intuitively by the designer.<sup>9</sup> If that is the case, several arguments could be put forward for an

industrialised architecture as assemblage of integrated and nested systems managed through the use of system structures as they are expressed by the model:

- Architectural advantage of nesting/embedding complexity (in discrete sub systems) while still leaving more flexible and robust the solution space than in closed all-encompassing building systems (economies of scope)
- Ecological advantage of being able to select the subsystems (deliveries) most adequate to the local situation (performance, transportation etc.)
- Business/legislative and liability advantage of dealing with products – not buildings
- Systematic product development, specialisation and quality improvement is more probable in (sub) systems as e.g. assemblies and chunks (integrated product deliveries) by allowing high up-front research and development expenses to be amortized across bigger and more international markets (economies of scale).
- Real industrialised/automated *production* rather than off-site *construction* is more feasible as solutions become commoditised as products (not simply traditional construction under roof)
- New market possibilities (compared to closed all-encompassing systems) within retrofitting of existing building stock as an alternative to demolition and new construction. This is particularly interesting concerning sustainability aspects.

Subsequent steps in the model development – in order to further refine and test the model – has been to apply it to a limited number of already realised building projects selected according to their supposed similarity with the theoretical scenarios presented above. This constitutes the empirical exploration of the model in the form of case analyses that make direct use of it. Important to state again is that the model only visualises the architect's or other stakeholders' specific focus of attention. It does not reflect complete material supply chains. Another ambition which is already opened is equally to be able to follow the disintegration or un-nesting of a building and its systems through reuse, disassembly and demolition after the end of its useful life. Although most buildings in our part of the world are conceptually designed as if they were to exist forever this is seldom the case. The world and our culture are nonlinear, turbulent, and dynamic entities – perhaps even at an accelerating rate. Changing needs put demands on buildings as systems to be adaptive over time. Concepts as design-for-disassembly and cradle-to-cradle design have been introduced.

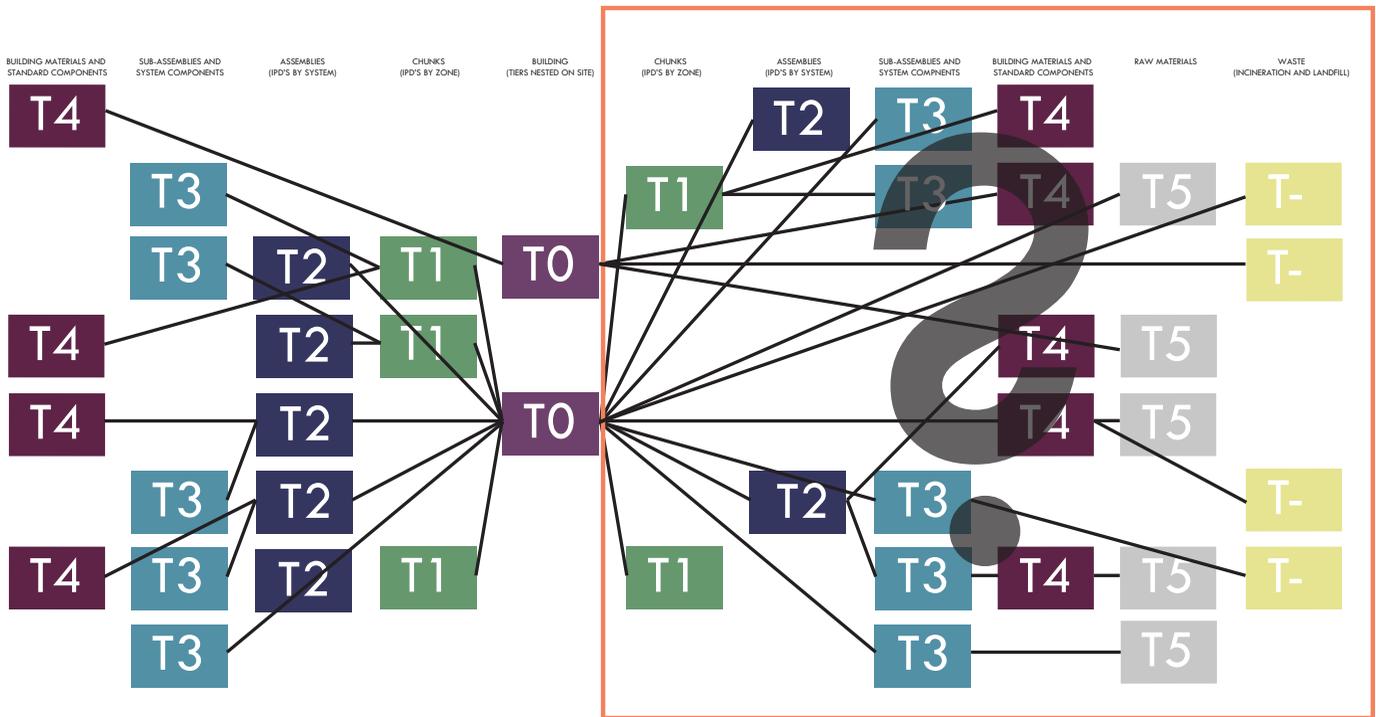


FIGURE IV.1.7  
SKETCH FOR A DISASSEMBLY SCENARIO EXPRESSED AS SYSTEM STRUCTURE.

10 See *Industrial production theory*, II.3

A mirrored version of the present model draft could provide a scheme for handling deliveries as sophisticated supply chain systems where, as Nagurney (2006) was cited earlier: *'used products may re-enter the supply chain at any point where residual value is recyclable'*.<sup>10</sup> (See figure IV.1.7)

### Model iteration

As described in the section of *Method and scientific approach* in the introductory Part I – 'Frame' of this thesis, the model is conceived through iterative loops that gradually increase the quality and applicability. The case analyses following this section form an important part of this iteration. This makes it, as it is also pointed out, hard to describe the model conception in a logic linear manner as dictated by the text as primary media. Due to the continuous modification it also becomes an endless task to completely update the model description and its later (or earlier?) specific application and appearance in the case analyses. Considering the proportions of the undertaken (self-imposed) assignment while keeping in mind the intended character of an open proposal rather than a fully finished tool, it has consequently been accepted as a condition in present thesis that various versions of the model figure in different places. It is the hope that these differences will produce reflection rather than confusion. Below some of the major divergences – or iterative loops experienced during the work with the model – are described.

The idea of lines between the different deliveries (the boxes) placed on their respective tiers works fine for simpler buildings or buildings where a very detailed system structure of simple upstream deliveries has been omitted. This can either be due to irrelevance for the chosen focus or because they actually are opaque from the chosen viewpoint (of e.g. the architect). If a system structure contains many highly integrated downstream deliveries as assemblies (T2) and chunks (T1) their substructures of materials and components are often rather an issue of attention for the manufacturers of these deliveries than for the architect that specifies them. The lines constitute an intuitively straight forward way to follow the deliveries and their nesting. However, if all nested sub-

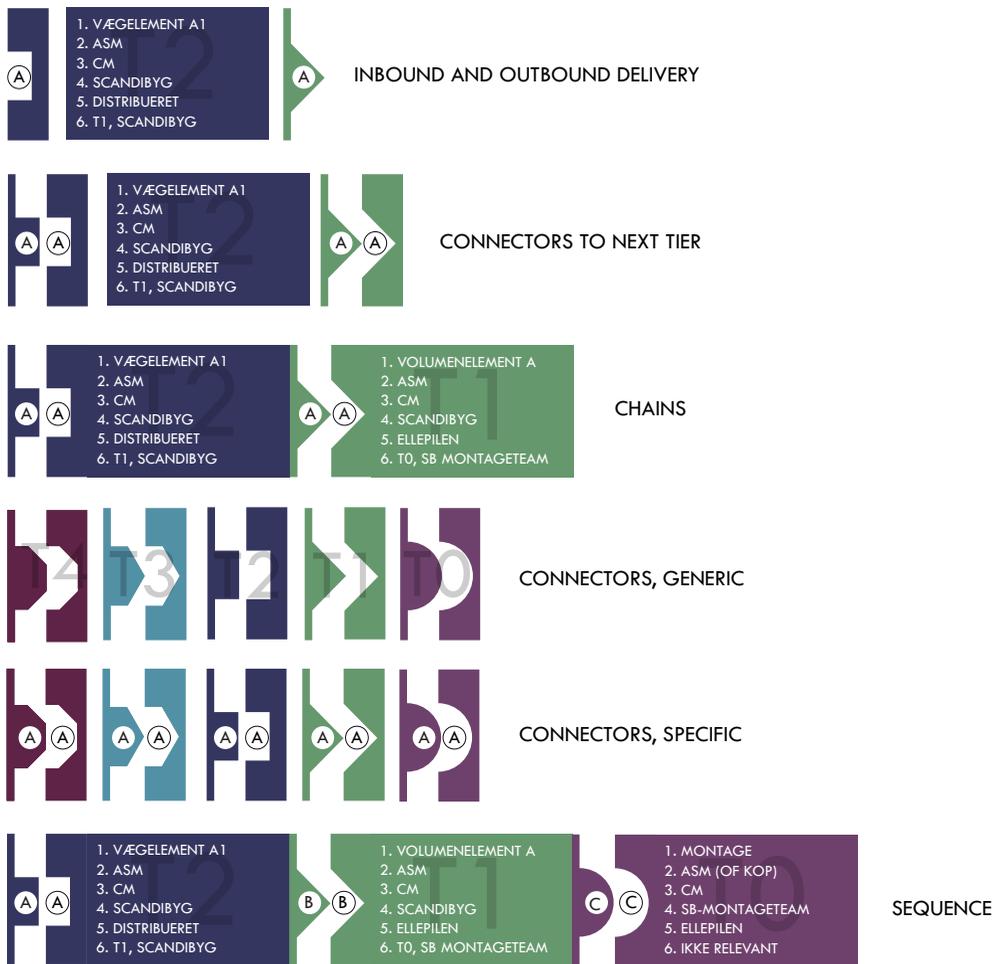


FIGURE IV.1.8 DELIVERIES AND SUPPLY CHAIN WITH CONNECTORS INSTEAD OF LINES

deliveries are to figure in the system structure – e.g. from a manufacturer or a contractor viewpoint, the number of lines (and deliveries) quickly exceeds what is easily visually perceivable. This consequently conflicts with one of the objectives of the model. In the Scandi byg case analysis, representing a manufacturer perspective, an alternative visualisation has been attempted. Here the lines have been replaced by *connectors* that by use of different geometrical interfaces indicate the receiver and the sender of a given delivery thus obviating the lines by integrating the corresponding information in each delivery (the box) itself. Figure IV.1.8 illustrates how this system works.

The connectors facilitate use of larger numbers of deliveries without losing control of the connections. The visual appearance is cleaner. The sender/receiver system however does require a more thorough scrutinising by the reader in order to understand a specific system structure.

The three dimensions of each product (delivery) have been modified considerably during the course of the thesis work. Initially, the dimension of *preparation* did not have the same one-to-one relation to the tiers of the system structure model but had its own categories (or levels). While the *standardisation* dimension is virtually unchanged except for its direction and some terminology, the service dimension is a later addition introduced to catch e.g. integration aspects of deliveries that are only sparsely off-site produced while still integrating considerable complexity – in some instances termed as *parallel* deliveries as opposed to *serial* (nested) deliveries. Not all coding found in this thesis comprise the service dimension.

T4	1. WORK PACKAGE/#	T2	2. SYSTEM LEVELS (INT/STD) 3. SUPPLIER? 4. DESTINATION (IN BUILDING) 5. WP- DEPENDENCY	T1	T0
T4	1. DRY LINING & FIRE STOPPING/3800	T2	2. ASM/OTS-CM 3. R&S DRI WALL LDT 4. CORES + BASEMENT, GROUND & 1ST FLOOR 5. WP ? 2300++2800+3700	T1	T0
T4	1. HOUSE MANAGEMENT FIT OUT/4100	T2	2. ASM/OTS-C2F-M2O? 3. SUPPLIER? 4. HOUSE MANAGEMENT 5. WP 2300+2800+3700+3800+4300+(5200)+6300+6500+7000+7400	T1	T0
T4	1. JOINERY/4150	T2	2. ASM/M2O-CM 3. SUPPLIER? 4. CORES 5. WP 2300+3530+3700+3800+4300+4550+5200+6500+6700+7000+7400	T1	T0
T4	1. TOILET CORE FIT OUT/4250	T2	2. ASM/OTS-M2O 3. SWIFT HORSMAN 4. CORES 5. WP 2300+2800+(3200)+3800+5200+6200+6300+6500+7000	T1	T0
	1. MEDIA WALL & VITRINE ARTWORK/4270		2. ASM/CM 3. JASON BRUGES STUDIO 4. ENTRANCE LOBBY 5. WP ? 3200+4550+6500+?		

FIGURE IV.1.9  
OPAQUE PARALLEL DELIVERY PO-  
TENTIALLY COMPRISING VARIOUS  
INTEGRATION LEVELS IN ONE SINGLE  
ONSITE DELIVERY. EXAMPLES FROM  
ARUP CASE.

The above mentioned parallel deliveries can in some cases simply be an expression of the traditional scenario as explained above, where delivery divisions primarily follow the traditional crafts working with upstream deliveries directly onsite. However in turnkey contractor or total consultant perspectives as the NCC and Arup cases, these parallel deliveries can also conceal nesting of highly offsite fabricated solutions that lies within contractual divisions following more product or performance based entities. These system structures break the tier divisions with deliveries comprising various integration levels in the same final onsite (T0) delivery. Figure IV.1.9 shows examples of such opaque parallel deliveries.

## LETTING GO

In the eagerness of systemising and controlling architectural design it is important to keep in mind as Meadows ironically states that:

“Encouraging variability and experimentation and diversity means ‘loosing control’. Let a thousand flowers bloom and anything could happen! Who wants that? Let’s play it safe and push this lever in the wrong direction by wiping out biological, cultural, social and market diversity!’  
(Meadows 2008:160)

Perhaps there is no need – or wish – at least from an architectural point of view to get the process of building and architectural design completely under control. This is not the same as saying that it does not make sense to understand and visualise buildings and their coming into being as complex systems of ideas (thoughts), processes and products. The model in its present and future states is a step in this direction but is not an ambition to establish an all-encompassing systems view on architecture and construction. However, the ability to handle complexity has become crucial in order not to loose architectural coherence in industrially produced architecture. What Maier & Rechting states for the systems architect (engineer) in the product industry could equally fit the building architect: ‘It is the responsibility of the architect to know and concentrate on the critical few details and interfaces that really matter and not become overloaded with the rest.’ (Maier & Rechting 2009:9)

## IV.2 SYSTEM STRUCTURE ANALYSES

- introduction to the case analyses

### INTRO

The following sections are the result of the application of the model to a number of case studies. As mentioned in the section *Method and scientific approach* in Part I – ‘Frame’, the primary case study at KieranTimberlake had at first the purpose of generating a draft for the model – a hypothesis about a *generally* applicable analytical model drawn from a *specific* study and analysis of an existing architectural project while simultaneously using the general insight gained from the theoretical and practical explorations as reflected in part II and part III. The choice of the primary case study has already been explained here.

Subsequently the model hypothesis was to be empirically tested on a number of secondary cases as analyses of the system structure of recently finished building projects. The selection of these secondary cases was chosen as to have supposed similarity with the theoretical (and simplified) scenarios developed from the first model draft. Furthermore cases were for supplementary variation tentatively chosen to represent different stakeholder perspectives concerning the building projects in focus i.e. the architect, the manufacturer, the contractor, the consultant etc.

### SELECTION CRITERIA

As discussed more generally in the section of *Method and scientific approach* the applied qualitative research design with a limited number of cases excludes any claim of representativity in the cases. Furthermore, a *supposed* similarity with the theoretical scenarios is not the same as actual similarity. However, by trying to choose cases with certain similarity with these theoretical scenarios that through the model does express variation in system structure, a preliminary assumption is that these (secondary) cases will equally express the same or at least *some* differences in the system structure expressed through the model. The different stakeholder perspectives should further accentuate this aspect of variation in the system structure. Even if this turn out not to be the

case the secondary cases would serve as an attempt to test and possibly *modify* the model as a hypothesis of a generally applicable model as stated earlier. Alternatively the model could be rejected as lacking any or at least significant explanative power within the studied field – industrialised architecture and the transition from a more traditional craft based approach. The exercise of the following analyses is thus *primarily* to test the model and its usefulness and *secondarily* to actually bring out interesting features from the specific case analyses. This prioritisation is due to the explorative stage of the current research and the model development.

The secondary case studies were carried out as shorter compressed versions of the format used in the primary case study. By using the experience from this initial study many of the same advantages of this ‘on location’ study was transferred to a shorter format. The secondary case studies consist of 2-4 days of field studies in a company and dealing with a specific recently finished building project. The project was chosen as well as key individuals (informants) located before arrival through introductory correspondence. The research format included a) interviews with several key individuals involved in the chosen project b) direct access to full project material (on location) c) flexible timing of appointments with key individuals, concerning access to project material d) check-out session with clearance of proprietary issues and e) supplementary understanding of the work methods and work culture in the company by being physically present in the environment for several days.

## CASE SELECTION

The following companies have been selected, each representing their specific perspective or viewpoint and with selected recently built cases as the object of study.

- a) Company: KieranTimberlake
  - An American architectural office located in Philadelphia, USA with a special focus on industrialised construction and the use of integrated products in architecture,
  - The architect’s perspective
  - Built case(s): Cellophane House™, a prototype house made for an exhibition at the MoMA in New York and Loblolly House, a holiday home made for one of the KieranTimberlake partners

- b) Company: Scandibyg
  - A Danish housing manufacturer located in Løgstør, Jutland. Scandibyg is specialised in prefabricated volumetric elements thus representing a high degree of completion,
  - The manufacturer's perspective
  - Built case(s): The day care facility Ellepilen made for the City of Copenhagen and a large number of dwellings within a social housing programme called Almenbolig+
- c) Company: NCC Construction
  - A major Danish contractor located in Hellerup, Copenhagen. NCC is specialised in property development and turnkey contracting within construction
  - The contractor's perspective
  - Built case(s): Company House Vallensbæk (office building) and a general office building concept called DK-kontorhuse (DK-office buildings)
- d) Company: Arup Associates
  - A British building consultant (subsidiary of Arup) located in London. Arup Associates (always) integrates architecture, structural engineering, environmental engineering, cost consultancy, urban design, and product design within one (multidisciplinary) studio
  - The architect/consultant's perspective (integrated)
  - Built case: Ropemaker Place as a 'shell & core' high end office building development in London

11 See *Appendix VI.6.A - activities and work plan*

## IV.3 KIERANTIMBERLAKE

System structures of Cellophane House™ and Loblolly House

### INTRO

Present analysis is based on material retrieved at KieranTimberlake (KT) from February to May 2010. The study draws on two cases from the office. Where the primary case is the Cellophane House™, the analysis and discussion is subsequently nuanced and put into perspective by introduction of the Loblolly House as a secondary case. After short descriptions of the research design, the cases and the architectural office, two system structure models are established and discussed in relation to each other as well as concerning their relation to more conventional construction scenarios. Important to note is that the study of the primary case, the Cellophane House™, along with the theoretical studies in Part II – ‘System’ has constituted the basis for the first draft of the system structure model which is the primary outcome of the present thesis. The model is used for and reiterated through the subsequent secondary case studies. In this analysis the model is used in a partly updated state.

### SPECIFIC DESIGN OF THIS STUDY – CONTRIBUTORS, PERIOD OF TIME, LOCAL CIRCUMSTANCES

The case study at KieranTimberlake was carried out as a part time research internship. An initial visit was done at the office already in October 2008 in connection with visiting both the Cellophane House™ (CH) at MoMA in New York and the Loblolly House on Taylors Island, Maryland. The visit identified several common areas of interest through mutual introductions and discussions and provided the basis for the later internship agreement seen as a kind of research exchange specified in an official *Memorandum of Understanding* signed by both parties. Concurrently from 2007 and on, both KT-partners, Stephen Kieran and James Timberlake, and the research director, Billie Faircloth have been visiting CINARK and the School of Architecture in Copenhagen. The research design for the study consisted of a) project material studies b) project team interviews c) related projects, material studies d) related internal interviews e) external studies f) processing and g) presentations.<sup>11</sup> The project

material studies include all project documentation for the CH from competition and design development phases, press material, and professional and internal photo documentation. The project team interviews consist of six semi structured qualitative interviews with the different teams and groupings related to the CH-project. These were 1) research director (pilot interview) 2) competition team 3) design development team 4) embodied energy and monitoring team 5) principal in charge, and 6) partners.<sup>12</sup> All interviews have been recorded and transcribed.<sup>13</sup> Related project material studies and interviews were less formalised and mostly carried out as non-recorded questions or discussions. External studies were limited to one day visits to the production facilities of the principle manufacturer or assembler of each of the two projects supplemented with shorter recorded interviews. Finally presentations were held as two major sessions for the entire office – an introductory kick-off presentation and a wrap-up presentation end the end of the stay. More informal presentations and discussions were held during the period of study and mostly in relation to the interviews. At the end of the study a checkout meeting was held with the research and the communication director in order to clear out proprietary issues concerning the retrieved and the produced research material.

From the KT office, direct contributors to the study have been James Timberlake (JT), Stephen Kieran (SK), David Riz (DR), Billie Faircloth (BF), Carin Whitney (CW), Mathew Krissel (MK), Andrew Schlatter (AS), Steven Johns (SJ), Christopher Macneal (CM), Rod Bates (RB), Jason Niebish (JL), Elizabeth Kahley (BC) and Marilia Rodrigues (MR). During external visits main contributors have been from the Cellophane House™ manufacturer, Kullman: Amy Marks and Chuck [X?] and from the Loblolly House manufacturer, Bensonwood: Hans Porchitz (HP) and Paul Boa (PB). Several others have assisted in different more indirect ways. The interviews will be referenced or directly cited in the analysis using the initials of the person, the interview number, and the corresponding line number from the transcription in the format (initials/interview #/line #).

## PROJECT TYPE – DESCRIPTION OF THE CASE(S)

The main case of this thesis, the Cellophane House™ (CH) is a full size structure originally made for a temporary exhibition. It is designed as a freestanding multi-storey single family house but does with its limited footprint, deep plan, and five storeys also allude to a more urban setting as a townhouse. The Cellophane House™ is the result of a competition held in 2007 by MoMA –

12 Interview guides can be found in appendix Interview guides

13 See *Appendix VI.6.A*, Interview transcriptions

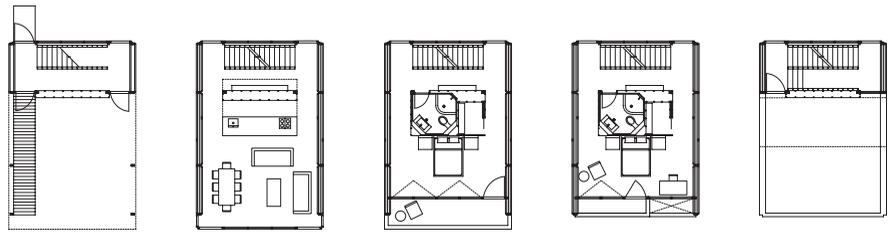
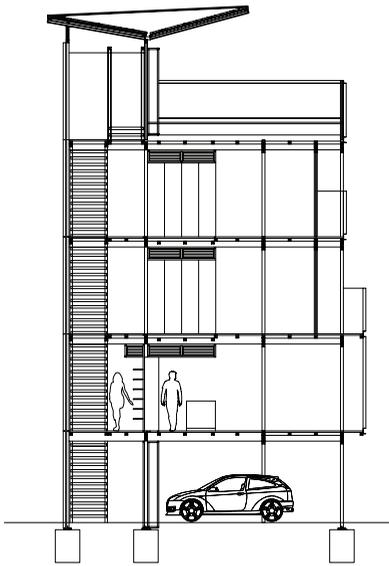


FIGURE IV.3.2  
CELOPHANE HOUSE™ - PLANS AND SECTION

- 14 See (Bergdoll & Christensen 2008)
- 15 (DR/5/40), (DR/5/55), (AS/2/57), (SK/6/89), (JL/7/40)
- 16 (MK/2/285) and (DR/5/68)

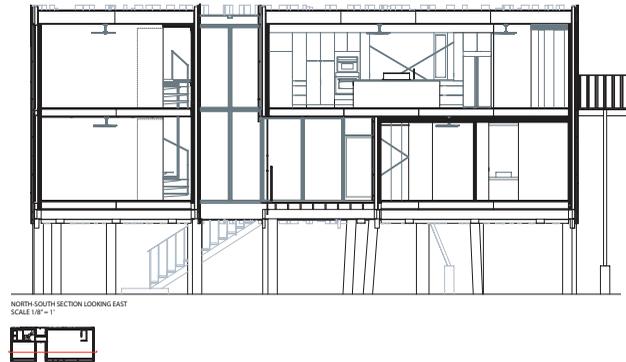


FIGURE IV.3.1  
CELOPHANE HOUSE™ AT MOMA IN NEW YORK IN 2008

The Museum of Modern Art in New York – which led to the selection of five projects, among these the Cellophane House™ (CH), which were to be built as a part of the exhibition *Home Delivery – Fabricating the Modern Dwelling* in 2008.<sup>14</sup> The competition brief asked for an off-site or prefabricated house that could be assembled in a very short period of time on a site close to MoMA in New York City. Proposals should include not only the concept of design, but also the fabrication process and a budget (DR/5/29). The CH project was explicitly designed for disassembly (DfD) thus making possible an afterlife as more than a temporary exhibition structure, and it is currently stored for possible re-assembly in a different location. Both as competition entry and final result the building draws considerably on earlier ideas and experiments from other KieranTimberlake (KT) projects and seeks to bring these a step further. Thus the *SmartWrap*™-PET film used on the façade is inspired by a pavilion by KT made for a Cooper-Hewitt exhibition in 2003 and the Bosch-Rexroth structural frame used was equally applied in the Loblolly House from 2007.<sup>15</sup> The Loblolly project is here used as a secondary case and will be introduced more in detail below. In line with this re-interpretation of earlier KT ideas another important characteristic of the building concept is the idea of mass customisation through the intended use of existing systems of more or less standardised nature as different kinds of infill applied to a robust architectural concept of a general frame – in this case the Bosch Rexroth system. This aspect has connection to the office's LivingHome project – a mass customisable marketed adaptation of the Loblolly single family house concept produced in California and marketed across the US. The aspect of mass-customisation will be treated more in detail below. Finally concepts of transparency and lightness are central for understanding the project.<sup>16</sup> Although the exhibition setup posed other requirements and gave other possibilities than had it been an inhabited structure, the CH should be understood as much more than just a pavilion. Partner, James Timberlake defines it rather as a prototype for a real house – or for a series of mass customised houses based on the same principles:

“[It was] truly and opportunity to [...] develop a program and a typology that could act as a prototype that then with a modest amount of modifications could go to production [...] the prototype gave us opportunities to try some things like applying polycarbonate floors and putting a polycarbonate stair in it that wouldn't necessarily go to production’

(JT/6/96)



The nature of prototype includes the element of test, and many unconventional materials and solutions were introduced as possibilities that can point into subsequent versions of the CH or into other KT-projects: *'There is every intention not to leave the Cellophane House™ behind but to figure out a way of commoditising it, should we have the economy and the developer/producer that is interested in that'* (JT/6/131)<sup>17</sup>. The CH can be seen as an investigation as to where current KT research efforts were at that time in a variety of projects (MK/2/67) or as taking the most compelling about some earlier ideas and pushing them into an extreme that was made possible by the competition setup (AS/2/74). The main part of the building was off-site produced as volumetric elements – or chunks - in New Jersey and came into New York on trucks.

### Secondary case – the Loblolly House

The Loblolly House is a single family detached holiday home located on a natural plot on Taylor's Island, Maryland. It was finished in 2007 thus timewise prior to the Cellophane House™. The building was conceptually conceived as consisting of five main elements – *the elements of a new architecture* in the words of the architects<sup>18</sup>. The building was partly delivered as these elements to and on the building site. Elements were:

- piling and collar beams – the interface between the irregular ground conditions and the low tolerance industrially produced building systems
- structural frame – a refinement of an aluminium frame system (Bosch Rexroth) originally applied for industrial production lines into a structural system for building construction
- floor and wall cartridges – planar prefabricated assemblies divided into 'intelligent' floors and 'dumb' walls concerning the degree of integration of different (installation) systems
- volumetric prefabricated chunks containing technical rooms and bathroom facilities and
- final fit-out as an external building skin, kitchen installation, furniture and other accessories.

The Loblolly House was, as the CH mainly offsite produced – in this case in New Hampshire by Bensonwood. The system structure analysis will include a comparison and discussion of the similarities and differences between these two projects and the way they were produced and constructed. While both have been widely off-site fabricated a major difference is the applied strategy of modularisation.

#### SECOND FLOOR PLAN

- LIVING ROOM
- DINING ROOM
- KITCHEN
- GUEST BEDROOM
- GUEST BATH
- MECHANICAL ROOM
- GLASS BRIDGE
- EXTERIOR STAIR LANDING
- SPIRAL STAIR

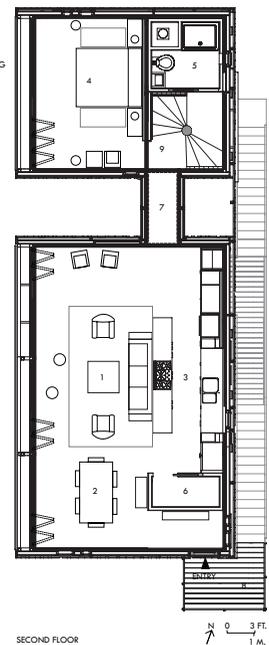


FIGURE IV.3.3  
LOBLLOLLY IS LOCATED ON A BEACH PLOT IN MARYLAND, USA

FIGURE IV.3.4  
LOBLLOLLY HOUSE – LONGITUDINAL SECTION AND PLAN OF THE UPPER FLOOR

17 The next (3rd) generation of SmartWrap™ facades was e.g. introduced in the winning competition entry for the new US Embassy in London settled in April 2010. In (Kieran & Timberlake, 2008:40f) the BIM model is presented as another way of prototyping a unique or one-off building 'benefitting from its precursor'

18 (Kieran & Timberlake 2008)

- 19 Information in this paragraph partially retrieved from [www.kierantimberlake.com/profile/profile\\_1.html](http://www.kierantimberlake.com/profile/profile_1.html) accessed on May 28, 2011
- 20 In the book on Loblolly House KT directly address this problem: *‘What if we no longer were to think backward from the first image of form so that conceiving and building could proceed in unison, not competition [...] the new tools of today promise to rejoin our processes of thinking and making’* (Kieran & Timberlake 2008:40) + *‘Thinking is the hardest part of beginning, because conceiving architecture and building it are not parallel processes’* (Kieran & Timberlake 2008:43). Andrew Schlatter from the CH competition team states: *‘We were thinking upfront about who would build this? Who could assemble it? Where would the pieces come from?’* (AS/2/167)

## THE COMPANY AND THE ZOOM OF THE ANALYSIS

The coding of the system structure models for the two cases, Cellophane House™ (CH) and Loblolly House (LH), are in this analysis seen primarily from the perspective of the architect represented by the architectural office KieranTimberlake. The office was founded in 1984 in Philadelphia by Stephen Kieran and James Timberlake and comprises today well over fifty professionals. The project portfolio includes new structures as well as renovation, reuse and conservation of existing structures with many projects for cultural and educational institutions and mostly in the US. A little unusual is that in both of the selected cases KT can be considered both client and architectural designer of the projects. Although MoMA curated the exhibition in the case of CH they were not clients in a traditional sense and it was KT themselves that disassembled and stored the building elsewhere after the exhibition. In the case of LH, the client was partner Stephen Kieran and wife. This combined with the prototype character of the CH somehow made it easier to experiment also on the contractual and procedural levels of the projects which is a special interest of the office. KT explicitly state process as the *first art* and claim to employ collective rather than singular intelligence in the making of architecture thus acknowledging the importance of interplay between architect, client and other stakeholders in the process of architectural creation. The notion of systems is used to define the creative work of the architect in the way that *‘The core acts of the architect are the creative selection, organization, integration and articulation of systems about the ideas, ideals and daily use of the inhabitant’*.<sup>19</sup> This emphasis on selection, organisation, integration, and articulation of systems rather than the idea of a detached architectural creative force or an isolated artistic conception seems crucial to KT’s approach to architectural creation at the same time being both pragmatic and innovative. This is reflected in both cases and leads naturally to an interest in production processes and supply chains. Seen in the context of the present thesis, this refers directly towards the outset hypothesis of an apparent growing distance between how architecture is conceived and how it is or can be produced. KT works consciously with bridging this gap and with using the industry, its production logic, and its systems and products as an active element in the architectural design process.<sup>20</sup>

## SYSTEM STRUCTURE – CODING AND SPECIAL PROJECT SPECIFIC FEATURES

Cellophane House™ (CH) being the primary case will be more thoroughly presented than the Loblolly House that will rather serve as comparison and background for discussion of the specific CH system structural features. The CH was organised around several individual trade contracts on several integration levels of delivery which were generally controlled by the architect, KT. Representing as the final result a bespoke design solution, the manufacturer, Kullman, did in this case not provide an integrated solution based on their particular standard systems, nor did they deliver turnkey on-site as it is often the case in other of their projects. In fact Kullman is specialised mainly in structural steel frame solutions and aluminum was new to them.<sup>21</sup> However, the competition brief's emphasis on an off-site or prefabricated house that could be assembled in a very short period of time made Kullman the primary system integrator in the system structure.<sup>22</sup> The building was thus from the start conceptualised as a series of highly integrated volumetric tier 1-chunks (T1) that were to be factory produced, transported to the site, stacked with a crane and bolted together with the use of a wrench. The idea included a similar process of disassembly where the same volumetric chunks after the exhibition were to be unscrewed, lifted down and onto a truck and relocated and reassembled in another place. The main driver for embedding most of the systems into these T1-deliveries (the chunks) at Kullman was rather dictated by the exhibition setup than the constraints of local weather conditions or other site considerations normally motivating a high degree of off-site completion. The quick on-site assembly was to be a part of the show

“*It was part of the show, yes. Particularly when you are doing a show like this it is not only about the design – it is about ideology. Half of our submittal probably talked about ideology and half about the design. This was going to be a much more public assembly and disassembly process than at Loblolly House. If we are holding ‘Refabricating Architecture’ as an example of how we should do things [...] this is the way you should do it – as chunks’*

(DR/5/197)<sup>23</sup>

- 21 ‘[For Kullman] This was a case of doing something completely one-off – completely customised – largely with systems and materials that they weren’t familiar with so this was not a case of designing for their construction capabilities’ CM/3/295
- 22 See the following Scandi Byg analysis for a similar Tier 1-off-site strategy
- 23 ‘Refabricating Architecture’ is a book published by Kieran-Timberlake describing how new production technologies are poised to transform the construction sector. (Kieran & Timberlake 2004)



FIGURE IV.3.5  
KIERANTIMBERLAKE'S SUPPLY CHAIN  
MODEL FOR THE CELLOPHANE  
HOUSE™

- 24 (Kieran & Timberlake 2008:42ff). Kieran Timberlake's supply chain model is also briefly introduced and discussed in *Method and scientific approach*, I.5 and in *Model presentation*, IV.1
- 25 The CH supply chain diagram works with two tiers both off-site and on-site whereas the earlier LH scheme had three off-site tiers. Where LH's tier 3 mainly seems to represent building materials and components and tier 2 subcontractors integrating or delivering these, this is not completely consistent. In the CH scheme 'tier 3' is directly termed materials and the tier 2 is suppliers that thus in some cases become two aspects of the same delivery as e.g. 'glass' delivered by 'Berkowitz Glass'

The building had to go up in less than two weeks and 80% of the building actually went up in only six days on-site (JT/6/377). Apart from the show aspect there was also a considerable economical incentive in minimising labour use on-site in central New York where prices are among the highest in the world.

### KT's supply chain models – and their modification

Being a bespoke solution that does not draw on the manufacturer's own standard solutions and systems did, despite the main strategy of T1-deliveries, bring the architect to focus intensively on upstream deliveries (T4-T2) that were procured directly from a supplier and not, through a contractor or, in this case, the building manufacturer. The high profile nature of the show enhanced the quest for unique and innovative materials and solutions. Although an idea was to use existing products these products were often – as e.g. the Bosch Rexroth aluminum frame system – transferred from different contexts and uses and were either applied directly or in a modified form in the CH-project. KT illustrate this procurement method of direct orders controlled by the architect in a redesigned supply-chain diagram. Accentuating a principle difference between construction and other production industries being that buildings are fastened to the ground, KT's redesigned supply chain breaks it up into off-site and on-site processes each with different tiers.<sup>24</sup>

The supply chain model was first introduced for the Loblolly House project and recoded for the CH-project (see figure IV.3.5). Interesting about this model (related to present research) is the capacity of displaying how the architect is working with materials, components and integrated systems as products or deliveries being supplied either to the building site or an off-site manufacturer. It also to some extent shows the sequencing, nesting, and combinations of these from subsystems over more integrated and complex ones to the final building. Although working with the concept of different tiers in sequence, the model does however not include the *integration level* as a consistent parameter of the different systems found in the diagrams.<sup>25</sup> Integration level would here refer to



(be defined as) the complexity of a subsystem at the moment of delivery. To use the model for this aspect is further complicated by the distinction between off-site and on-site suppliers in separate supply chains and the two have therefore been (re)joined in the system structure model applied in this thesis.<sup>26</sup> This does however not obviate the important point from KieranTimberlake's supply chain model that construction always is a combination of on-site and off-site processes and that this combination can vary considerably between projects. This is one of the reasons why in the first place it makes sense to elaborate a supply chain – or a system structure!

FIGURE IV.3.6 SYSTEM STRUCTURE OF THE CELLOPHANE HOUSE™

26 KieranTimberlake's supply chain model and its modification in the present thesis is also explained in *Model presentation*, IV.1

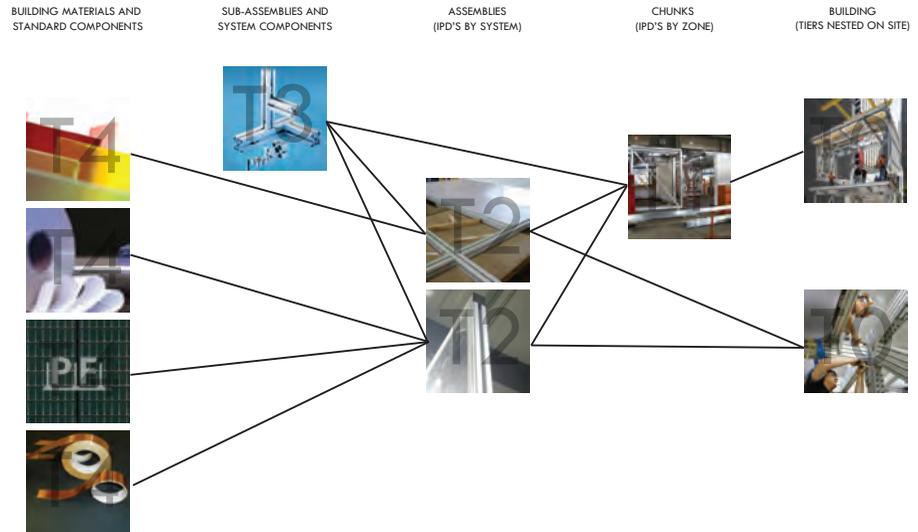


FIGURE IV.3.7  
A SEGMENT OF THE CELLOPHANE HOUSE™ SYSTEM STRUCTURE CLEARLY DISPLAYS CHAINS OF NESTED (SERIAL) DELIVERIES

- 27 The Bosch Rexroth profiles comes with standard grooves that are used for fixing and also can serve as track for e.g. sliding doors.
- 28 By weight is meant that they comprise a relatively large percentage of the total material, labour and economy spent in the project as a whole.
- 29 (JT/6/341)
- 30 Senior associate and responsible for technical review of the CH, Christopher Macneal, expresses it like this: ‘We were working with systems within systems because from very early on we were interested in [...] the Rexroth system which is a very developed system and [...] – as an intriguing part of it - embedding it in another system. That is the systems of chunks of fabrication where the connection are not simple a connection between one beam element and a column element [...] – that is already in the chunk – it becomes the next level of connection. (CM/3/58)

### The Cellophane House™ system structure

Being a smaller and relatively simple building that, although prepared for it, does not comprise the normal mechanical systems and ducting, the CH system structure contains only a limited total number of deliveries (See figure IV.3.6). At the MoMa site, no water outlet and inlet was provided and heating and cooling was considered redundant during the exhibition period (July to October). However, the simplicity is also substantiated by the mentioned conceptual ideas of mass customisation and design for disassembly (DfD) resulting in a thorough and conscious selection of solutions with simple and reversible connections and relatively high standardisation levels (OTS or C2F). The choice of the sophisticated Bosch Rexroth frame as structural system combined with custom made connectors easily accommodate the different infill systems with very little need for additional fixing solutions.<sup>27</sup> (See e.g. figure IV.3.8). Finally, the simple but non-traditional system structure can be explained by the specific focus or viewpoint in this case, the architect's, where (sub) supply chains for the more integrated (downstream) deliveries as e.g. kitchen cabinets or bathroom pods often remain opaque. While the CH thus has few tier 4 (T4) and tier 3 (T3) deliveries it also has few tier 0 (T0) deliveries on-site due to the high degree of off-site fabrication. This means on the other hand that the two integrated system levels – tier 2 (T2) and tier 1 (T1) have relatively high weight.<sup>28</sup> The T1 and T2 deliveries can be considered the primary elements – or systems – of the CH. The T1 chunks had an 80 % degree of completion upon delivery on-site thus integrating most upstream deliveries already from the factory including several of the T2 deliveries as staircase and most partition walls and SmartWrap™ panels.<sup>29</sup> Others were integrated on-site i.e. kitchen cabinets and bathroom pods (T1). Some partition walls and SmartWrap™ panels could not be factory integrated due to the specific on-site assembly sequence or the risk of transportation damage and were instead delivered to site for final fit-out. The Bosch Rexroth frame, although being the basic structural system, becomes in CH a (T3) subsystem to the chunks. This is different from the Loblolly House where the same aluminum frame system is the primary system delivered as a KOP onsite and erected as the frame for onsite infill.<sup>30</sup> Although in the system structure, the Bosch Rexroth frame is hierarchically not considered the primary system it was *conceptually* still a leading element in the competition and is far the most visually dominating element of the finished building.

## MASS CUSTOMISATION

### *Specific concepts and features*

The idea of mass customisation is as mentioned a central part of the architectural concept of the CH as well as a general goal or ‘ideology’ in the office in general. The use of the Bosch Rexroth system as the frame for mass customised infill was determined early in the competition phase, but could conceptually have been replaced by other frame systems. The idea was the frame and not the specific (Bosch) product which was rather chosen from earlier experience in the LH and the SmartWrap™ pavilion for its sophistication and elaborated accessory sample and for its obvious qualities when it comes to disassembly.<sup>31</sup> The Bosch system works in a certain scale – it wouldn’t work for high rise (DR/5/217). Having this separation between what is structure and what is not gives a lot of freedom when it comes to infill. (DR/5/235). By use of the Bosch Rexroth system as frame, the intention was to use both standard and innovative materials in a mass customisable way (JT/6/53) by hanging, placing, stretching, and bolting them onto the frame. In KT’s official press-kit the CH is described as

“[...] first and foremost, a matrix for holding materials together in such a way that they create an inhabitable enclosure. The critical term here is holding, as opposed to fixing. Materials that are held are allowed to retain their identity as discrete elements, and can be released at any time. Materials that are fixed to one another can be freed only through the expenditure of great amounts of energy. The actual materials are, in a sense, irrelevant: it is the manner in which they are joined together that defines the essence of a structure.’

(KieranTimberlake press-kit 2008)

As the economy and realisation of the project was partly based on donations from different manufacturers, KT also used the occasion to apply the CH as a kind a showcase for some of the more innovative vendors they had used in the past (DR/5/59). The very short amount of time for both competition, design development and production also demanded going with already existing and easily cut-to-fit products (SJ/3/124). Thus the specific accommodation of materials in the frame became in a way mass customised where, as partners came on board, the design development team would tweak the design to accommodate their system or product (DR/5/109). The slightly odd building site



FIGURE IV.3.8  
THE GROOVES OF THE BOSCH REX-  
ROTH PROFILES SERVE THE SLIDING  
DOORS OF THE NORTH FACADE

- 31 A steel frame system would often be welded and thus harder to take apart for reassembly

for a detached single family house enhanced the CH's aspect of – as a prototype – being a broader non-site specific platform. This is very different from the Loblolly House project that, although drawing on similar ideas, is the specific result of a specific site (JT/6/62). Still, (according to principal in charge, David Riz), there could have been a more rigorous systematising of the components having probably too many one offs (DR/5/383). One of the lessons learned in the CH concerning mass customisation in construction could be the idea of adopting off-the-shelf (OTS) materials and components (T4 and T3-deliveries) from some other use to create new integrated systems for a different application (AS/2/415). The Bosch frame, developed for industrial production line facilities, combined with the custom made steel connectors is the prime example but others as the honeycomb polycarbonate staging panels used for flooring or the PET film as base material for the integrated SmartWrap™ panels are equally adaptations from other contexts. However, it is also possible that systems that are more systematically developed directly for architectural use could be applied – as long as they are flexible enough. There are probably aspects of building that would benefit from being treated like appliances that the architect could specify within a known system. In fact this is already the case within e.g. mechanical building systems (CM/3/211).

#### *Design for Disassembly – and for reassembly*

The Cellophane House™ to some extent directly tackled the question of design for disassembly (DfD) as part of the originating design concept. Choices of materials, systems and design solutions were thus to a considerable extent dictated by their ability to be disassembled (JT/6/77). The disassembly of the house was as integral an experiment as putting it up in the first place (BC/7/235)

“One of the things that I concentrated on in this proposal was the system in terms of how things were assembled – how the Bosch was integrated – these plug/unplug, wrap/unwrap – this idea of reversible construction and mechanical connections – design for disassembly with off-the-shelf pieces’

(AS/2/408)

The idea was on the one hand that the CH would have zero waste at the end of its useful life by being integrated into different recycling streams. On the other hand the idea was also that, before reaching this state, it would have a second or multiple afterlives as reassembled in another location and used for



FIGURE IV.3.9  
EXAMPLES OF LABELS AND CODING  
SYSTEM USED FOR THE DISASSEMBLED  
COMPONENTS

another purpose. Hence, design for reassembly was equally an issue – a little different from the DfD. This led to the unusual exercise of designing the *disassembly* process (JL/7/77) and although the idea was planted from the outset and to some extent already was integrated into the design at competition and design development level, a special DfD team was assigned the specific task of getting the house down by the end of the MoMA exhibition. The overall task was ‘*how to get this building down as fast as possible with the least amount of waste for the least amount of money*’ (JL/7/84). Several strategies and scenarios were at stake: One was to sell it, take it down as the factory produced chunks it was made of, ship it to some other location and reassemble it directly. This required a client willing to buy the building as a whole. Another strategy was to partly or completely dismantle the building into its components and materials that could then be sold as discrete elements for use in other contexts, and finally the building could be recycled as materials each one going into its specific stream. The latter option did not seem ideal for a house that had only been in use for four months (DR/5/264). Although there were negotiations, at the end the house was neither sold as complete nor by parts. The cheapest thing would have been just to rip the building down, demolish it, and sell for scrap but maintaining the intention of disassembly alternatively it was decided to store it for possible later reassembly (JL/7/80).

32 The notion of ‘family’ used by the disassembly team (BC/7/205) corresponds closely to an organisation and delivery of an assembly ‘by system’ rather than ‘by zone’ as defined in *Systems terminology*, (II.5)

The transport and storage circumstances ended up dictating how the CH was disassembled as KT couldn’t afford shipping chunks out of New Jersey and the storing as chunks (T1 volumetric elements) (JT/6/230). A factory disassembly which would have solved some craning and weather issues on-site was equally beyond the budget. Instead of loading 15 flatbeds – one per chunk – the house was, with some exceptions, dismantled onsite into the smallest possible parts and packed like a ‘Swiss watch’ (DR/5/149) on only four flatbeds and a closed tractor trailer used for the more sensible parts. Every flatbed that got out of the equation not only saved the money to get the flatbed there but also to get it out and to store it. First, however, the building was brought to the ground as chunks and this was done in only four days (JT/6/283). In order to combine efficient packing with keeping track of the many parts for later reassembly, the disassembly team developed a consistent labelling system including a packing ID for all the parts which were then packed by family of item so that e.g. all the Bosch Rexroth framing got on one flatbed. (See figure IV.3.9).<sup>32</sup> The Bosch Rexroth and the Varier-panels used for the interior partition walls were delivered from the factory with ID-numbers – systems that had its root already

- 33 The bahtpods were e.g. taken apart.
- 34 See also (CM/3/338): *‘[I]t was designed to have a specific relationship between the parts – a specific configuration. It could have been designed to reconfigurable but that wasn’t part of the process’*
- 35 The 98% recovery is a measure from the embodied energy analysis. It does however give a good idea of the material proportion that was recovered

in the BIM-model used in the design development phase – but everything else had to be done from scratch and after-the-fact while the building came down. A logical next step for subsequent projects including a systematic DfD would evidently be to apply such a labelling before the building goes up in the first place (BC/7/235). That would require the DfD to become a more integrated part of the design development phase. From an estimate of three days for labelling it took the team five weeks while simultaneously packing all the parts. Although most of the building was brought down to its original T3 and T4 deliveries, that even in some cases until then had been opaque for the architect as integrated in T2/T1 deliveries<sup>33</sup>, some elements were retained as assemblies: The SmartWrap™ panels, the polycarbonate partition walls, part of the balconies and the staircase. The latter were the heaviest individual components in the buildings and were neither designed to stand on their own nor to be brought down to component level. The stairs were braced, lifted with a small forklift and placed on the back of a drop deck flatbed. All five stair assemblies were shipped whole. A few items had to be scrapped. The roof and gutter flashing and the 3M-double sided tape joining the partition walls came easily off the panels but could, as non reversible attachments, neither be reused for reassembly nor for recycling. A couple of other items were also damaged by accident during the process. Finally 30-40 percent of the bolts had to be recycled as metal because they either got stripped during the assembly or the disassembly process (JL/7/451).

Another revelation during disassembly was that even if the building was to be reassembled in another location it would have to come completely apart first. The bolts used in the first case were normal black oxide hardened steel bolts and would – although working fine for the exhibition – not withstand a longer period on e.g. a beach in California. Depending on where it would be going up some of the elements would have to change (JL/7/139). Although reselling by component was one of the re-use scenarios the CH was not explicitly designed for reassembly in other configurations than the CH itself. At the T1-chunk level, different combinations are not possible (BC/7/261).<sup>34</sup> However, T2-floor, -wall or -partition panels as well as most T3 and T4 deliveries could potentially be reconfigurable as parts in other buildings. Figure IV.3.10 is an attempt to elaborate a system structure expressing how the CH through its disassembly was brought back to varying system levels. Disassembly does not necessarily mean to disassemble all the way back to (raw) materials (MK/2/474). Certain integration levels of delivery that can still be appropriate for other use. Other things will have to be scrapped. In the case of the CH, 98% was recovered for direct reassembly.<sup>35</sup>

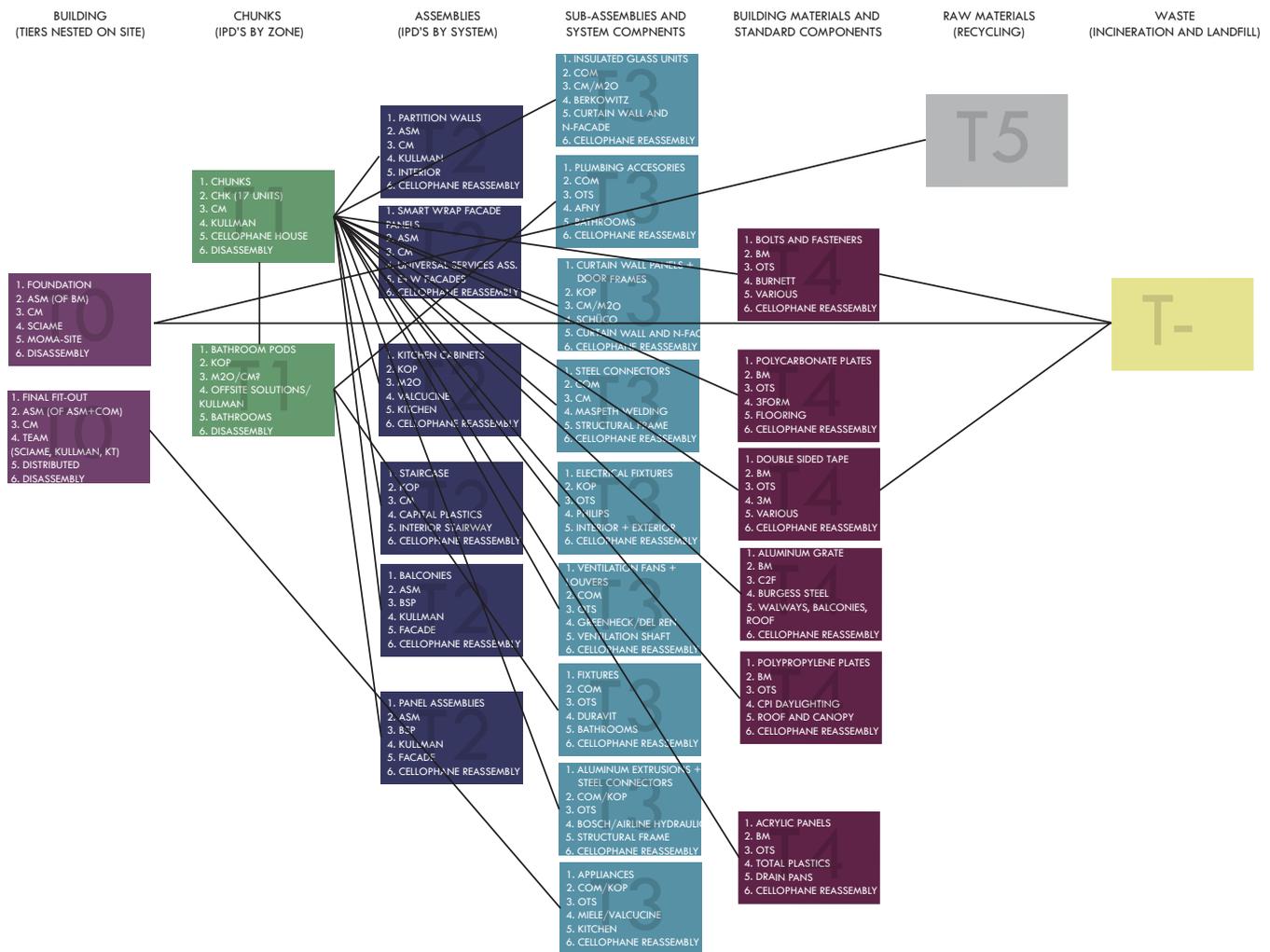


FIGURE IV.3.10 CELLOPHANE HOUSE™ SYSTEM STRUCTURE OF DISASSEMBLY, SKETCH

The disassembly process and the specific design of it contributed to a general awareness of issues concerning transportation, different environments at different locations, and inevitable wear and tear (BC/7/127). If the design mandate for a project is rapid assembly and disassembly then materials must be evaluated based on that criteria which also includes the criteria of durability and weatherability (BF/4/145). Water proofing details in particular seem hard to solve as ‘dry’ connections that can easily come apart – and together again – without producing waste. Another material criteria in question is that of embodied energy which will be treated more in detail below. If rapidly disassemblable structures e.g. meant for short or temporary use include materials high on embodied energy – as e.g. aluminum – then their potential afterlife on different system levels become more critical than if rapidly renewable resources with low embodied – as e.g. wood – are used. DfD can work as a special kind of design driver that however will be more relevant in some cases than in others depending on the purpose and lifespan of the building in question. Evidently it is harder imagining a disassembly process fifty years down the road, but

- 36 This distinction is forwarded by Stephen Kieran in the example of the staircase which is classified as construction rather than assembly (although still constituting an assembly in the building)
- 37 See e.g. [http://en.wikipedia.org/wiki/Embodied\\_energy](http://en.wikipedia.org/wiki/Embodied_energy) accessed on May 28, 2011
- 38 *'[On] the issue of carbon vs. energy part of the challenge is that different countries have different fuel sources – if you are doing something in France it is a lot of nuclear energy – your energy amount will be constant but your carbon will vary. That is why we prefer to do both because it allows you to say that if you deploy it in a different context you can change those energy figures depending on the local 'flavour' of production.'* (RB/4/64)

CH made it possible to test many ideas connected to a more general strategy of DfD. Again, as with the question of off-site/on-site, a DfD-strategy whatever general it might be will always need adjustment and adaptation to each specific project and its specific context. The issue of embodied energy underlines this need for project specificity.

### *Embodied Energy*

One of the main rationales behind the strategy of assembly vs. construction in the CH is that from an environmental point of view it is better to disassemble and redeploy because you are preserving embodied energy as opposed to scrapping and starting from new (RB/4/30).<sup>36</sup> For the CH-project, the KT research group worked specifically with assessing the embodied energy. The concept, however, is difficult to define and delimit in an at the same time both meaningful and operational way. Conceptually, embodied energy can be defined as the energy used in the work to make a product, bring it to market and dispose of it at the end of its useful life.<sup>37</sup> This definition relates it closely to the concept and the techniques of life cycle analysis (LCA). In practice however, in order not to end up trying to count the grains of sand on the beach any method of accounting for embodied energy needs to focus on particular parts of the life cycle. Furthermore, even when analytically isolating parts of the life cycle for doing an embodied energy analysis of a product or its materials, the results depend heavily on the specific location where the processes and thus the energy use take place. Seen e.g. from a carbon perspective, although energy use might be determined for a process, the related carbon emission can vary considerably.<sup>38</sup> This means that amounts of embodied energy are difficult to compare *between* projects on an 'apples-to-apples' basis both concerning energy amount and environmental impact. However, the overall goal mostly being to reduce energy use still seem to make embodied energy (EE) – and the different way to grasp parts of it – a useful concept to work with.

For the CH, the KT research group ended up drawing the line as looking at the energy applied from resource extraction to factory gate (RB/4/74). This means that the applied EE-analysis does not account for any assembly of the components but exclusively look at the production, provision and (possible later) disposal of the raw materials that are used in these components and assemblies. This choice was mainly defined by the data and the tools available within a reasonable budget, time frame and work effort. By using the elements from the Revit model and literally weighing the physical parts as they came down during

disassembly a dataset was created and combined with material information from a CES material selector.<sup>39</sup> This, of course, yields the question of utility of the results: The research team explains that the value of the analysis lies in the fact that the CH – as well as to some extent also the Loblolly House – is designed for disassembly and reassembly. The results of the EE-analysis can be used to complement the design for disassembly strategy with a value of recycled embodied energy (BF/4/116). Disassembly requires, as mentioned in the previous paragraph, materials that can withstand that type of use and those materials come with certain burdens of EE (RB/4/121). The Bosch Rexroth aluminum frame e.g. has an enormous amount of EE but at the same time it is highly durable, reusable and recyclable – both in the CH, as profiles and as raw material thus in a way amortising that EE over the life of the building, and concerning the possible afterlife of the specific components or the material (DR/5/55). The EE-analysis documented that 98% percent of the material EE was recovered for reassembly (BF/4/270). What was lost could mainly be assigned to the concrete pad casted onsite, the flashing and tape, and the damaged bolts cf. above.

The EE analysis was done after-the-fact during disassembly and was in this sense not directly informing the design development and assembly phases for the CH project. For KT and the research team, however, the EE-analysis is itself also seen as a prototype and a test of the applied concept of assembly, disassembly and reassembly in the CH (and Loblolly House) project(s) (BF/4/33). It has to be understood as the first in a series of iterations moving towards refinement (RB/4/299). An important discovery of the analysis is that the deployment of weight is huge a factor – lightness as a design criteria has considerable significance when it comes to EE.

“*I had never seen data backing up this understanding of lightness. It [...] reconfirms that you do want to know how much a building and the components weighs and that weight actually matters. The stronger lighter perhaps more high intensive energy components at the end of the day ended up being better from an EE standpoint than a low intensity energy manufactured material that is used everywhere.*”

(BF/4/187)

However, while EE is important to consider, a project can end up being driven by other design considerations with equal or more importance. Basically the EE analysis gives another layer of data to qualify building designs but it will

39 The CES material selector provides capabilities for rational materials selection and for plotting and comparing engineering, economic, and environmental properties. The tool and database is developed at University of Cambridge, UK – see. e.g. <http://www.grantadesign.com/products/ces/> accessed on May 28, 2011

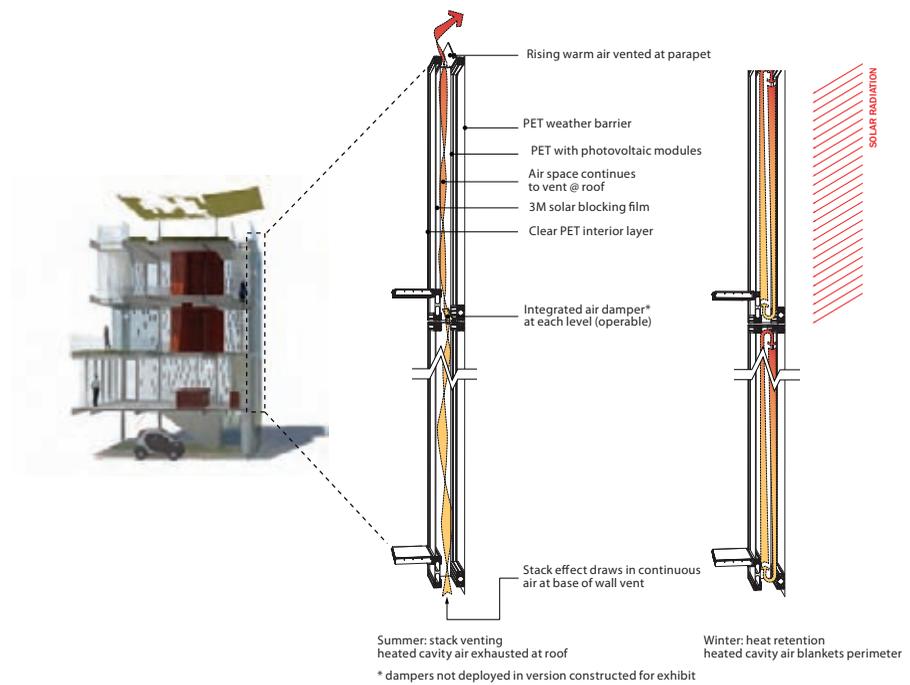


FIGURE IV.3.11  
STACK EFFECT IN THE FOUR-LAYERED  
VENTED CAVITY FACADES

never be the primary design driver. While the CH project is explicitly looking for recovery of EE through materials with capacity for reuse there is another important issue in cases where this recovery is not going to take place. Re-use and recycling – into different waste streams – as two different strategies do not necessarily yield the same results (RB/4/551).

### Monitoring

Apart from the embodied energy analysis that was closely related to the fact that the CH was designed for disassembly, the KT research team also performed a building monitoring programme that draw considerably on experience from a similar programme in the Loblolly House project. Both embodied energy analysis and building monitoring are processes for providing feedback which is a central and desired attainable thing that KT uses to go forward in order to determine whether or not there is validity in earlier made design assertions (BF/4/356 & RB/4/369). Focus was in the CH-case limited to the performance of the two (east and west oriented) SmartWrap™ facades that as four-layer vented cavity facades (a double exterior and a double interior layer) already in the competition entry was claimed to have both insulating qualities and providing thermal stack effect for ventilation during peak sun exposure. (See figure IV.3.11)

Although again being a post fact analysis for the CH (a opposed to a simulation) and therefore difficult to use as input directly informing the design process of that building, the produced dataset did produce new knowledge about the chosen form, the material and the design of it – it actually explained the form being different from what had been expected and intentioned from the outset. This knowledge can directly be applied to subsequent projects. The dataset gave information about the performance of the vented cavity and allowed an enhanced understanding of the PET-material used in the SmartWrap™ panels (RB/4/442). While air pressure, temperature and wind speed in different locations of the cavity were expected to show a stack effect particularly building up during peak sun exposure – as typically known from e.g. double glazed façade solutions often used in high-rise buildings – it actually turned out that less rigidity of the PET-film compared to e.g. glass broke this effect



FIGURE IV.3.12  
CITÉ RADIEUSE IN BERLIN BY LE COR-  
BUSIER. THE SUPPOSEDLY ULTIMATE  
MACHINE FOR LIVING

and produced a pressure and temperature equalised environment with minor turbulence inside the cavity. On the other hand the four layer design integrating a 3M infrared absorption layer on the exterior side of the cavity was able to considerably reduce the heat gain and combined with good possibilities of cross ventilation through north and south facades there was no problem of overheating. Both interior temperature and humidity was actually quite pleasant (RB/4/498) with no need for mechanical air-conditioning inside the building. This, of course, can only be concluded for that particular period of time (summer) and that specific location (climate and site) but it still gives valuable feedback on a general (system) level that can be used in subsequent projects.

Although some monitoring have been done in previous projects – like e.g. in the Loblolly House – the monitoring programme and feedback from the CH helped to get focus on this aspect as a supplementary design driver and there is now a greater push at KT towards monitoring all the projects as well as integrating the monitoring design earlier in the design process (RB/4/520). Again, although important, there are many other considerations that give a project direction and monitoring programmes and their results will never be the primary drivers for design.

### *Prototype vs. house*

The claimed status of the CH as a prototype is quite unusual in architectural design. Buildings designed by architects are – contrary to most industrialised production with designers involved – mostly one-offs. Buildings are generally project and site specific and repetition on building level is often limited to take place within the same project as additive structures of equal or similar building units.<sup>40</sup> The building-as-a-car or *machine for living* as envisioned by the modernist movement has never truly had architectural success (See figure IV.3.12) Although many housing manufacturers or builders work with standardised schemes, techniques and processes their process of optimisation is rather directed towards economical efficiency, price stability, and technical quality on component level than towards systematic development and refinement of an overall architectural concept. The notion of prototyping – if used at all – is for actual *products* mostly limited to the integration level of components (tier 3) whereas prototyping for *projects* in some cases can include more integrated solutions as e.g. façade systems, complicated joint details or fully outfitted spatial cells (tier 2 and 1). Product development through prototyping is, to use another word, only little used in relation to architectural wholes (tier 0). This has of

- 40 *The structuralist movement* in architecture in the 1960's represented e.g. by architects like Herman Hertzberger is an emblematic example of such repetition used within the same building project. In general, cellular building types like hotels, hospitals, dormitories and some office buildings also make use of repetition – but again mostly on project level.

course partly to do with a construction economy based on discrete projects, but also relates to the fact, that buildings are *conceived* and *perceived* as one-offs that do not, in an architectural sense, draw substantially on any system level that exceeds the project level. If they happen to do, this is rather considered a lack of architectural ingenuity than the contrary. What constitutes the *system structure* of a building is traditionally not considered an object of architectural interest and design effort. KieranTimberlake look differently at this aspect and, as mentioned above, explicitly considered the CH to be a prototype – the occasion to build a real house that due to its specific condition of not being inhabited in the first case made it possible on the one hand to test innovative solutions, materials and – not least – the processes and, on the other hand, made possible to downplay investment in terms of technical infrastructure

” *We didn't have the demands in terms of infrastructure – in terms of mechanical, electrical and plumbing infrastructure. We designed it to have chases and things like that – but we discussed that if somebody bought it and we had to make it work it would take some time on our part to integrate those systems that we speculated upon but didn't have to provide*  
(DR/5/84)

Although codified as a temporary exhibition pavilion – not a residence – the building still had to meet New York City code requirements e.g. for safety (DR/5/89) and the idea was always that this could be a house that someone could live in. The practical aspects were thought through, provided for, but not executed (AS/2/259). During design development it also ‘*morphed into [...] a study or investigation in logistics – how do you get the products to the site? Where are they fabricated? And how do they get installed?*’ (SJ/3/47). This focus on (production and construction) process is characteristic for KT and enhances the nature of the CH being a provocative design statement using familiar materials in some less familiar ways. The prototype character should not only be understood on building scale or level. KT often make component mock-ups in the office’s workshop and there is a general wish of getting more iterations in the prototyping and trying to prototype and model assemblies (CM/3/616). Another way of enhancing the number of iterations of a building thus bringing the making of a building back into or at least closer to the design phase is through use of BIM and 3D-modelling, where the building is put together in a virtual model, which can also be seen as a kind prototype that can furthermore provide direct and complete information for production

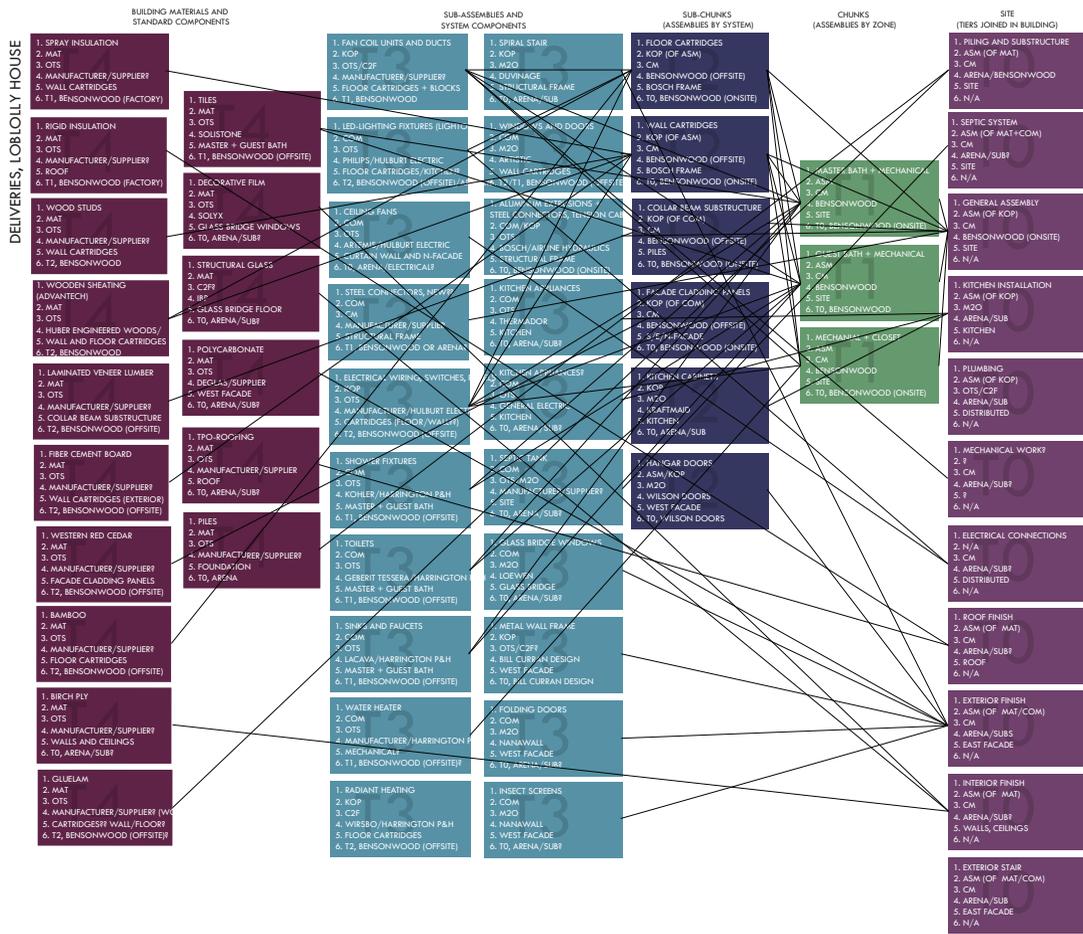


FIGURE IV.3.13 THE SYSTEM STRUCTURE OF THE LH

without having to do tedious translations between different kinds of drawings and documentation material. BIM-modelling was to some extent applied in both the CH and the LH projects.<sup>41</sup> However, BIM being still in embryo there are differences between how BIM application in construction is discursively constructed and how reality is. The divergence between on the one hand the articulation in media of the CH in particular and offsite production in general and on the other hand how things are actually produced is often considerable (vision vs. reality).

41 For a discussion of BIM as bringing closer *thinking* and *building* see also (KieranTimberlake 2008, 40ff)

**Prefab as high end/low end/single family or?**

The MoMA exhibition did apart from the CH and four other full size buildings also include a historical review of pre- or off-site construction and could be seen as a promotion of this kind of buildings. The competition brief had a cost stipulation inviting proposals to be applicable not just for high end housing (AS/2/36). However, the principal in charge of the CH, David Riz, does not think that a show like MoMA's changes people's minds about prefabrication. The five full size projects selected by the curators were rather selected for their different artistic and formal expression than for their innovative approaches to the question of off-site fabrication (DR/5/293). They were somehow detached from the general preconception of this way of producing buildings. Off-site fabrication is almost exclusively a typology limited to a low end fragment of the single family housing market and although the CH pointed towards use in other contexts it is,

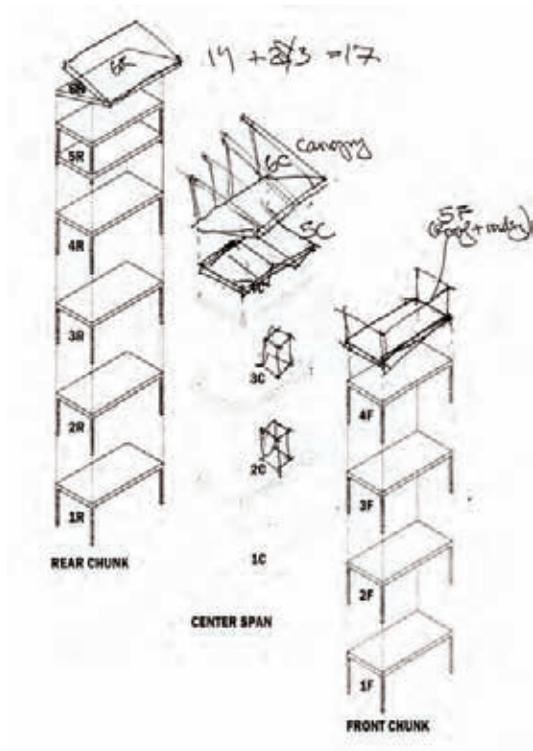


FIGURE IV.3.14  
THE DIFFERENT CHUNKS OF THE CH  
(WITH AUTHOR'S ADDITIONS)

- 42 *System connections* is one of the three interface types mentioned by KieranTimberlake in 'Refabricating Architecture'. The others are *connection joints* and *closure joints*. (Kieran & Timberlake 2004)
- 43 'We were very consciously doing something and taking a different storyline or a different narrative of the assembly' (MK/3/251) – See also (MK/3/410)

at least in the US predominantly a suburban idea (DR/5/279). This is very hard to change. Most people see prefabricated housing as low end and have negative connotations to it as trailers and the like. On the other hand, a small high end segment sees it as a way of getting high quality one-offs just like buying expensive cars. Prefabrication has a strong filter of social class which is a little like for high rise dwelling towers which are either midtown high end condominiums or low end social housing while the middle class is somewhere else (DR/5/319).

#### *Cellophane House™ vs. Loblolly House - degree of prefabrication*

Some significant differences between the Cellophane House™ (CH) and the Loblolly House (LH) can be explained from a system structural perspective. One particularly important is the difference in the final on-site delivery from the main manufacturer – respectively Kullman and Bensonwood. The two projects represent considerably different strategies of modularisation which can be illustrated through their different system structures. Where LH has certain chunk idea (T1), the CH goes much further into that realm (DR/5/159). In the LH, the chunks – here called *blocks* by the architect – are limited to the most system-intensive spaces such as bathrooms and mechanical rooms whereas other spaces are made through on-site assembly of panelised (T2) floor and wall assemblies called *cartridges*. Both blocks and cartridges are in the LH inserted into a (T3) prefabricated but on-site assembled version of the Bosch Rexroth frame – here termed the *scaffold* – delivered as a kit-of-parts. Despite this reduction in (T1) chunk deliveries, the LH still has a relatively high degree of off-site system integration due to the nesting of wiring and mechanical systems into the floor cartridges that are delivered as assemblies (ASM) with 'plug-and-play' system connections.<sup>42</sup> The wall cartridges are less system intensive thus introducing a further distinction between smart and dumb cartridges (DR/5/168) – both to be considered as T2-deliveries.

In the CH on other hand the nesting of upstream deliveries (T4-T2) into the chunks (T1) is deliberately maximised with one of the only limitations being the earlier mentioned transportation and on-site assembly issues that resulted in on-site assembly of some few of these.<sup>43</sup> The (T3) Bosch Rexroth frame, again delivered as a kit-of-parts but this time to the factory, here becomes a

sub-element – although the primary one – of the (T1) chunks. Flooring, partition wall panels, SmartWrap™ exterior wall panels and other more or less upstream deliveries are fixed to this frame on chunk level in the factory.

” *‘We were working with systems within systems because from very early on we were interested in embedding [the Bosch Rexroth system] in another system. That is the system of chunks of fabrication [...] we were both engaging with and getting around or tweaking the rules of one system to make it work as part of the greater system – the modules [or chunks (ed.)]’*  
(MK/3/58)

One of the main reasons for the (T1) chunking strategy applied for the CH was, as mentioned earlier, the extremely limited period of time for the on-site assembly and the site constraints such as difficult access and only little space for laying out construction elements.<sup>44</sup> Where the CH is thus mainly assembled onsite as chunks ‘by zone’, the LH is mainly assembled on-site as assemblies ‘by system’ supplemented with other systems constituting the proposed *elements of a new architecture*: a) the piles and collar beams, b) the structural frame, c) the floor and wall cartridges, d) the blocks, and e) the final fit-out.<sup>45</sup>

Both time, economy and site constraints were not as critical for the LH project where, although the vision was equally here fast onsite assembly based on a high degree of prefabrication, the intention was also to examine possible new divisions in construction – the elements of a new architecture, as explained above. LH was put together in rural Maryland where labour and rent of equipment is cheap and KT had a fixed fee contract with Bensonwood (DR/5/191).

” *‘Largely you have to make a decision first about [on-site] time before you make a decision about tactic. If time is critical generally speaking the more you do off-site the faster the assembly on-site will be. [...] On Cellophane House™ time [on-site] was a huge premium [...] Whereas [for] Loblolly House time wasn’t such a premium and be there 6-8 weeks onsite was acceptable’*  
(SK/6/378)

In many ways the conceptual division of constituent elements in the LH project seems clearer and more ‘innovative’ than for its successor, the CH, where other foci such as the design for disassembly and mass customisation perhaps had

44 See also (CM/3/254) and (JT/6/390)

45 For an explanation of the distinction between assembling ‘by zone’ and ‘by system’ see II.5

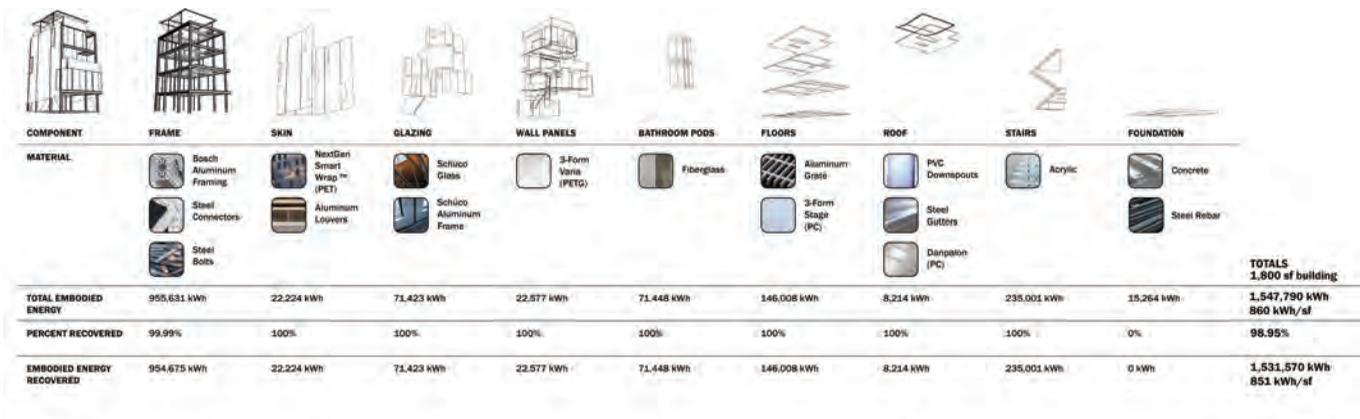


FIGURE IV.3.15  
WASTE STREAM ANALYSIS FOR CH

- 46 By-system-entities (T2) as subchunks to the by-zone entities (T1) – a chunk idea with embedded systems
- 47 See also (BF/1/167) concerning the project specificity of prefabrication strategy

more attention. Design for disassembly was also claimed to be an integral part of the LH. However, if disassembled for *reassembly* the LH would have to stay mainly on the level of T2-deliveries. If cartridges and blocks were to be brought further apart as the original T3 and T4 deliveries many of the elements would lose their reassembly capacity and consequently the reclaiming of these would be reduced to recycling into their respective waste streams. A recycling scenario into different waste streams was analysed in detail by KT for the CH, not the LH (See figure IV.3.15).

#### Off-site vs. on-site

Learning from the two different projects described here a next version of the CH or another similar project that would have to be fully functional also concerning mechanical systems could be a hybrid of the two strategies ('by zone' and 'by system') using the (T1) chunking system as the primary while each of these chunks could contain different nested and perhaps easily disassemblable (T2) deliveries that could be connected as distributed systems through 'plug-and-play' system connections between the chunks (DR/5/172).<sup>46</sup> The appropriateness of such a hybrid strategy would of course depend on the nature of the specific project and the demands during the on-site assembly process. A challenge always is defining how much can be done off-site vs. on-site. Each project, given its local conditions like labour rates, union issues, and site constraints combined with material choices and timing, offers specific possibilities (MK/2/304).<sup>47</sup> An important point is that at a certain point off-site construction or prefabrication always has to meet the site and here lies some of its complexity. Although in some cases manufacturers do turnkey solutions, most often – and particularly for one-off solutions like the LH and CH - there will be an interface between a fabricator and an assembler. If a building is off-site manufactured in a location that is distant from the site it will often be the most desirable to have a local assembler who knows the code and have a local network in order to organise the process on-site. However, because there is so little experience in defining and managing this interface both contractually and practically, KT for both the LH and CH had to play an active role as facilitator between those two sides and even sometimes lending physical help (DR/5/350). Another issue adding to this perspective is that where many of the T2-deliveries (cartridges, substructure and façade cladding) and all the T1-deliveries (bathrooms and mechanical rooms) of the LH came from the same manufacturer, Bensonwood, these could, as discrete deliveries by system integrated on-site, theoretically have been produced and supplied by different entities.

However, as the standardisation level of these integrated systems was low, the need for coordination between such potentially discrete suppliers would have become a considerable task for the architect acting as facilitator.

The fundamental flaw that most make with off-site construction is, according to partner James Timberlake, that they design something first and then subsequently try to take it apart in order to produce it. This is difficult and inexpedient due to the important link and interdependency between process and result (JT/6/394). The problem – as pointed out in Part I – ‘Frame’ of this thesis – of bridging the gap between how architecture is conceived and how it is or can be produced again shine through as a specific interest of the KT office. People apparently aren’t willing to invest upfront time in learning how to take buildings apart (or put them together). They want to have one single method that trumps every aspect for every imaginable solution (JT/6/406) – one single optimised way of off-site delivery. This is not possible. The balance between different aspects and different degrees of off-site vs. on-site solutions will always be project specific and therefore needs to be integrated from early design phases as part of the architectural design itself. This is an important feature of both the LH and the CH.

## INTEGRATED PRODUCT DELIVERIES – EXAMPLES & INNOVATION IN COMMODITISATION

### *General*

As introduced above, the CH and the LH projects represent different ways of modularisation and different balances between off-site production and on-site construction. The system structure model enables the establishment of a conceptual distinction between two principle forms of integrated product deliveries: the T1-chunks ‘by zone’ and the T2-assemblies ‘by system’ and although the two buildings are not clear versions of one or the other they do, as mentioned, have a bias towards this. While a range of T2-deliveries combined with few T1-deliveries dominate the LH scheme of (T0) on-site assembly the CH is characterised mainly by its T1-chunks arriving to the site with the T2 deliveries nested already from the factory. As a special feature of the CH, these T1-chunks are based on the concept of mass customisation that by nesting a considerable amount of standardised ready-mades (OTS or C2F) on T4 and T3-delivery level into the T1-chunk makes the concept more open to changes over time or in different versions while reducing design complexity in each case. The CH is a prototype of a building while the LH is a one-off building.

The idea of accommodating existing products as direct deliveries (with high standardisation levels) is far more prevalent in the CH than in the LH and further enhances the need to take into account already from early design phases the way the building is divided up into elements and put together. However, only few standardised products are used on the more complex T2 and T1 levels. In the LH e.g. the cartridges, substructure and façade cladding panels are all bespoke (BSP) whereas the hangar doors and the kitchen cabinets are made-to-order (M2O). In the CH staircase, partition walls and SmartWrap™ panels are bespoke (BSP) whereas bathroom pods and kitchen cabinets are M2O. No off-the-shelf (OTS) or cut-to-fit (C2F) products are found on integrated product delivery levels (T2 and T1). Bathroom pods could theoretically in many cases be OTS standards, but the market is so far not really prepared to make use of such a product, that would have to be integrated in early design phases and subsequently determine certain features of the rest of the building such as the location of risers and waste pipes.

### *The chunks*

The chunks that constituted the primary T1-delivery of the CH have already been presented in some detail above that do not need to be repeated. Quite interesting though – and particular to the use of volumetric chunks in the CH – is the choice of using a combination of two towers of stacked ‘table top’-chunks and a number of bridge-chunks spanning between these (see figure IV.3.14).

“*The front modules and the back modules [chunks, ed.] were boxes with columns at the corners and structure between them. The centre piece was a bridge between the front and the back and its wall panels came in afterwards*”

(CM/3/430)

While the back tower contains the T2 staircase nested into it from the Kullman factory, the bridges carry the bathroom pods that were placed there on-site before hoisting them into place. The front tower is basically open space towards the north façade’s sliding doors and balconies. This strategy almost eliminates the double construction which is otherwise so common to prefabrication based on volumetric elements, or chunks, and improves both the reading of the building as a single piece rather than a stack of modules as well as the sensation of large open interior spaces (MK/2/205)/(AS/2/236). By omitting the ceilings and simply using the floor plates from the storey above, the design of the chunks is

further simplified. The downside is that more upstream deliveries (T4-T2) have to be mounted on-site partly to give access to the bracket joints partly because of fragile detailing. In order to enhance stability during transportation from the factory to the building site some temporary bracing was used and removed on-site during the T0-chunk assembly. As mentioned above the chunks were about 80% complete as T1-chunk deliveries from the factory.

#### ***Bosch Rexroth aluminum frame***

The Bosch Rexroth frame used on both the CH and the LH are in their respective system structures coded as a T3-delivery. The system represents a huge variety of parts and accessories that can be combined in an infinite number of spatial configurations which could make it candidate for a T2 status as an assembly by system. However, as developed originally for factory scaffolding it does not constitute a complete and directly applicable structural building system in itself. It needs the complimentary custom made steel connectors to become such a system. As these have been designed and are produced and delivered separately either onsite (for the LH) or on factory (for the CH), the structural system is system-structure-wise in both cases considered as two T3-component deliveries rather than one integrated and more complex T2-assembly. Potentially the combination of aluminum extrusions and steel connectors could be commoditised into one single integrated product delivery. Originally the intention in the CH was to push the refinement of the connector towards a click-system where the bolting process became redundant (SJ/3/591). This idea of accommodating an existing system to a different use is typical to the way KT have worked with mass customisation in the CH. The Bosch Rexroth was for a certain degree chosen for expediency and effectiveness but it didn't come without compromises, one of them as mentioned earlier being an extremely high amount of embodied energy (RB/4/174) another one being the price. During the disassembly of the CH the Bosch Rexroth was, as described under *design for disassembly*, brought all the ways back to T3-level with exception of the profiles used in the partitions walls and the SmartWrap™ panels that stayed on T2-level.

#### ***Acrylic staircase***

The acrylic staircase in the CH was delivered as a bespoke (BSP) kit-of-parts T2 delivery to be assembled and nested into the T1-chunks by Kullman at the factory. Together with the Bosch Rexroth frame the staircase is one of the iconic pieces in building contributing with a more artistic touch (DR/5/116).



FIGURE IV.3.16  
ACRYLIC STAIRCASE – ONE OF THE  
ICONIC ELEMENTS OF THE CH

48 SmartWrap™ was introduced in the SmartWrap™ pavilion made by KieranTimberlake for a Cooper-Hewitt exhibition in New York in 2003. The integrated systems were here conceptual proposals and were not fully functional: *‘The SW was definitely an extension – it was the SW II of what had been developed at Cooper Hewitt. In this one [CH] James Timberlake was suggesting that while the SW don’t have to work perfectly they can’t be as at Cooper Hewitt just supposition or proposition about what a plastic wall could be. In this case we really wanted it to work in some aspects’* (SJ/3/76)

49 For further details and illustration see above paragraph on monitoring of the CH.

As assembly the staircase was, as one of the few elements, not designed for disassembly thus integrating tread, sidepieces and lighting into a number of fixed and glued modules corresponding to a whole ride of stairs up to a landing (SK/6/146). James Timberlake classifies the staircase as construction as *opposed* to assembly in the sense, that the staircase is not directly recyclable and do not come apart into its constituent sub deliveries without being damaged (JT/6/138). For comparison the LH steel stair was assembled thread by thread onsite and could come apart in the same way. The staircase as general building element is a typical example of how a T2-delivery can develop into more standardised and commoditised versions. One of the advantages in this sense is the relatively clear interface to its surroundings as well as a limited and well defined function. Completely bespoke stairs as the one in the CH are only seldom found today and most solutions are delivered as assemblies – often as a finished kit-of-parts.

#### **Partition walls and SmartWrap™ panels**

Both interior partition walls and exterior façade panels were made as Bosch Rexroth frames with infill together forming two separate T2-deliveries. Again alluding to the initial idea of mass customisation this infill could comprise many different materials. The supplementary conceptual ideas for the CH of transparency and lightness combined with KT’s earlier experience with the SmartWrap™ (SW) - a PET-film with different functions integrated i.e. photovoltaics, sensors, LED’s and colors/decoration – dictated the use of this film for the exterior facades that should have fully functional photovoltaics contributing directly to the power supply of the building.<sup>48</sup> The CH SmartWrap™ thus became a second generation prototype of this material that also included extending the idea from a concept of a single layer composite material into the idea of an assembly (CM/3/82). The proposal envisioned a double panel construction, each panel with two layers of film, forming an intermediate cavity for insulation and ventilation.<sup>49</sup> The specific design and size of the panels were informed by physical experimentation with stretching of the film over the frames which again informed back to the overall building scheme (AS/2/120). The SW-panels were, contrary to the partition walls, not produced by Kullman, the main fabricator, but were delivered separately by Universal Services Associates – partly to Kullman for the nesting into the T1-chunks, partly to the site for final fit-out assembly (T0). Although bespoke (BSP), the SW panels are a good example of a discrete off-site produced T2-delivery with different nested T4 and T3 deliveries (i.e. PET-film, 3M-shading film, photovoltaic film, copper tape and the Bosch



FIGURE IV.3.17  
A DETACHED SMARTWRAP™ PANEL  
FROM THE CELLOPHANE HOUSE™ AT  
DISPLAY IN THE KIERANTIMBERLAKE  
OFFICE

Rexroth frame).<sup>50</sup> The partition walls were produced by Kullman but still as discrete elements that were then mostly nested into the (T1) chunks at the factory. Some panels were however on-site mounted (T0) for practical assembly reasons. Apart from the aluminium frame, the partition walls included 3form Varier wall panels, and some double sided tape – both T4-deliveries.

### Bathroom pods

The bathroom pod is, as mentioned earlier, one of the few more established discrete T1-deliveries existing on the market and thus one of the deliveries of the CH that comes closest to the ideas expressed in *Refabricating Architecture*.<sup>51</sup> For the CH, originally a made-to-order (M2O) product from the British fabricator, Offsite Solutions, was chosen – again as a discrete off-site produced delivery with different nested upstream deliveries (T3 and T4) where most of these would be opaque to the architect/client and based on the specific system and production method behind the product.<sup>52</sup> Overall layout and choice of fixtures (T3), however, was within the realm of the architect. In the end Kullman took over the delivery of the bathpods through a licence with Offsite Solutions and today Kullman produce and deliver several bathpod products on their own.<sup>53</sup> The pods were delivered separately and sealed to the site and placed on the bridge chunks before they were hoisted into position.

### Other integrated product deliveries

The south façade of the CH is a full height curtain wall with a combination of photovoltaic panels and operable windows based on insulated glass units (ICU's). Although curtain walls are often delivered as discrete and fully finished unitised (T2) systems that with brackets and gaskets constitute an entire façade, this solutions was not chosen for the CH – partly due to transportation and hoisting issues.<sup>54</sup> Any kind of shifting in the aluminium frame could have caused the glass to break so alternatively it was decided to install ICU's and photovoltaic panels as part of the final fit-out delivery on-site (T0).<sup>55</sup> However, the frames including the sliding doors on the north façade were factory installed at Kullman (T1). Thus, as with the aluminum framing, the curtain wall delivery was split up into two separate T3-deliveries, here with different tier destinations (T1 & T0).



FIGURE IV.3.18  
WRAPPED BATHPOD ON BRIDGE  
CHUNK

- 50 'There is a really strong desire to include photovoltaics so I went out and found out what companies were doing what to see what could be done. As it turned up we ended up with [Power Film] instead of the organic [printed]. It wasn't quite there' (RB/4/12)
- 51 '*The bathroom was a product. The stairs could have been a product but that was a custom made sculptural piece. The bathroom had a background of engineering, design, testing and prototyping behind it*' (CM/3/190). See also (Kieran & Timberlake 2004). Generally concerning the bathpod see Customisable architectural subsystems, III.2
- 52 In the CH-case architect and client are one and the same.
- 53 See <http://www.offsitesolutions.biz/> and <http://www.kullman.com/bathrooms/bathroompods.htm>



FIGURE IV.3.19  
THE KITCHEN DELIVERY INSTALLED BY  
VALCUCINE

- 54 *‘The delivery of the curtain wall to site was always worrisome because any kind of shifting in that frame would have broken the glass. Unfortunately for this project it had to be onsite installed because the glass was a bit of a nightmare.’ (SJ/3/206). For an example of the curtain wall as a true T2-delivery see e.g. the Arup Associates-case later in this part.*
- 55 Final fit-out is coded as an independent delivery of the CH system structure.
- 56 The service level is one of the three dimensions of integrated complexity as defined in the Taxonomy of System terminology, II.5

Although not fully functional installation-wise at the MoMA-exhibition, the CH includes kitchen cabinets and appurtenant appliances that were all delivered (T2) and installed on-site (T0) by Valcucine. Kitchen deliveries are – probably even more than the bathroom pods – a well established discrete off-site produced delivery with many different suppliers and levels of price/quality on the market. Interesting about this kind of delivery in the present context is that it often includes installation and in some cases even subsequent service thus representing an example of a high service level that are only seldom found in construction deliveries.<sup>56</sup> In the CH case Valcucine delivered and installed thus leaving most of the upstream deliveries opaque to the architect/client that apart from the choosing type and layout didn’t have to care about the nested supply chain behind the delivery. This kind of delivery resembles the concept of work packages as used in the Arup Associates case below, where the system structure is split into discrete parallel deliveries spanning all system levels from T4 to T0 but, as opposed to traditional craft based construction, also includes a large amount of off-site work and processes.

## EXPLANATIVE POWER OF THE MODEL

The first draft of the system structure model draws, as mentioned in the introduction, on the preliminary results from the primary case study of the thesis, the Cellophane House™ by KieranTimberlake. The choice of this case has from the outset been KieranTimberlake’s specific interest in and attempts to work with and clarify the supply chains of construction - particularly the parts of it related to off-site fabricated buildings and the balance between off-site and on-site processes. The CH case was chosen as the primary due to the office’s scope of interest lying very close to the frame of the present research as well as due to the particularly explorative nature of the CH case within this field. Given this fact it can perhaps seem a little like arguing in a circle to discuss the explanative power of the model concerning this case that, in a way, gave birth to it. However, the first draft of the system structure model should – with reference to the section on *‘Method and scientific approach’* – be seen as an act of abduction leading to *‘the suggestion of a probable or satisfying hypothesis about what needs to be explained’*.<sup>57</sup> The hypothesis is only a first model draft

which should ‘*subsequently [be] tested and refined through successive approximation*’.<sup>58</sup> The present model is thus a result of several reiterations of the first version over theoretical scenarios to other secondary cases and is consequently claimed to be more general than at the outset. At the same time, the model as a hypothesis is never a direct reflection of the object studied and will always be subject to an interpretation of the observer of the case – here the researcher. The model is exterior to the case itself and a discussion of its explanative power is thus relevant even if it is just a first model draft.

Both for the CH as well as for the LH, the system structure models show considerable distribution of deliveries into the different tiers of the model combined with a relatively limited number of upstream deliveries on T4 and T3-level and only few T0-deliveries/processes.<sup>59</sup> This can be explained by the specific focus on off-site or prefabrication in both projects that moves deliveries towards or nest them into the more complex off-site T2 and T1-tiers (the middle tiers of the system structure model). The distribution brings both system structures close to the theoretical scenario of ‘future industrialised architecture’.<sup>60</sup> However, the CH has a larger concentration on the T1-tier compared to a LH concentration mainly on the T2-tier. The fact that one of the specifically claimed aims of the CH was to maximise off-site fabrication – which is not necessarily the same as optimising the use of it – does bring it closer to the theoretical scenario of ‘conventional prefabrication’ than the LH. This aim was predominantly determined by the competition setup, the brief and the limited amount of time available on-site. The highest possible degree of prefabrication does somehow lead to T1-deliveries whereas the highest possible industrialisation perhaps rather points towards T2-deliveries or a combination of T1 and T2’s – the latter both as direct deliveries on-site as well as nested into the T1’s from the factory. Prefabrication and industrialisation are – although related – not the same thing and prefabrication processes are often very close to conventional construction even though they are made in a factory environment. As pointed out later in the analysis of the Scandi Byg case, large volumetric elements (T1) are e.g. not the most obvious object for automated production and need much more sophisticated robotics than when working on planar or smaller scale assemblies and components (T2 and T3).<sup>61</sup> On the other hand, the focus in the CH project on mass customisation and the use of ready-mades from different fabricators as direct infill in the aluminum frame seem more industrialised than the rather conventionally assembled chip-board cartridges of the LH manufactured with use of a considerable amount of manual labour force in the factory.

57 See *Method and scientific approach*, I.5

58 Ibid

59 The different case studies are not directly comparable due to their different levels of complexity and different focus or viewpoint (architect, contractor, manufacturer or ‘total consultant’). While other cases like the day care facility by Scandi Byg or the office building by NCC have a relatively high number of upstream deliveries this is partly due to these two aspects.

60 The theoretical scenarios are explained in *Model presentation*, IV.1

61 Scandi Byg that primarily deliver volumetric chunks and have chosen production wise to draw a line between a highly automated production of planar assemblies that subsequently are joined together into chunks and finished by use of more manually dominated processes. See the Scandi Byg case, IV.4

In fact the comparison of the two different strategies applied for respectively the LH and the CH is easily expressed through the use of the system structure models and the related concepts and seem to underline the explanative power of the model. The two cases are both of them good examples of a nuanced and deliberate approach to the challenges and possibilities in off-site fabrication each with their specific and project dependant context that shapes their different system structures. This can be read out of the coding of the model. The design for disassembly process that was accomplished for the CH points towards an equally relevant use of the model and the notion of system structure when it comes to taking a building apart for reassembly or for recycling by the end of its useful life. The CH was not intended to be brought down to the level it actually was at the end – it was thought as staying as chunks until the end of its useful life. Early considerations of how and to what extent to brake a building up into elements of different complexity can be informed design wise both from the way it is put together as well as how it can be taken apart and the system structure can easily encompass both levels under one common scheme and terminology.

Building monitoring and embodied energy analysis as they were applied to the CH clarify the difficulty of implementing all-encompassing analytical techniques and procedures to as complex an artifact as a building. The focused and more delimited ‘prototype’-analyses performed for the CH points towards potential design feedback on the level of building elements or integrated product deliveries as the Smart Warp panels, the Bosch Rexroth system, the curtain wall etc. The establishment and enhanced commoditisation of such integrated products can benefit from such analytic feedback. Again, the system structure potentially helps to illustrate and discuss pros and cons of different design scenarios for the same project.

Starting to look more closely into both KT cases and using the system structure as the lense, a lot of the nuances of how KT actually uses existing systems are clarified: By using existing systems and standardised solutions already from early design phases these can be used actively as generators for the architecture and the architectural concepts and the detailing of these two buildings. Just keeping the model as the post fact analytical result it so far is, helps to understand and explain this strategy as opposed to the very simplistic conception of prefabrication that often dominates the debate where buildings are classified as either (completely) off-site fabricated or as traditional on-site construction.

*“There is a very simplistic and un-nuanced version of prefab that exists and always wants to keep the myth alive: ‘16 chunks, we put it up and no-one sweated [...] just using white gloves. What you are showing with your tiers is that all of these different products are connected to a set of protocols which are connected to a series of people that have to communicate with each other’*

(BF/1/209)<sup>62</sup>

The appropriate degree of prefabrication and different levels of industrialisation is and will always be project and context dependant and it is never an either/or-choice between on-site and off-site processes. Furthermore, it is important for the result to bring in architectural considerations in the choice of balance between the two (theoretical) extremes – not just production time and economy. In this way future construction projects can perhaps develop towards higher degrees of industrialisation and prefabrication without sacrificing architectural diversity and quality for efficiency.

#### ***From project delivery to product delivery – industrialisation of the lower tiers<sup>63</sup>***

If non bespoke industrialised deliveries are to be developed on complex integration levels as expressed by the T1 and T2-deliveries it requires engagement from the industry and perhaps a movement towards higher commoditisation levels where manufacturers takes over both larger parts of the specification task (the preparation and standardisation dimensions) as well as a larger part of the liability issues (the service dimension) of deliveries.

*“In every project there are certain repeated elements: stairs and railings and bathrooms that initially you invent them and reinvent them but after a while you discover that there are some solutions that work really well and you establish them and they become a standard. I think almost the same systems could – if you had a series of fabricators who really engaged – be the first ones to be taken on as major chunks [or assemblies (ed.)] in a real offsite fabrication’*

(CM/3/198)

- 62 See also press cuttings on the CH in the interview guide, appendix VI.6.A
- 63 Even industrialisation of the T0 is relevant – this is partly the Lean track but also includes the movement from construction to assembly processes on-site – based on highly complex prepared, standardised and serviced off-site produced integrated product deliveries.

## IV.4 SCANDI BYG

The system structure of all-encompassing factory produced housing solutions

### INTRO

The following analysis is based on study at Scandi Byg in Løgstør (Denmark) in September 2010. As representing a study of a building manufacturer mainly delivering all-encompassing building solutions, particular focus is put on the internal organisation of the production. The study includes a specific built day care facility as well as a production line for a large series of dwellings. After a short introduction to the cases, the ‘zoom’ or viewpoint of the analysis, the company and the specific procedure used for the case study and data collection, two system structures are established and discussed. In a final paragraph the explanative power of the model is discussed in relation to the chosen viewpoint.

### PROJECT TYPE – DESCRIPTION OF THE CASES

The project type in this study is buildings made of factory produced volumetric elements with a high degree of off-site completion supplemented with only limited preparatory and final works on the building site. The specific built project studied is *Ellepilen* – a day care facility designed by the Danish architectural office ONV-arkitekter and produced by Scandi Byg for the City of Copenhagen in 2010. The analysis and the discussion are further nuanced by the introduction of a newly initiated production of a large number of dwellings being realised as several individual building complexes within one common concept and organisational framework for social housing. The concept is called *Almenbolig+* (social housing+) and provides within a fixed unit price social dwellings for local housing associations under the general housing association KAB – Københavns Almennyttige Boligselskab (Copenhagen Social Housing Association). Scandi Byg has won the first contract for these projects comprising approximately 650 dwelling units distributed over local projects of varying size. Although at the moment of the study (September 2010), the production of the first projects have just started, they are still interesting as a supplement to the discussion of *Ellepilen* in the sense that, whereas the day care institution is a one-of-a-kind, this large



number of dwellings represents only three different standardised solutions with a limited number of optional choices or modifications possible on the project level. Having these standardised bases give an excellent possibility to establish a truly industrialised production line with continuous repetition of a wide range of different processes. Scandi Byg uses this specific contract as a lever to build up general experience within areas i.e. just-in-time and automation principles that subsequently is anticipated to be applicable to one-of-a-kind projects like *Ellepilen*. Finally, the analysis also draws on couple of inputs from a laboratory project carried out by Scandi Byg for a major pharmaceutical company.

## THE COMPANY AND THE 'ZOOM' OF THE ANALYSIS

The concept and the specific project are in this case primarily seen from the perspective of a building manufacturer who however also acts in the role of main contractor. Scandi Byg A/S was established in 1978 and is today a subsidiary under the major Danish contracting company MT Højgaard A/S. The company is located in Northern Jutland in Løgstør and comprises two production facilities, own drawing office and administration. Scandi Byg develops, systemises and produces light prefabricated building structures for larger private and public clients. This means that detached single family housing – with few exceptions – lies outside the business area which typically encompasses midsize and larger housing estates, office buildings and office extensions as well as schools and other public institutions. Branded as *SB Modul* (SB Module), Scandi Byg furthermore produces site huts, pavilions, and other temporary and portable cabins. All projects are produced and delivered as highly finished and fully outfitted volumetric chunks although the degree can vary slightly between projects.

FIGURE IV.4.1  
STREET VIEW OF ELLEPILEN

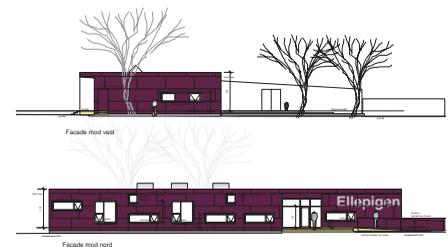


FIGURE IV.4.2  
NORTH AND WEST ELEVATIONS, ELLEPILEN

- 64 Scandi Byg contractually mainly acts as turnkey contractor in building projects. A limited number of fixed and ad-hoc subcontractors delivers solutions in the factory as well as preparatory and accomplishing works on-site
- 65 For a definition of *flexible structuration* see *General systems thinking*, II.4
- 66 The *total integrated complexity value* is an expression of the degree of integration of a delivery and gives an indication of how much design work that potentially can be ‘saved’ by using this (product) solution. See *Taxonomy in Systems terminology*, II.5
- 67 See *KieranTimberlake* case, IV.3

Important to point out is that analysing *Ellepilen* from the viewpoint of the manufacturer does not necessarily yield the same system structural view as if it had been seen from the viewpoint of the architect, the client or a traditional contractor.<sup>64</sup> The chosen viewpoint has influence on how the system structure folds out due to the model’s quality of *flexible structuration* that allows focus on different parts or different levels of complexity in the overall system constituting the final building.<sup>65</sup> The choice of viewpoint in this case has consciously been chosen with regard to the overall purpose with the analysis which is to test the explanatory power of the developed model within different types of cases and seen from different viewpoints. However, the analysis is also – and can consequently be read as – an analysis of the particular case(s). An initial assumption within this case analysis is that the manufacturer viewpoint enhances focus on the more fundamental upstream deliveries on tier 4 (building materials and standard components) compared to what would be the focus of e.g. the architect in the same project – as least as long as the architect uses the standard structural solutions and joint details provided by the manufacturer’s building system concerning e.g. slabs, walls and roofs. By relying on the integrated complexity inherent in these subsystems, the architect can direct focus towards other aspects as shape, dimensions and location of larger technical systems which are not included in the standard solution. The manufacturer undertakes detail design of the elements, the procurement of sub-deliveries, the production, the delivery and the installation on the building site as closed volumetric chunks. The *total integrated complexity value* of these volumetric elements is potentially very high thus facilitating a more free choice of design attention for e.g. the architect.<sup>66</sup>

## SPECIFIC DESIGN OF THIS STUDY – CONTRIBUTORS, PERIOD OF TIME, LOCAL CIRCUMSTANCES

The case study at Scandi Byg was carried out as a combination of different qualitative research techniques and was inspired by the experience from the more intensive primary case study at KieranTimberlake.<sup>67</sup> The day care facility as case was chosen as a point of departure through an introductory telephone conversation with CEO, Jesper Hoffman, who also pointed out key individuals involved in this project. The main study consisted of a subsequent two-day study in the company in Løgstør. Activities included interviews, guided visit at the production facilities (*Almenbolig+*) as well as study and preliminary analysis of project material i.e. descriptions, drawings, presentation material



FIGURE IV.4.3  
PLAN OF ELLEPILEN

and illustrations. The physical presence in the company strongly facilitated access to this material. Interviews and conversations were held with sales director, Flemming Dalgaard, project architect at *Ellepilen*, Finn Christensen and head of production development, Allan Pedersen Kjølner. While the sales director gave an overall introduction to Scandi Byg and the way their projects are run in general as well as a general introduction to Ellepilen and other types of Scandi Byg projects, the project architect provided detailed information about the case and the process of production and installation on-site. The head of production development presented the newly established production line for the Almenbolig+ project as well as provided an introduction to Scandi Byg's future strategy for enhanced industrialisation and automation of their general production. The two-day study was finished with a summative discussion of preliminary findings with CEO, Jesper Hoffman. A subsequent visit at the day-care facility including an informal presentation and discussion of the final result with an employee provided supplementary insight and gave a better idea of the actual architectural result.

## SYSTEM STRUCTURE – CODING AND SPECIAL PROJECT SPECIFIC FEATURES

As producer of volumetric chunks with a high degree of off-site completion corresponding to tier 1 in the system structure model, Scandi Byg assembles most deliveries (tier 4 to tier 2) in these integrated product deliveries before

- 68 The tier 3 and tier 4-deliveries will always be present as nested at some point of the entire supply chain. A tier 5 of raw materials is equally inherently present. The modelled system structure, however, seeks to display the particular viewpoint in focus chosen for the coding – in this case the manufacturer perspective at Scandi Byg.
- 69 A kind of intermediate solution between volumetric chunks and planar assemblies is found in the building system NCC-Komplett from the Swedish NCC. This '2½-dimensional' system, where e.g. finished kitchen units are mounted on the walls from the factory, would in the present model figure as T2-deliveries that however included a higher amount of subsystems as nested. For a presentation of the NCC-Komplett system see (Beim, Nielsen & Vibæk 2010:126). The Podwal-product presented in III.3 is a similar example.

they are delivered for final assembly on the building site. As with most of their projects, the final on-site assembly of *Ellepilen* (on tier 0) was equally handled by Scandi Byg themselves except for minor preparatory and finishing works as well as the landscape treatment. The established system structure of the project (See figure IV.4.4) comprises, compared to the two system structures from the Kieran Timberlake case, a relatively large number of tier 3 and 4 deliveries. This can, as initially assumed (above), partly be explained by the manufacturer focus of the analysis. Equally, the system structure of *Ellepilen* shows a collection of the more integrated (downstream) tier 2-deliveries that subsequently are nested either (and most often) via tier-1 deliveries of volumetric chunks or (in a few instances) directly as deliveries on-site (on tier 0).<sup>68</sup> This structure can be interpreted as a strategy aiming at maximising the degree of off-site completion – read: integrating the highest possible number of deliveries and consequently also of complexity – before delivery at the building site (on tier 0). The advantages of such a strategy can be a minimised dependency on weather conditions and less risks of encapsulated humidity in the light construction elements and assemblies while the primary drawbacks are the difficult handling of the considerably big and heavy volumetric chunks that need to be shipped to the building site as expensive specially escorted transports. Another issue is that the volumetric chunks contain considerable amounts of 'air' or void space compared to flatpack assembly solutions on tier 2-level or to tier 3 to 4-deliveries supplied directly to the building site. However, the tier 1-delivery enables a much higher number of tier 3 to 4-deliveries to become nested before the building site (upstream) than if tier 2-planar assemblies are supplied directly.<sup>69</sup> Both versions of off-site produced deliveries (volumetric chunks or planar assemblies as slabs and walls) are common in a Danish context but Scandi Byg has exclusively specialised in the delivery of the tier 1-volumetric chunk solution. The tier 2-slabs and walls do not leave the factory as discrete deliveries – even though they are mostly produced that way. The description of the system structure of the *Almenbolig+*-production line (below) will elaborate further on this issue that seem to represent a clear division between different manufacturers on the market. Either they do volumetric chunks or they do planar assemblies – combinations are unusual.

The discussion of advantages and drawbacks of a relatively high degree of integrated complexity within off-site produced large tier-1 deliveries is accentuated by place and project specific conditions as climate and geographic and infra-structural location. There are many clear advantages for a relatively humid and

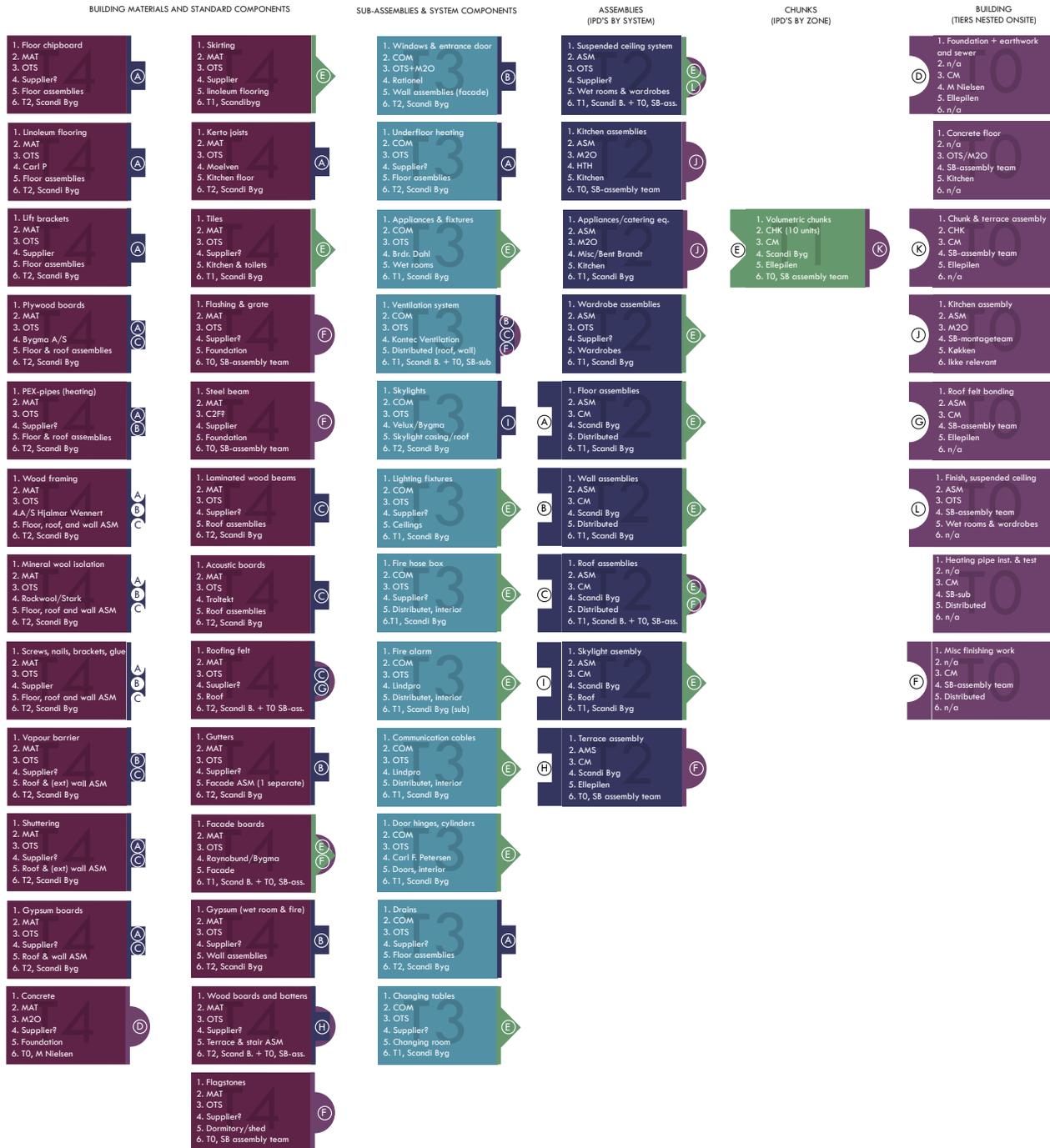


FIGURE IV.4.4 SYSTEM STRUCTURE, ELLEPILEN

rainy climate like Denmark that on the other hand would be rather insignificant in a drier climate where the infrastructural issue would consequently have higher relative weight. Both the distance between manufacturer and final destination and the local accessibility will *always* have decisive impact concerning how big and how integrated deliveries can be while still being cost efficient compared to less integrated solutions. Apart from the transportation issue there also exists a range of economical, organisational and legislative issues that can vary considerably according to the specific national and regional context. Whether a building is industrially manufactured is not only a question of prefabrication

70 This quality of the system structure is linked to general systems theory and is elsewhere referred to as isomorphisms (similar forms or structures). See *General systems theory*, II.4

– and it is *never* an either/or question. In order to make the best possible use of industrialised and off-site fabrication the right *project specific* balance has to be considered. This between, on the one hand, the different kinds of deliveries on different tiers and their nesting into each other off-site and, on the other hand, their direct delivery to the building site for tier 0 installation.

#### ***Changes in system structure – specific discussion***

Some issues during the course of the project realisation have resulted in changes of the system structure of *Ellepilen* compared to the initially planned pattern. However, important here is to point out that neither for the manufacturer (Scandi Byg) nor for the architect (ONV) these changes have in the present case been interpreted as changes in any system structure. They are simply changes to the project. Visualising these changes by use of their system structure is so far exclusively an exercise performed within the present research project. The assumption is that, when viewed through the optics of a system structure, such changes can be put into words in a different way that work on another abstraction level (like the tiers) and potentially shed light on and make comparable similar *system structural* changes that are constituted by completely different deliveries if they are considered on a detailed level.<sup>70</sup> The explanative power of the system structure gives a different overview of the consequences of project change related to production and construction processes.

#### ***Reduction of integrated complexity – enhanced complexity in focus***

For the design of *Ellepilen*, the architect chose to equip the kitchen and the adjacent storage room with a continuous casted floor. As kitchen and storage room are located within the same volumetric chunk this, in the first case, did not cause any obstacle. Off-site produced casted floors are not standard but are sometimes used in e.g. bathrooms. The casted floor resulted in a change of the standard construction of the floor plate due to the demand for level free access from adjacent linoleum flooring. Standard joist were replaced with lower and more expensive laminated joists (Kerto joists) that have better load capacity in order to make space for the casting. However, even though placed entirely within the same volumetric chunk, the size of the continuous floor was estimated too big and consequently too fragile for transportation from the factory to building site. The risk of cracks would be considerable and a possibly cracked floor would be past recovery once brought to site. The solution was that the laminated tier 4-joists were factory installed into the tier 2-floor slab assembly which was subsequently nested into the tier 1-volumetric chunk equally factory

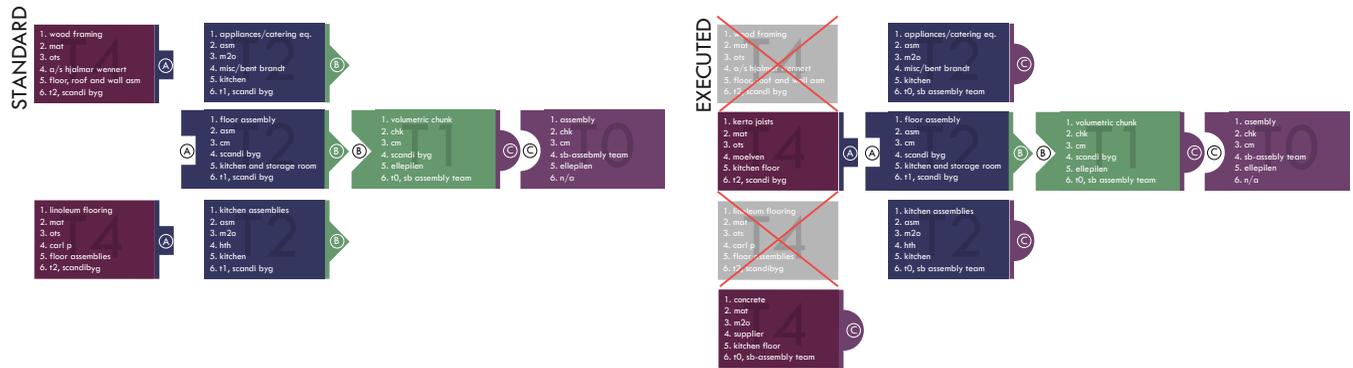


FIGURE IV.4.5  
SUBSYSTEM STRUCTURE OF KITCHEN  
SOLUTION – STANDARD AND AS  
EXECUTED

assembled. The casting, however, had to be postponed as an extra tier 0-delivery on the construction site after the tier 0-chunk installation. Casted floors of the size designed by the architect were not a known and well tested standard solution. This again forced other changes to be made from the standard solution: Also the kitchen installation located upon the casted floor had to be postponed to the construction site instead of, as is the standard, being nested already at the tier 1-chunk level. The individual kitchen units are often procured as kit-of-parts from the kitchen supplier rather than as the finished assemblies (which is normally how an end-user would have them delivered). The factory environment and the trained staff make it more cost efficient to assemble them in-house. In the case of *Ellepilen* this was no longer the case and the slightly more expensive solution of preassembled tier 2-kitchen elements were installed on-site. Figure IV.4.5 displays as a focused system structure, the changes from the originally planned standardised and highly integrated tier 1-delivery of a chunk to a more complex mix of several deliveries on-site. However, by having chosen another kitchen floor solution or perhaps by having split the continuous casting into smaller modules, more deliveries could have been maintained as deliveries nested further upstream. Price-wise this would probably have been a cheaper solution while better combining Scandi Byg’s standardised supply chain and integration process (nesting) with the design specification of the architect. Idea and its realisation would have been better tuned! Whether the quality of the present solution is better than the sketched alternative is an issue open for discussion. One of the explicit arguments, forwarded by manufacturers as Scandi Byg, for maximising the number of nested deliveries in the tier 1-volumetric chunks is that the controlled factory environment, the integrated building process and the early nesting in general gives a better base for achieving high *technical* quality and for keeping up with the time schedule. This does, however, not in itself lead to architectural quality in a broader definition.

The day care facility includes the installation of a distributed tier 3-ventilation system that is already from the factory nested into the tier 2-roof and wall assemblies. The system is served by a ventilation device that is located in a technical room behind one of the wardrobes. The considerable size of the ventilation device makes it impossible to install after the installation of the partition walls enclosing the device. Consequently it has to be installed prior to access door and partition wall. In the factory environment this did not pose any particular problem but when the delivery of the device was delayed it could no longer be nested into the tier 1-volumetric chunk at the factory. Installation had, as

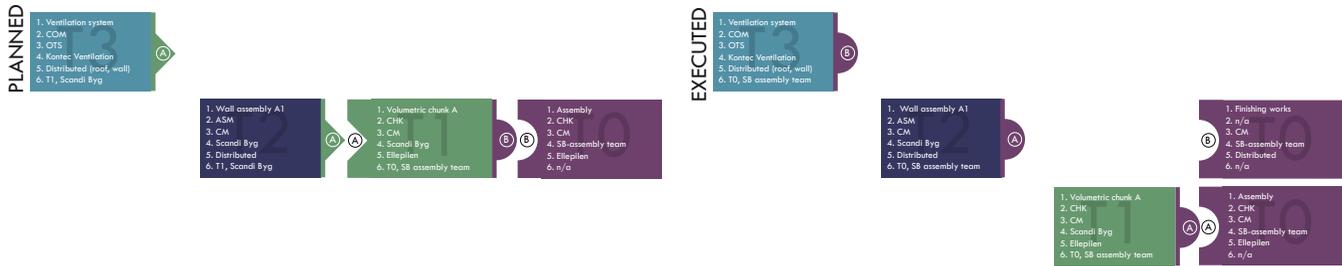


FIGURE IV.4.6  
SUBSYSTEM STRUCTURE OF VENTILATION DEVICE – PLANNED AND AS EXECUTED

71 Scandi Byg does normally not deliver planar tier 2-assemblies for on-site installation. In this case, the assemblies are simple non-insulated constructions that are not to the same extent sensitive to temporary weather exposure during installation.

above, to be postponed to on-site installation. As the aggregate has to go in before the partition wall, this tier 2-wall assembly equally had to be postponed and delivered to the construction site instead of the standard prior nesting at the factory as part of the tier 1-chunk delivery. (See figure IV.4.6). Further three discrete wall assemblies and a small roof assembly for the shed behind the dormitory chunk (all tier 2-deliveries) were delivered directly for on-site tier 0-installation. The shed has flagstone flooring directly laid on the ground making inadequate the chunk solution.<sup>71</sup> While it for the ventilation aggregate is a postponed delivery that impedes nesting the tier 2-wall assembly into the tier 1-chunk at the factory, the second instance is the result of a decision made at the outset of delivering discrete wall and roof elements as being the most appropriate. A chunk solution would probably have required temporary bracing during transportation. This was actually used for the ‘table-top’ chunks of the *Cellophane House* described in the KieranTimberlake case above.

### Limited integration

The degree of prefabrication can in some cases be too high and inappropriate. Scandi Byg installs as a standard the suspended ceilings in offices and institutions as nested into the tier 1-chunks already in the factory. In the case of connection joints for distributed installation systems (e.g. ductwork) across chunks at on-site (tier 0) installation, the ceilings can be taken down as single sheets in order to get access. This however represents – although in a limited amount – triple work (sheets up, down and up again). Alternatively, the installation of the affected sheets can be postponed and these placed within the sealed tier 1-chunk as it leaves the factory. In a recently finished laboratory project by Scandi Byg, the intensive on-site (tier 0-)installation work on the hidden ductwork above the suspended ceilings required a large amount of these to be taken down again after factory installation. Here the triple amount of work became problematic. Apart from more work, both subsequent on-site processes are furthermore subject to more uncertainty due to the less controlled ‘production environment’ compared to the factory setting. Seen from a system structural point of view, the problem was that the suspended ceilings at the outset should have been nested on the building site (tier 0) rather than into the volumetric chunks (tier 1). (See figure IV.4.7) In the same project, Scandi Byg had procured preassembled tier 2-installation shafts as a made-to-order delivery (M2O) to be nested into the tier 1-chunk deliveries. However, as with the ventilation device above, delayed delivery from the supplier demanded postponement which caused a displacement in the system structure: The tier 2-shaft had to be

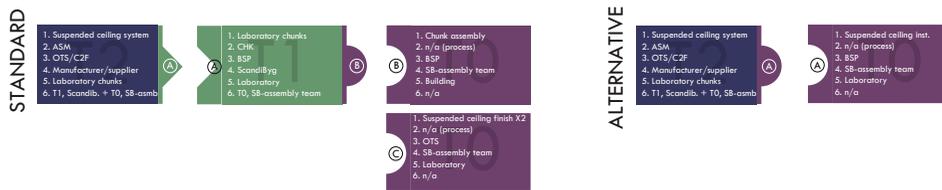


FIGURE IV.4.7  
MOVING TIER 2-CEILING DELIVERY FROM TIER 1 TO TIER 0 THUS AVOIDING TRIPLE WORK

installed onsite. Due to the limited information available for this outsourced delivery, access hatches in the tier 1-chunks could not be factory installed either. The uncertainty about the exact location of these displaced this sub-delivery posterior to the shaft installation on-site. As shafts came as full-storey assemblies, the on-site installation of the shaft further had to be coordinated directly with the tier 0-chunk assembly. The result was a postponed hand-over due to considerably increased on-site work.

## INTEGRATED PRODUCT DELIVERIES – EXAMPLES & INNOVATION

*Ellepilen* seen as a system structure displays a number of integrated product deliveries (tier 1 and 2). Some are more well established and standardised, some are specific for the project type, some are manufacturer specific (Scandi Byg’s in-house proprietary solutions) and a couple of them can be seen as innovations that have a more general applicability if considered as types that potentially could create new market standards.<sup>72</sup>

### Tier 2-deliveries

The suspended ceilings, the standard kitchen assemblies and the catering facilities (professional kitchen) belong to the first category of well established and more standardised deliveries (made-to-order – M2O and off-the-shelf – OTS products), while the wardrobe-delivery is very specific for day care facilities.<sup>73</sup> (See figure IV.4.8) Floor assemblies, wall assemblies and roof assemblies are all manufacturer specific internal assemblies in the sense that they are developed by Scandi Byg and are exclusively used within Scandi Byg’s own specific system. According to the present coding of the system structure these tier 2-deliveries are supplied to Scandi Byg by themselves (figure IV.4.4). One could argue that these internal subsystems analytically should be coded as (external) tier 3 and 4-deliveries of materials and components directly nested into the volumetric tier 1-chunks as sketched in the theoretical scenario of *traditional prefabrication*.<sup>74</sup> However, the inclusion of the intermediate levels shows something about the production process at the factory which is particularly relevant from the viewpoint of the manufacturer as in the present case. An imagined scenario could also be that Scandi Byg either supplied these tier 2-deliveries (planar assemblies as floors, walls, and roofs) to other external receivers i.e. manufacturers or contractors or themselves procured these assemblies exter-

- 72 These innovative deliveries are particularly interesting in the context of the present research as representing new possible paths for enhanced complexity integration in architectural design.
- 73 The wardrobe delivery is the only so-called ‘client delivery’ of the project where the City of Copenhagen has a general procurement agreement with a specific supplier.
- 74 For an introduction to the theoretical scenarios elaborated using the system structure model, see *Model presentation*, IV.1



FIGURE IV.4.8  
OFF-THE-SHELF TIER 2-WARDROBE DELIVERIES ARE SPECIFICALLY DEVELOPED FOR DAY CARE FACILITIES



FIGURE IV.4.9  
THE VOLUMETRIC ELEMENTS MEETS  
THE GROUND MEDIATED BY TERRACE  
AND STAIR ELEMENTS

75 *Development and classification  
of integrated product deliveries,*  
III.3

nally (outsourcing). Such a strategy could provide for a more stable production volume if the planned automation of Scandi Byg's production line is successful. The fact that Scandi Byg actually *does* start with the production of discrete planar assemblies and subsequently assemble these into volumetric chunks points towards the theoretical scenario of *future industrialised architecture* where a considerable part of the system structure is integrated/prepared as tier 1 and tier 2-deliveries before final nesting as tier 0-assembly on the building site. Assemblies like floorslabs, roofs, and walls could potentially create market standards as mass customised integrated product deliveries (made-to-order – M2O). Concrete hollow core slabs is an example of such a market standard widely used in a Danish context. Completely standardised off-the-shelf – OTS or cut-to-fit – C2F-products of this type are probably less realistic. A cut-to-fit delivery of this kind would also, due to its considerable size, constitute a waste and resource issue that needs to be handled.

The tier 2-terrace assemblies used on the south façade where the building opens up towards the playground area are bespoke (BSP), but could in principle also be a mass customised integrated product delivery (made-to-order – M2O) where wood species, board profiles and specific measures could vary but be based on a fixed structural principle and a standardised production process. This production scenario is even more obvious for use in the deployed integrated skylight solution that apart from tier 4-materials also nests a tier 3-skylight. In the analysed project, however, Scandi Byg again becomes its own supplier although the assemblies are produced separately as discrete assemblies. In line with several already established prefabricated attic products (tier 2-assemblies), the skylight assembly has a nature as a clearly delimited subsystem that functionally as well as physically makes it highly marketable as a discrete integrated product delivery.<sup>75</sup> The many technical performance demands concerning e.g. waterproofing, insulation value and light transmission could form the basis

for the integration of a considerable amount of non project specific knowledge into a common product structure (or product architecture).<sup>76</sup> The production of the (project) specific versions of such a product could then be more or less automated based on parametric design rules defined by the structure. The general applicability of an integrated skylight solution enhances the probability of hitting a sufficiently big market to make the product profitable through the combined strategy of economies of scale and economies of scope (mass production vs. responsiveness). A question would be whether a product structure (a subsystem structure) could be developed that could serve several markets internationally and consequently further consolidate the market volume needed to support an industrialised production. Exactly the question of sufficient market volume is probably one of the most important obstacles for a further commoditisation of integrated product deliveries in construction today.

### Tier 1-deliveries

When it comes to on-site deliveries, *Ellepilen* is as mentioned mainly based on tier 1-volumetric chunks. These chunks have in the present case the feature that the slightly sloping roof is delivered as nested into the tier 1-chunk from the factory. Often roofs are built from less integrated tier 3 and 4-deliveries on-site as trusses and roof battens or, if prefabricated, delivered as discrete tier 2-subsystems directly to the building site. While the roof splits up according to the chunks it constitutes two continuous surfaces with a pitch towards a mid diagonal leading away the rainwater towards the southeast corner of the building. Despite the different roof heights for every chunk, this solution has been chosen in order to minimise site work. No 3D-technology has been used to control correspondence between roof heights. The roof surface receives a first layer of roofing felt as nested onto the tier 1-chunks from the factory followed by felt strips burned onto the roof between the chunks and finally a finishing layer. The two latter are delivered as tier 4-deliveries installed on-site (on tier 0)

Being a one-of-kind project of a limited size, *Ellepilen* does not use integrated tier 1-toilet and bathroom-chunks. In the present case these have been built up by pieces (tier 3 and 4-deliveries) directly in the chunks. The small batch size combined with project specific circumstances concerning lead time and vacant staff in the factory has probably determined this choice where Scandi Byg in other cases – as e.g. in the *Almenbolig+* production – use finished tier 1-bathpods procured from an external manufacturer. Such deliveries can either be supplied on-site or be nested into the tier 1-chunks.



FIGURE IV.4.10  
A FINISHED AND WRAPPED VOLUMETRIC CHUNK LEAVING THE PRODUCTION LINE AT SCANDI BYG

76 Product structure or product architecture can be seen as a product internal system structure.

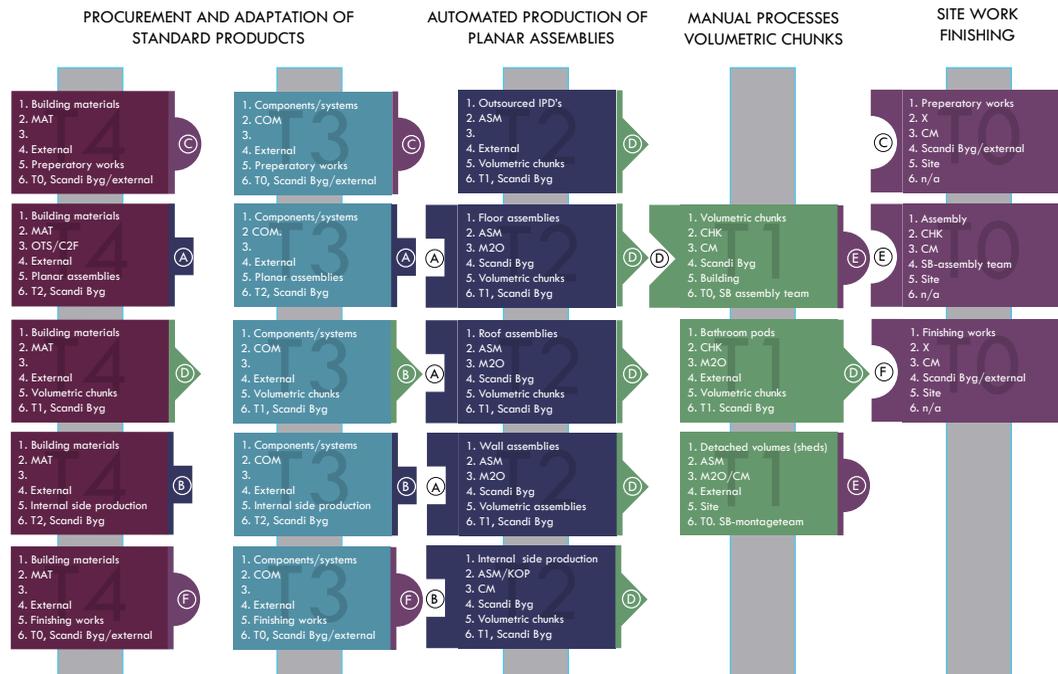


FIGURE IV.4.11  
SYSTEM STRUCTURE OF SCANDI BYG'S  
FUTURE GENERAL PRODUCTION LINE.

77 Based on the interview with  
Head of Production Planning,  
Allan Pedersen Kjølner, Scandi  
Byg

78 At the time of the study as by  
September 2010

## INDUSTRIALISED AND AUTOMISED PRODUCTION LINE AT SCANDI BYG – THE ALMENBOLIG+ CASE<sup>77</sup>

With point of departure in a large contract comprising approximately 650 dwellings constituting a first phase of the social dwelling concept *Almenbolig+*, Scandi Byg is presently working on enhanced industrialisation and automation of their production line.<sup>78</sup> The idea is that the specific production planning for the delivery of this contract subsequently should be transferred and adapted to Scandi Byg's general production line that is mainly producing one-of-kind or few-of-a-kind projects. A particular focus is to what extent such a production line can be automated. As it is today, the production is mostly manual although assisted by craning and power tools while pulling the product through a production line rather than – as onsite – building in a fixed location. The considerable batch size of, in this case, almost identical dwellings forms a good basis for developing and optimising the general production line as well as for implementing robotics for automation. The goal is that almost any of Scandi Byg's projects can be built on such an automated or semi-automated production line – *Ellepilen* could be such a project in the future. Based on the *almenbolig+* production line, Figure IV.4.11 displays an attempt to code such a general production line as a system structure within the model

The production is – by Scandi Byg themselves – split into three general parts that each of them has a certain number of work stations. Apart from the production line in the factory, the on-site assembly as well as supplementary initial and final works are also included. The total number of work stations in the factory is ultimately defined by the size of the facility. The three phases are

- a) procurement and adaptation of standard materials and components
- b) production of planar assemblies (floor slabs, wall, and roof elements)
- c) production of volumetric chunks



In the *first part* (a) tier 4 and 3-materials and components are procured as standard off-the-shelf - OTS products i.e. sheets, timber, insulation, fittings etc. Adaptation is handled manually with use simple machinery. A semi-automated scenario is also considered in order to regulate the flow rate. By keeping processes in-house the point of product variance (here the specific measures of sheets and timber) are brought closer to the final customer resulting in a more flexible production line.<sup>79</sup> Alternatively, sheets and timber can be ordered directly cut-to-fit – C2F from the supplier which reduces processing in the factory but also increases procurement costs by leaving a larger part of the value creation (or supply chain) outside the factory. Another drawback of the outsourcing scenario can be enhanced inventory needs.<sup>80</sup> In general, suppliers in the building industry are not geared towards supplying small customised batch sizes. The most important, however, is a steady flow through all the general parts and each of the work stations. Less important is the achievement of the fastest possible production within each of the work stations seen isolated. This will only lead to relatively useless suboptimisation and can even distort the overall flow.<sup>81</sup>

In the *second part*, the production of planar assemblies, the production line is split into three parallel sub lines for respectively producing tier 2-floor, wall, and roof assemblies. In this part, the vision is that all processes are pure assembly. All adaptation or processing of the components should be located before (upstream), beside (parallel) or after (downstream) these parallel sub lines that are the primary objective for automation through the integration of robotics. On the three planar assembly lines both surface finish (i.e. painting) as well as the nesting of different technical systems (i.e. electrical cabling, heating and ventilation ductwork) is sought maximised – again however with the main focus on the steady flow of the entire line.

In the *third part*, the production of volumetric chunks, the three sub lines from the second part are joined into one single main line leading to the final tier 1-delivery leaving the factory. In this part the planar assemblies are joined into volumes, that are finished and fitted out through the integration or nesting of various supplementary deliveries on different tier-levels (1-4). These are e.g. bathroom chunks, kitchen assemblies, windows and doors, stairs, fixtures etc. In some case, these supplementary tier 1 and tier 2-deliveries are produced partly in-house by Scandi Byg on a kind of side lines thus creating a ‘fishbone’ production structure. Within the *Almenbolig+* production, the bathrooms are

FIGURE IV.4.12  
TODAY PLANAR ASSEMBLIES AS FLOORS ARE STILL PRODUCED PREDOMINANTLY MANUALLY

- 79 Cf. responsiveness, economies of scope and delayed differentiation, see *Industrial production theory*, II.3
- 80 Standard materials and component are easier to store and handle and take up less space.
- 81 This way of looking at the system as a whole of interconnected parts and processes is a distinct property of systems approaches. In this case what is at stake can be classified as systems engineering – a hard fact systems approach. See *Industrial production*, II.3



FIGURE IV.4.13  
THE MAIN LINE HAS VARIOUS 'FISH-  
BONE' SIDELINES AS E.G. KITCHEN  
ASSEMBLY

outsourced and arrive as finished volumetric chunks while the kitchen assemblies are delivered to the factory as a tier 3-kits-of-parts, and joined as a finished tier 2 assembly on one of these side lines before they are inserted into the volumetric chunks. The same is the case for the waste pipes, the circuit breaker panels and others, if they are not outsourced – partly or completely. The flow and the price determine the ideal solution. The tier 2-installation shaft used in the laboratory project as referenced above is an example of this. On the last work station of the line, the finished tier 1-delivery is wrapped in plastic for transportation and subsequent tier 0-assembly on the building site.

The lead time for the present *Almenbolig+* production line is 6 to 7 days from stock to finished and wrapped volumetric chunk. A primary bottleneck of the present production line is the initial joining of the planar assemblies into a volumetric chunk on the last main line. Through enhanced automation of the second part, the planar assembly lines, this problem will be further accentuated. However, it is difficult to speed up this particular process if not two parallel work stations are established – or even two parallel lines for the entire third and final part. This is not possible within the present production facility. Other processes like e.g. drying time for fillers and paint are also potential bottlenecks but can often be distributed over several work stations thus tuning the general flow. Alternatively, processes from the chunk line can be moved to parallel lines on the second level or to sidelines but the issue of space in the facility limits the flexibility to make such changes. The main philosophy is to move as much as possible down to parallel processes (second part parallel sub lines or third part side lines). Installation of windows and doors is presently done from work stations on the last main line (third part). If these are moved upstream for installation on the wall assembly line (second part) it will put higher demands on the tolerances of the wall assemblies in order not to have windows and doors sticking to the frame. With the presently available technology in the facility this has so far been turned down, but things can change.

Another alternative concerning bottlenecks at some points and overcapacity at other points can be to exploit the overcapacity for other purposes. This could be to produce planar assemblies or other parts for Scandi Byg's second production facility, that is located only a few kilometres away. However, even this small distance is not optimal with regard to internal road transportation of e.g. the relatively big planar assemblies (floors, walls and roofs). They could also be sold externally as discrete tier 2-assemblies. Scandi Byg does normally not provide



this kind of product for direct sale, but it could be a scenario to consider in order to maintain a steady flow while maximising the use of the production facilities.

## EXPLANATIVE POWER OF THE MODEL

The system structure model is created drawing on inspiration from a very industrially thought – and perhaps not quite as industrially produced – building project, the *Cellophane House* by Kieran Timberlake.<sup>82</sup> In this project, the discussion of prefabrication vs. on-site construction is an explicit and integrated part of both concept and process. This suggests that the explanative power of the model is good in relation to Scandi Byg and their specific focus on manufacturing (being a building manufacturer). Scandi Byg explicitly works with a strategy of maximising off-site fabrication and have, as explained above, initiated a process towards enhanced automation of their production facility. Compared to the theoretical scenarios advanced in the beginning of this part IV – ‘Model’, Scandi Byg can be located somewhere between *traditional prefabrication* and *future industrialised architecture*.<sup>83</sup> The internal production line and its logic is clearly expressed through the model and its system of deliveries on different tiers defined by their integrated complexity. However, the model also shows that there still is – and probably always will be – a considerable number of project and context specific circumstances, that require deliveries that break with the linear logic of a traditional industrialised production line as known from mass production in parts of the product industry. The need for flexibility and product variance late in the process (delayed differentiation), even within a heavily standardised housing concept as *Almenbolig+*, works against the completely standardised production line and process that is normally the object for an automated production.

FIGURE IV.4.14  
PROTOTYPE AS A FULL SIZE MOCK-UP  
OUTSIDE THE PRODUCTION FACILITY

82 See Kieran Timberlake case, IV.3

83 See *Model Presentation*, IV.1

A weakness in the model can in the present case be that the clarity and visual perceivability on the less integrated tiers (3 and 4) is partly lost due to the relatively high number of different deliveries on these tiers. The high number of deliveries can, as mentioned, partly be explained with the manufacturer viewpoint chosen for the analysis. An architectural viewpoint would probably have less upstream deliveries in the model coding. Again, it becomes a question of the level of detail – or the ‘zoom’ of the analysis – that one chooses for the analysis. A way to enhance the clarity and reduce the number of deliveries expressed in the model could be to concentrate on the deviations from the standard solutions provided by the manufacturer. This would better match the viewpoint or perspective of the architect, where e.g. standards floor or wall assemblies just would figure as tier 2-integrated product deliveries with no nested upstream tier 3 and 4 deliveries. They would be implicit in the delivery as integrated complexity with no particular need for attention from the architect.

One of the advantages of, as Scandi Byg does, to work with maximised off-site integration of what is subsequently delivered to the building site is that by nesting deliveries as early as possible in the building process (into tier 1 and 2-deliveries) there is more time available to incorporate these subsystems and not the least to accommodate to possible delays or errors occurring throughout the process. This can have huge advantages if the deliveries are highly project specific i.e. made-to-order – M2O towards bespoke – BSP solutions where the finished result is perhaps not fully known up until the moment of delivery. The alternative, to procure e.g. tier 2-deliveries directly for integration on the building site probably works better, if these deliveries are well established and more standardised i.e. made-to-order – M2O towards off-the-shelf – OTS solutions. These, on the other hand are relatively few on the market when it comes to the integrated product deliveries (tier 1 and 2). The model seems to display such issues in a way that facilitates discussion.

## IV.5 NCC

### The system structure of an office building concept

#### INTRO

This analysis is founded on material retrieved during a study at NCC Construction Denmark in September 2010. The study draws on a general concept for office buildings as well as a specific built office building related to this concept although this rather as being the outset for than as a result of the concept. After a short description of the procedure used for the case study and data collection follows an introduction to the company and the 'zoom' of the analysis. Subsequently a description of the cases – the concept and the particular project – is found before moving to the establishment and discussion of the system structure which here represents a special version reflecting the conceptual nature of the cases and NCC's particular focus on process. This way of coding the system structure somehow challenges the definition of the system entities (the constituent elements) and the way they are related to each other. In a final paragraph the explanative power of the model applied to this particular case is discussed.

#### SPECIFIC DESIGN OF THIS STUDY – CONTRIBUTORS, PERIOD OF TIME, LOCAL CIRCUMSTANCES

The case study was carried out as a four day study in the NCC main office in Hellerup, Denmark. The choice of the office building concept and the related specific office building as cases was made from introductory conversations with Anders Kudsk (AK), Chief Advisor of IT and Business Development and industrial PhD-student at NCC and Lars Henrik Hansen (LH), Head of Concept planning - both from NCC. The location of the study was determined to be the design group which organisationally belongs under the IT-section. The design group counts a limited number of architects and building technicians concerned with concept development. A preliminary meeting upon arrival had been set up with LH and AK and a secrecy agreement was signed in order to clear access to potentially confidential project material. A short subsequent interview was carried out with Claus Schmidt (CS), Head of Project and Process Planning.

- 84 Interview transcriptions are located in appendix VI.6.C Interview 1-3.
- 85 The term *module* as used by NCC themselves is a little unusual as constituting a super level to what they call models which are merely different versions of façade cladding for the same module. New modules would here refer to new physical and formal restrictions of the overall 'Danske Kontorhuse'-concept.

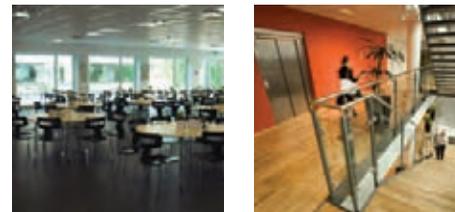
The study was finalised with a check-out meeting with LH in order to clear the use of the retrieved project material. Meetings and interview will be referenced with the initials of the person, the interview number and the corresponding line number in the format (initials/interview #/line #).<sup>84</sup> Most of the time available in the office was used for studying the general concept material and the project material from the execution of the specific office building project.

## THE COMPANY AND THE 'ZOOM' OF THE ANALYSIS

The concept and the specific project are in this case primarily seen from the perspective of a (turnkey) contractor. NCC Construction Danmark is one of the major Danish contractors and was established in the late 1990's as a subsidiary of the big Swedish contractor and developer NCC AB. NCC also does roads and other infrastructural projects. Although mainly concerned with the execution and construction of designs initiated by other parties, in the present case NCC acts as both contractor, consultant and developer (the latter role undertaken by NCC Property Development), and has thus been in charge of all design phases in both concept and project. The integration of the different roles has made it possible to integrate design concepts and solutions more directly with the way they are subsequently executed on the building site (bridging concept and construction) which also means that the concept from the outset has been based on a highly pragmatic approach making use of existing knowledge and well known technology and construction solutions. The visionary aspects of the concept thus rather lies on the contracting side than on the architectural side as well as in the idea of developing an (all-encompassing) building concept that is meant to be sold as a product thus exceeding the project level that mostly characterises the construction sector.

## PROJECT TYPE – DESCRIPTION OF THE CASE(S)

The project type is a building concept for office buildings that, based on a collection of well known and tested solutions, claims to offer customers high quality at a competitive price. The concept, called *Danske Kontorhuse* (Danish Office Buildings), is meant as the first *module*<sup>85</sup> in a series and is, according to NCC themselves, probably too narrow seen in the light of the present state of the market where it is only estimated to hit around five percent of the Danish office market (LH/1/230).



“At the time [of development] we called it modules. A module is when we have a building [concept] with a certain depth that can vary in length and height within certain ranges. Another in the pipeline is a little smaller [...] and have another variance in length and height. That will be another module. A third has an H-shape’

(LH/3/188)

By engaging in the concept a lot of basic features both process and product wise are already defined while other – with core value for the clients in focus – are left open as specific configurations of the concept in each project. A specific office building project was used as an outset for the development of the concept. This project was developed for NCC’s own developer division – NCC Property Development – that focuses on property development within office, retail and logistics.<sup>86</sup> The project – *Vallensbæk Company House* – is a 4 storey development in two phases located in the outskirts of Copenhagen. Phases were finished in respectively 2009 and 2010 as office decks for later tenant specific fit-out combined with fully outfitted common facilities as lobby and reception area, canteen, circulation and service areas. This equals to some extent, as we will see, the Arup case following this section although addressing another segment of clients.<sup>87</sup> (See figure IV.5.1).

The general concept, *Danske Kontorhuse*, is defined as a three to six storey *company house*<sup>88</sup> in the shape of a single wing building with a fixed depth of 18 meters gross and a variable length between 66 and 110 meters gross according to specific client needs. Among other standardised features are fixed storey and clearance height as well as standard cores including staircases, elevator, installation shafts, handicap toilet, kitchenette, cleaning repository and general storage. Equally, remaining toilets cores are standardised but variable in number while the basement as standard includes mechanical room, and changing rooms. Other common facilities as canteen and fitness room are optional. Different façade claddings can be added to the standard building envelope thus forming what is termed different *models*. All models meet the European Green Building Programme requiring an extra 25% reduction in energy consumption compared to current national standards.<sup>89</sup> The developed concept was meant to be sold directly to external clients both as domiciles (client = occupant) as well as tenanted properties (client = owner/landlord). The concept material can be handed out to external consultants, i.e. architects, as the base for the develop-

FIGURE IV.5.1  
VALLENSBÆK COMPANY HOUSE

FIGURE IV.5.2  
INTERIORS FROM VALLENSBÆK  
COMPANY HOUSE, COMMON FACILITIES

86 <http://www.ncc.dk/da/OM-NCC/NCC-i-Danmark/NCC-Property-Development-AS/> accessed on July 11, 2011

87 The Arup case – Ropemaker Place centrally located in London – is addressing high end office tenants whereas Vallensbæk Company House, although infrastructurally well located, rather addresses mid-range or less established branch offices.

88 Defined by NCC as a multi-storey office building containing one or several separate companies with shared facilities.

89 See <http://www.eu-greenbuilding.org/> accessed on July 11, 2011

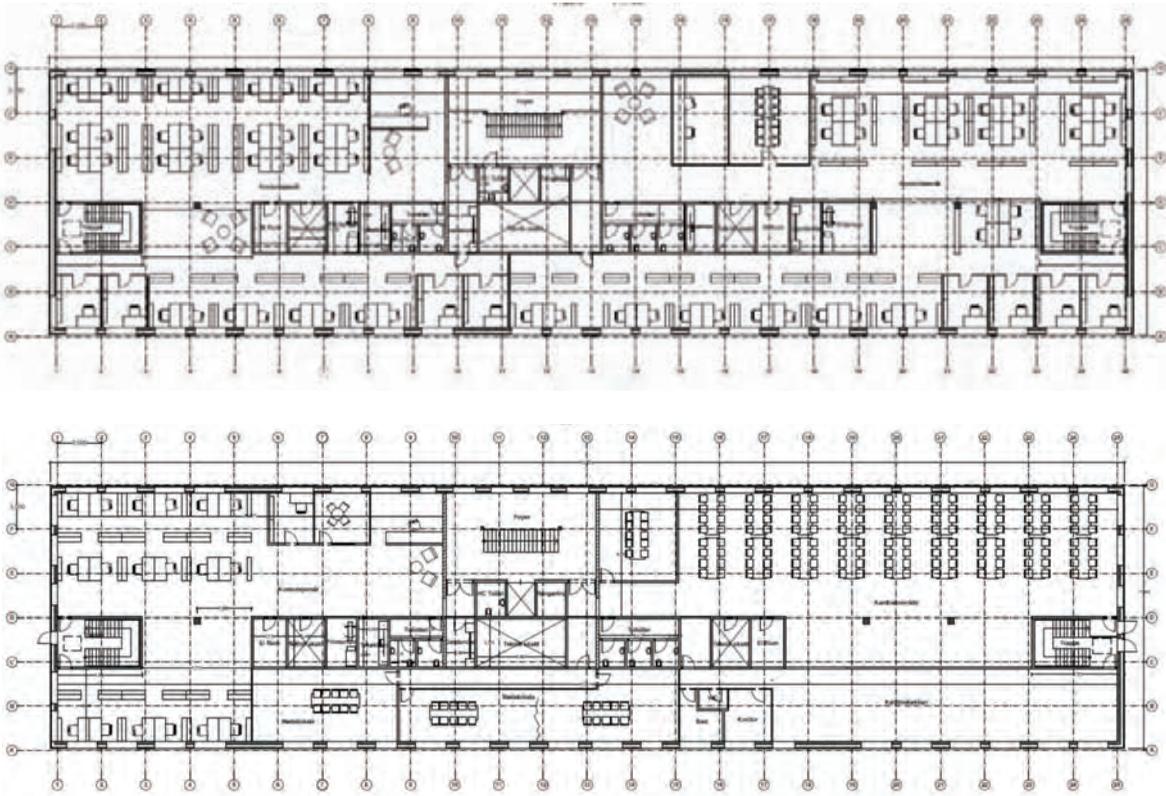


FIGURE IV.5.3  
UPPER FLOOR PLAN AND GROUND  
LEVEL OF DANSKE KONTORHUS,  
BASIS-MODEL

ment of specific projects within the concept. Both the specific project analysed and the general concept are primarily based on conventional construction methods with no particular focus on prefabrication or integrated product deliveries. However, conventional construction in Denmark – if not *all* construction – usually encompasses some degree of prefabrication i.e. concrete slabs and panels, window sections or even bath- or toilet pods. The specific solutions will be treated more in detail below.

## SYSTEM STRUCTURE – CODING AND SPECIAL PROJECT SPECIFIC FEATURES

As a (turnkey) contractor, NCC is naturally focussed on the execution and construction phases or stages of a building project. Project design and design development are, if in-house, mostly limited to the technical engineering disciplines as mechanical systems and plumbing and are based on proposed layouts from external architects and structural engineers. NCC generally bid on turnkey contracts which are subsequently internally split up on a number of (domestic) subcontractors that mainly deliver on-site tier 0-solutions. This means that the detail design is often fairly well defined and fixed when NCC takes over whereas the way this design is split up into subcontracts and then built is defined by NCC as a weighing of factors like time, price, availability and quality. This post fact translation is tedious and time consuming and leads, apart from cost-cutting measures, to uncertainty in what is with a production term called ‘lead time’ – the time it takes to produce an object. In the studied case(s), a main idea for NCC is to take command over *all* phases which are then directly accommodated to and

restricted by a more streamlined construction phase. The ‘modularisation’ of the construction process into its constituent elements is at the outset based on the company’s conventional procedures and thus mainly follows the traditional craft based divisions (the subcontractors) although in a contemporary more specialised version with a relatively large number of subcontracts. However, NCC has also worked with the question of product development in a more ‘physical’ sense e.g. through the development and marketing of an integrated installation shaft for multi-storey housing projects. Such ideas could be integrated as a further physical commoditisation of the concept. Having defined internally and being in power of the overall framework through the concept, potentially enables NCC to model the system structure towards a more industrialised approach without depending on decisions made by external consultants as in a conventional project setup.

### *Subcontracts as parallel deliveries*

Following the above mentioned subcontracting division, the system structure of both *Danske Kontorhuse* (DKH) and the specific *Vallensbæk Company House* (VCH) project can then be modelled according to the different trades or crafts involved in each project. Seen from the perspective of the main or turnkey contractor, NCC, the project is physically delivered by these different subcontractors according to the descriptions elaborated by NCC themselves. How these individual subcontracts are actually produced and delivered as specific mixes of more or less prepared, standardised, and serviced sub-deliveries has principally little importance to NCC as long as they meet the requirements of the description and as long as the price and suggested delivery time is satisfactory. This means that the primary system entity of the system structure at first becomes the subcontracts as a number of parallel deliveries that theoretically, each of them, encompasses sub-deliveries on various tier-levels (T4-T1). These sub-deliveries, however, remain mostly opaque to the main contractor. Each subcontractor delivers and in most cases also installs a final part of the building onsite corresponding to a delivery on tier-level 0.

Differences in the subcontracts between concept (DKH) and project (VCH) are few. Where the DKH includes 20 contracts, the specific VCH project encompasses 19: In VCH, carpentry (TØM), joinery (SNE), window sealing (FUG) and some of the building envelope (FAC) has been joined into one single contract while plumbing (VVS) on the other hand is split into two: plumbing and air condition. Other minor subcontracts as fire insulation (BRA) and NCC’s own miscellaneous work (NCC) has been omitted in the specific VCH-project.

FIGURE IV.5.4  
THE SYSTEM STRUCTURE FOR DANSKE  
KONTORHUSE EXPRESSED AS PARALLEL  
SUBCONTRACTS

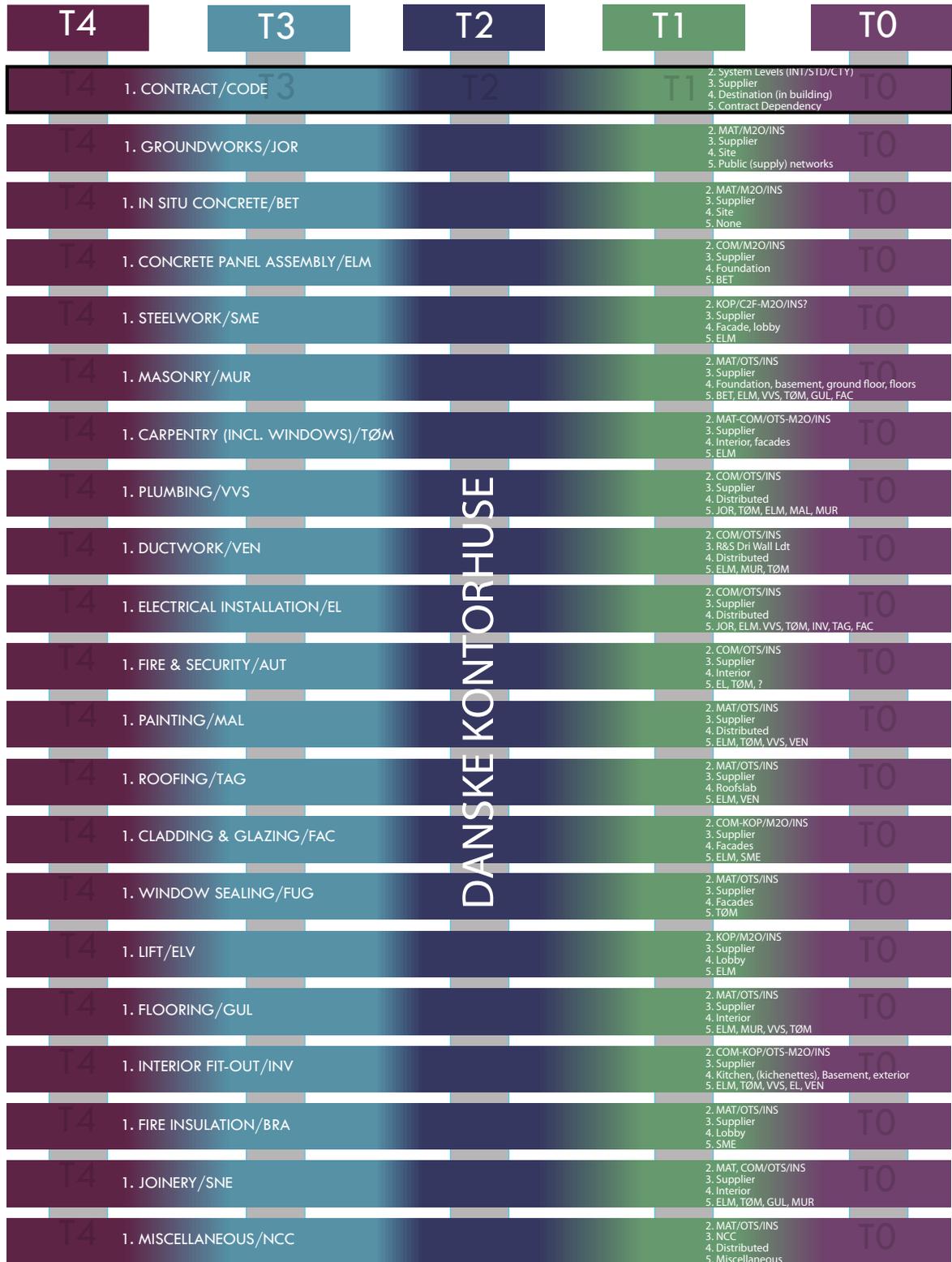
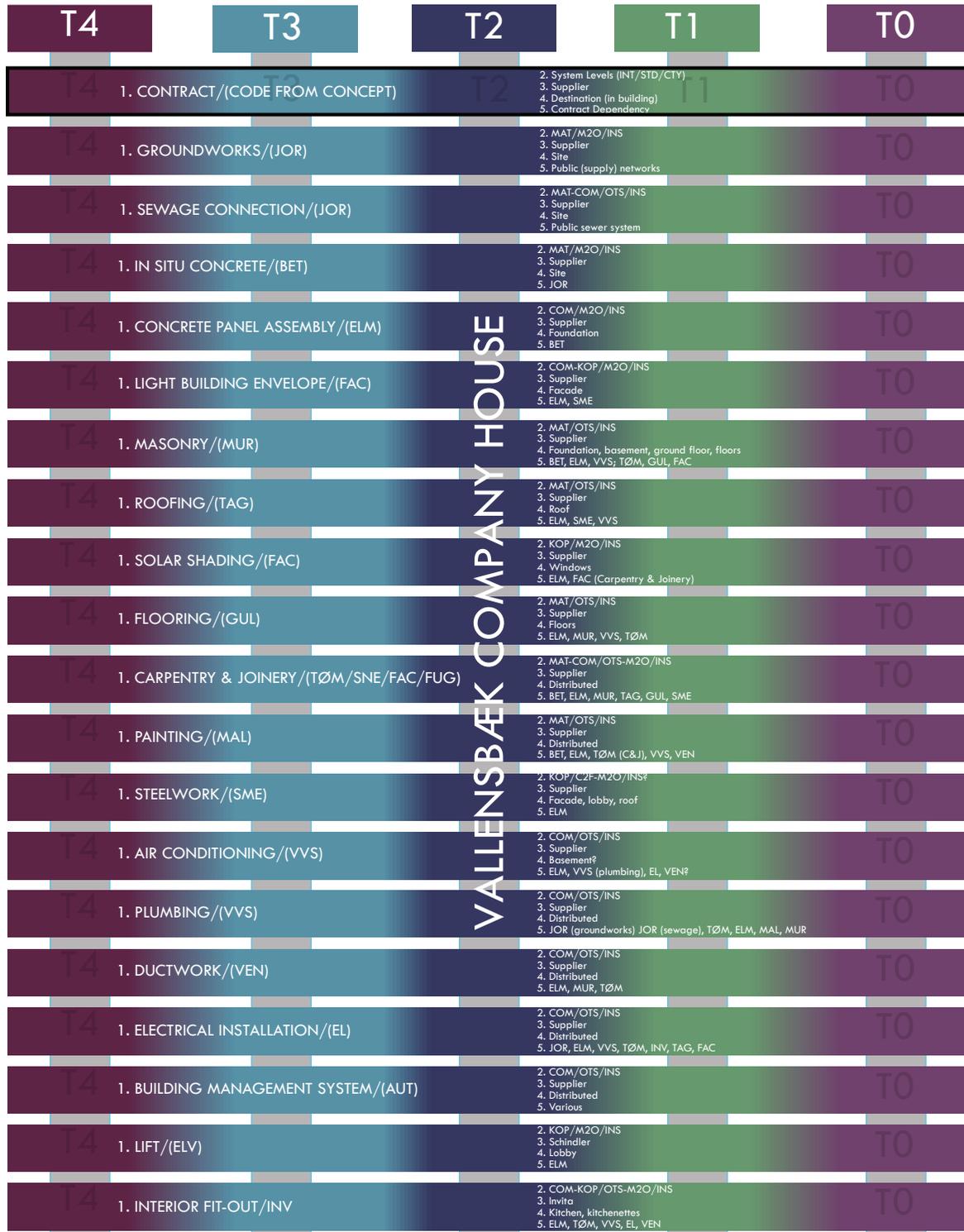


FIGURE IV.5.5  
THE SYSTEM STRUCTURE FOR VALLENS-  
BÆK COMPANY HOUSE EXPRESSED AS  
PARALLEL SUBCONTRACTS



- 90 Here 'module' is used in the more common sense of a discrete part of a whole. See 'part II - System' on 'Systems Terminology (II.5)
- 91 Another main incentive for off-site processes vs. on-site is the labour cost which often is lower off-site due to potentially enhanced use of unskilled labour.
- 92 However, as the previous case also showed, Scandi Byg is currently moving towards a more genuine industrialised *production* of their volumetric chunks based on several internal tiers and more automation in the factory processes.
- 93 The Swedish mother company made an attempt to develop a widely off-site produced solution in-house for dwellings. However, investments in this system, called NCC-Komplett, did not break even within the expected period of time and was closed down. For more details see Beim, Nielsen & Vibæk (2010)

(See figures IV.5.4 & IV.5.5). Miscellaneous work could e.g. be to install (INS) a delivery supplied (SPL) by a subcontractor.

However, the apparent indifference towards the more detailed system structure is only theoretical. On-site construction requires coordination between the different trades and subcontractors both time- and workspace-wise and this can in this case only be done efficiently by the turnkey contractor, NCC. This coordination could be fairly simple if – as in traditional construction a century or more ago – trades were few and the physical interfaces between these were simple both process- and space-wise. This is not the case even in a relatively standardised concept like DKH. Construction has, as argued earlier, become considerably more complex and most subcontracts as e.g. masonry work, flooring, painting, plumbing, ventilation and electrical installation are highly distributed deliveries meaning that they are *integrated* in the building as a whole rather than constituting clearly perceivable and physically distinguishable *modules*.<sup>90</sup> This means that all on-site processes connected to each sub-contract require considerable coordination with other sub-contracts and their sub-deliveries that consequently demand attention from the turnkey contractor. This complexity is a very common problematic in turnkey contracting and one of the main incentives for moving processes into off-site sub-deliveries – at least in the form of 'construction-under-roof' where site conditions are neutralised by a more controlled production environment.<sup>91</sup> The previous case in this part, Scandi Byg, represented until recently clearly this strategy of construction under roof where off-site construction based on relatively traditional and mostly manually based methods are executed in a controlled factory environment and mainly by unskilled labour.<sup>92</sup>

#### *Connecting client decisions and construction schedule*

NCC does not adapt the same strategy as Scand Byg and generally, as a turnkey contractor in a more traditional sense, sticks to an on-site scenario and focus.<sup>93</sup> In order to control and desirably reduce the complexity in attention, emphasis is put on the elaboration of a sophisticated and dynamic scheduling tool that can help coordinating the different dependencies among the subcontracts and among the different phases or stages that the each particular project goes through in order to prepare for a smooth final delivery on Tier 0 (on-site). The scheduling tool as a kind of advanced project stage model aims at 'packaging' and connecting client decisions (within the framework of the concept) with sub-

sequent design development tasks, procurement, delivery and finally construction/installation according to standardised packages and contractual divisions.<sup>94</sup> This in such a way that any change within one phase or package will have direct influence on subsequent downstream phases or packages ultimately changing the entire schedule. For DKH, the tool divides client decisions into 11 decision packages (BP), 9 design packages (PP), 16 procurement packages (IP) and 16 delivery packages (LP) that are ultimately connected to 20 different subcontracts (UX) and all put into one single schedule – (BPILU). (See figure IV.5.6).<sup>95</sup>

” ‘What is special about that schedule which we have spent considerable time on working out is that it is one big coherent schedule. You get five different [sub] schedules out of one file. If you move a delivery, all the rest will move as well. This is new.’

(LH/3/134)

Theoretically the packages and their connections express exhaustively where the client has influence on the project (through the decision packages) whereas all other decisions and subsequent tasks (of design, procurement, delivery and construction/installation) are standardised within the concept. The different packages are thus ideally an expression of all tasks to be performed on the specific project level while all other tasks already has been accomplished (and standardised) on the concept level. In the construction/installation phase (UX), the standardised concept tasks and the project specific tasks merge into one unified construction/installation plan.

The decision packages (BP) are divided according entities and themes that make sense for the client while the subcontracts and the construction schedule are divided according to the focus of the main contractor, NCC. The scheduling tool *translates* these client entities or themes into sub-contractor entities and sub-tasks while assuring consistency time- and solution-wise throughout the different phases. This means that e.g. the client’s response to BP4 – *Interior surfaces* or BP7 – *Catering Facilities* at the end are combined with the standards of the concept and translated into specific sub-deliveries and construction tasks within several sub-contracts i.e. *Carpentry (TØM)*, *Masonry (MUR)*, *Joinery (SNE)*, *Painting (MAL)*, *Flooring (GUL)* or *Interior Fit-out (INV)* (See figure 4463). The client is more interested and skilled concerning the service ‘Catering Facility’ than preoccupied with the specific trades involved in delivering this service. By packaging relevant decisions – and only these – in categories

94 For a presentation of different commonly used project stage models see *Classification systems in construction*, II.2

95 The applied abbreviations refer to the corresponding Danish terms (*Beslutning*, *Projektering*, *Indkøb*, *Leverance* and *Udførelse* = BPILU)

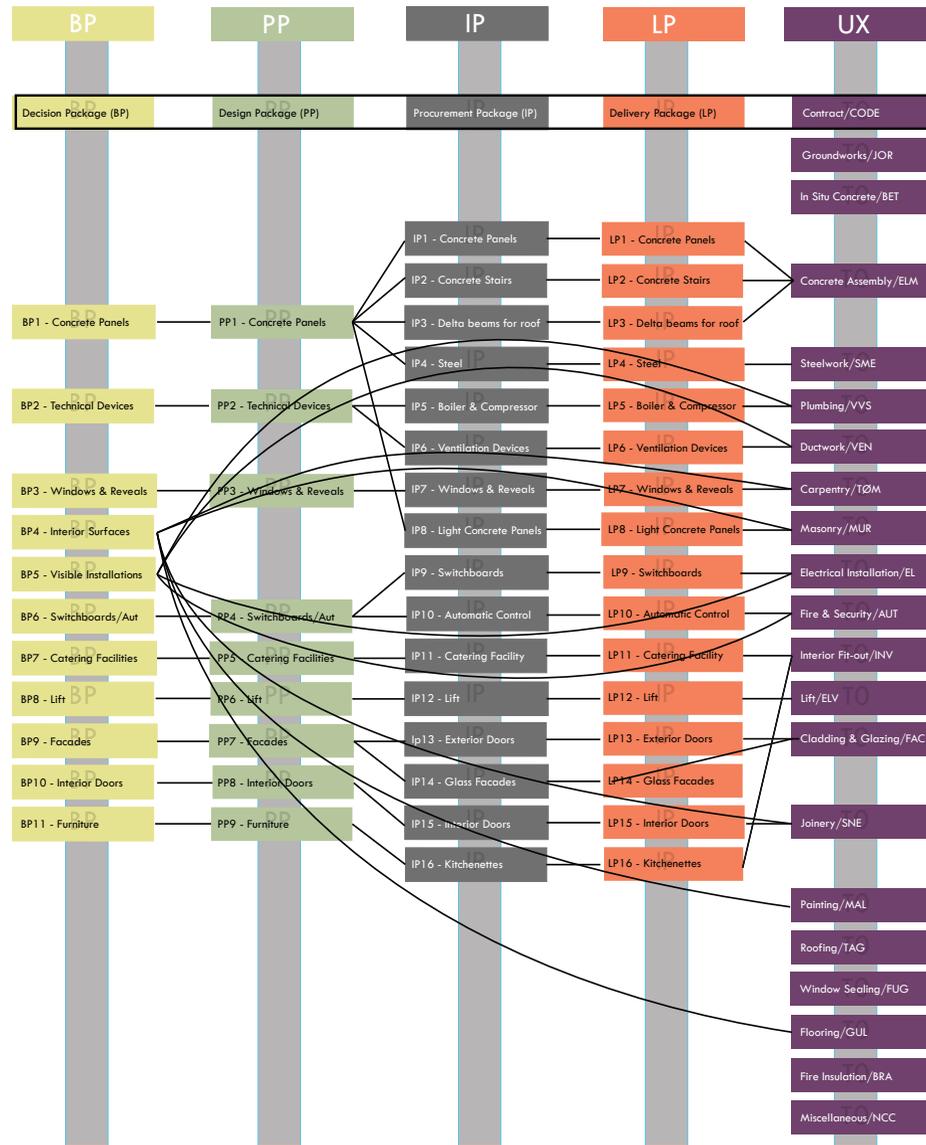


FIGURE IV.5.6  
NCC'S BPILU-STRUCTURE SHOWING  
THE DIFFERENT DECISION PACKAGES  
(BOXES) AND THEIR INTERCONNEC-  
TIONS (LINES)

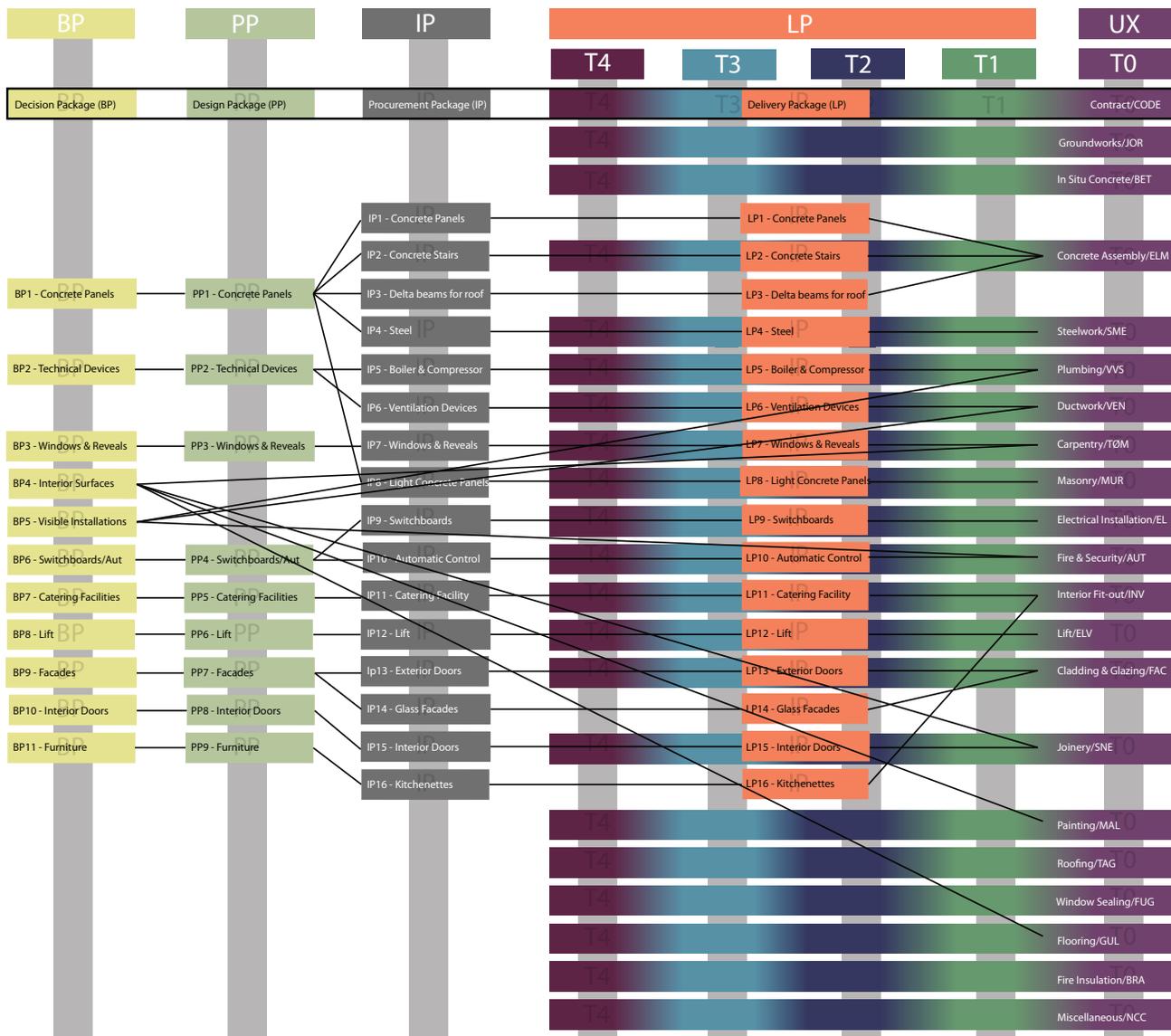
96 For a short introduction to supply chains and supply chain management see *Industrial production theory*, II.3

97 See definition in *Systems terminology*, II.5

relevant to the client, reduction of complexity in focus is obtained both for the client and for the contractor where the latter can both focus the interaction with client and reduce the amount of design work required in each project by drawing on standardised solutions (= *integrated complexity*) that exceed the project level. Information is *timely and accurate* as in an optimised supply chain (Hugo 2006:6).<sup>96</sup>

### Process schedule and system structure

The system structure and the model of it as defined within this thesis concentrates in its present state exclusively on deliveries or systems than include some physical element to be inserted in the final building. It focuses on the (primary) material supply chain whereas (secondary) service deliveries have been left out.<sup>97</sup> These physical deliveries can be combinations of materials, components, assemblies *and* the processes and knowledge to produce, deliver, or install them into a subsequent tier level (i.e. tier 0) but the final result of the delivery remains physical. The system structure is physical although resulting from different processes just like the product architecture of an industrial product. NCC's packages above are rather concerned with *processes* as system entity. The structure expressed in



the BPILU-model is the structure of a process whereas the specific *physical* division results from the way the process is divided into contracts and their subtasks and deliveries. Moreover client decisions and design development work are also processes but have no direct physical content. They are immaterial information or *knowledge*. However, the system structure also expresses some aspects of process in the form of simplified supply chains. When it, as used in this thesis, divides into different tier-levels and the deliveries become nested into each other from the less complex upstream deliveries on tier 4 and tier 3 over the more complex and integrated deliveries on tier 2 and tier 1 to the final tier 0-deliveries on-site, it is both displaying structure and process. Figure IV.5.7 shows an attempt to relate the two different models showing how aspects of process cross over with aspects of (physical) system structure. The system structure model is somehow both about what in the product industry would be called product architecture and about supply chain (management).

FIGURE IV.5.7  
BPILU AND SYSTEM STRUCTURE MERGED – BPILU IS MORE DETAILED ON PROCESS AND THE SYSTEM STRUCTURE MORE DETAILED ON PHYSICAL DELIVERY.

Although all subcontractors deliver on-site (tier 0) they potentially all encompass deliveries from further upstream tier levels (tier 4-1). These sub-structures (of deliveries and processes) mostly remain opaque to the contractor if they



FIGURE IV.5.8  
PARALLEL OPAQUE DELIVERIES IS A  
QUESTION OF VIEWPOINT. FURTHER  
DETAILING REVEALS SERIALLY NESTED  
SUBSYSTEMS

are not specifically described in the specifications produced either in-house or provided by an external consultant (architect and/or engineer). A subcontract as Painting (MAL) e.g. combines simple tier 4-deliveries with tier 0-processes into the final building integrated paint on e.g. the walls whereas the Concrete Assembly-delivery (ELM) combines tier 4-materials (i.e. joint concrete, mortar, and reinforcement), tier 3-components (columns, couplers and other embedded parts), and tier 2-assemblies (insulated concrete panels and reinforced concrete slabs) into the tier 0-assembly (onsite) of the structural building system. Important to point out is that a system structure always expresses a specific level of detailing that corresponds to the viewpoint it is seen from. In this case, the zoom is, as mentioned, the turnkey contractor's who is interested in what final works that belong under what contracts. If, however, we go further down in detail, these parallel deliveries (the subcontracts) can each of them be divided into a combination of sub-deliveries on different tiers. Some of these can be nested into each other. See figure IV.5.8

## INTEGRATED PRODUCT DELIVERIES – EXAMPLES

Due to the selected focus on subcontractor delivery as system entity combined with the fairly traditional organisational setup where most of these contractors deliver and install on-site corresponding to well known trade divisions, the system structure does not display the possible but opaque upstream sub-deliveries within each contract. As main contractor, NCC mostly does not have explicit focus on how different upstream deliveries are combined before they arrive for installation on-site as tier 0-deliveries. If specified, in most projects this would be the job of an external architect or engineer. However, in the *Danske Kontorbuse* concept NCC are in control of the entire value chain from conceptual

design over design development to procurement, delivery and construction and have actually made the descriptions. However, the choice of sustaining traditional trade divisions as the main system structure does not necessarily encourage the (traditional) subcontractors to make intensive use of more integrated off-site produced solutions – even if there could be both short term (time) and long term (quality) benefits from the use of such solutions. If the descriptions provided by NCC or external consultants do not point towards or at least to some extent are open towards alternative contractual divisions and/or physical solutions, the final choice of subcontractors will almost exclusively be about choosing the lowest bid – not necessarily the best solution from an architectural point of view.<sup>98</sup> Opening up for new solutions requires other incentives, other ways of describing and perhaps an earlier active involvement of the subcontractors in finding the best solution. *Early procurement* as mentioned in Part II – ‘System’ is an example.<sup>99</sup> The paragraphs below list up some of the few more integrated deliveries that are actually used in the specific office project and assumed for the general concept. Also other potentially suitable integrated product deliveries are discussed

### Concrete panels and slabs

Both *Vallensbæk Company House* and *Danske Kontorhuse* are based on a prefabricated concrete structural building system consisting of insulated façade elements, pre-stressed hollow core slabs and columns. This kind of structural system is very common in a Danish context where intensive in-situ work is seldom applied due to high labour costs on-site. Furthermore the Danish prefabrication concrete industry is very dominating on the market compared to other structural systems such as wood or steel based systems. In the system structure terminology both façade elements and slabs as planar elements represent tier 2-assemblies while the columns as more simple structural ‘lines’ figures as tier 3-components. Concerning standardisation level, all three can be characterised as made-to-order deliveries (M2O) based on a standardised production method and material composition and, within the concept, furthermore with fixed construction dimensions. The façade elements (approx. 3,5 m high X 6 m long) are prepared as sandwich constructions with insulation between an exterior and an interior layer of concrete. The interior part is prepared for electrical wiring and communication cabling while the exterior accommodates a later added tier 3-solar shading or other additional tier 3-façade claddings (according to the different models). Window location and window size is flexible within the structural constraints of each panel assembly that e.g. has a ‘column’ in

98 A similar view is also introduced in the *Kieran Timberlake* case. See IV.3. The following Arup Associates case, IV.6, introduces several alternative contractual divisions in a high end project where quality is primary to price.

99 See the section *Classification systems in construction* (Part II – ‘System’) where one of the stage models explicitly opens up for the possibility of early procurement.



FIGURE IV.5.9  
GLASS FAÇADE BY SCHÜCO IN VAL-  
LENSBÆK COMPANY HOUSE

100 For a delivery where a large unitised high-end solution was applied see the description of the Schneider façade cladding solution in the Arup-case, IV.6, later in this part.

101 See *Model presentation*, IV.1

the middle thus subdividing the basic façade module to 3 meters. The hollow core slab-assembly is one the most standardised precast tier 2-products on the market. Although perhaps not literally an off-the-shelf delivery (OTS), such slabs often have standard lengths and can to some extent be delivered/installed as cut-to-fit (C2F) assemblies or be accommodated on-site.

#### *Glass façade, doors and windows*

The Vallensbæk Company House consists, contrary to the general concept (or module), of two concrete wings connected by a lighter glass section with reception and service facilities thus forming a ‘H’ plan (See figure IV.5.9). The connecting glass section is clad with a tier 2-façade delivery made by Schüco – one of the major cladding manufacturers worldwide. Schüco delivers both stick-built solutions as a kit-of-parts and unitised panel assemblies (ASM) to be mounted on brackets and joined only by gaskets on-site. In this case a unitised solution was chosen. The entrance door including weather porch as a separate delivery was a stick-built kit-of-parts delivery due to the relatively limited size of the contract that made off-site production less cost effective.<sup>100</sup> The general concept (DKH) exclusively encompasses concrete facades although the façade modules in the lobby and reception area can have larger openings giving a vertical impression crossing over several floors. These and all other openings in both cases are fitted with tier 3-window and door deliveries.

#### *Other integrated product deliveries*

Most other sub-deliveries in the subcontracts are installed in quite traditional ways based on materials (MAT) and components (COM) delivered on-site and often require a considerable amount of adaptation and use of labour. This way of delivery closely corresponds to the theoretical scenario of ‘*contemporary onsite construction*’.<sup>101</sup> However, some of the sub-deliveries are already established standardised and marketed products with high preparation and standardisation levels. Solutions for both the catering facilities and the kitchenettes come as made-to-order (M2O) tier 2-assemblies based on projects elaborated by or in collaboration with the supplier and are based on highly standardised modules and measures. Another example is the lift delivered by Schindler, who also design, deliver and install lift solutions based on relatively few design inputs from NCC (as client/consultant) concerning available area, load requirement, surface design etc. while most design information already is embedded as standard configurations in their products. Equally, as in many office designs, tier 2-suspended ceiling systems, DEKO and Rockfon, are used. These systems

have the advantage of giving easy access to hidden installations above each office floor i.e. electrical wiring, data cabling, ventilation, heating and plumbing installation and often integrate fittings for lighting, ventilation, sprinkler and other fixtures. Suspended ceilings mostly arrive to site as stick solutions. Finally, the applied drywall solution by Danogips has characteristics of an integrated product delivery by comprising a completely designed system solution. It is however not prepared and delivered as such a coherent system but rather as various discrete tier 4-deliveries based on standard measures and with considerable adaptation needed on-site. Both service and preparation levels are low. Other partition wall systems – as e.g. glass partitions – exist as highly prepared and commoditised assemblies delivered to site but are not applied in the present case.<sup>102</sup>

#### **Potential use of IPD's in the DKH-concept**

The DKH-concept includes, as described above, standard cores including staircases, elevator, installation shafts, handicap toilet, kitchenette, cleaning repository and general storage. Although plan sizes varies, the core layout is fixed. Equally optional additional toilet cores are standardised. These cores would be an obvious target for more integrated deliveries that could even become further commoditised if sales volume of the concept went up or if they were sold as separate products for other contexts. As for the toilets, many products already exist on the market (bathpods) – mostly as made-to-order solutions (M2O) with considerable design flexibility offered to the client.<sup>103</sup> For the residential sector most solutions are tier 1-volumetric elements fully fitted and often sealed upon arrival to site. For larger toilet areas in offices and public buildings, volumetric elements are in some cases replaced by modular tier 2-wall assemblies that literally can be plugged together onsite.<sup>104</sup> When the volumes get bigger and installations per m<sup>2</sup> get relatively lower, tier 2-solutions can be a wiser choice. Although toilet and bathpod systems seldom represent high degrees of automation production wise, the controlled factory environment combined with the fact that they are known as established products on the market often makes both tier 1 and tier 2 solutions very cost-effective even for small batches. Concerning the installation shafts of the concept, NCC themselves have already developed a prefabricated tier 1-shaft system for residential projects. This system could evidently be adapted for use in office projects like the DKH-concept, where the project economy would not only benefit from the semi-automated configuration of the individual shaft solution but also could gain from the advantages of real mass-production by having larger batches of exactly or almost the same

102 See e.g. the *Transwall*-products shortly presented in the product catalogue of III.3

103 See *Customisable architectural subsystems*, III.2 and the *Pod-wall*-product shortly presented in III.3

104 For an example of this kind of toilet core delivery see the Arup-case later in this part and the *Powall*-product in III.3

- 105 KieranTimberlake's Lobolly House described in IV.3 includes volumetric chunks for mechanical rooms.
- 106 Authors own translation of models taken from the concept presentation.
- 107 For a description of the theoretical scenarios, see *Model presentation*, IV.1

solution. Equally, mechanical rooms could be delivered both as volumetric tier 1-chunks or panelised tier 2-assemblies whereas general storage and cleaning repository most obviously could form panelised solutions due to the high amount of 'empty space' in these if delivered as volumetric tier 1-chunks.<sup>105</sup>

As a supplementary feature, the different façade choices – in the concept material termed as *models* – could be unitised solutions equal to the possibilities of the glass cladding used in the *Vallensbæk Company House*. The standard model, called *DK-Basis*, just have the bare concrete surface of the structural façade elements that are only interrupted by the window openings and optional single panels between the windows to enhance the horizontal lines of the facade. Other models require extra charge and are created by installing an additional façade cladding on top of the concrete panel. The concept material outlines several models that are however until now only initial ideas meant for inspiration (panel look, screen look, lamella look, glass look and mirror look)<sup>106</sup> By developing a standardised bracket solution, these façade models could become a truly mass customisable feature of the DKH office concept with a more or less open solution space.

## EXPLANATIVE POWER OF THE MODEL

The coding of the DKH-office concept as a system structure is quite different from the two earlier cases of KieranTimberlake and Scandbyg, that distribute deliveries over all tier levels and display several chains of nested deliveries (from upstream tier 4 to downstream tier 0. Seen from the viewpoint of the contractor, NCC, the DKH concept and the specific VCH project on the contrary sustain a structure close to the theoretical scenario of 'contemporary on-site construction'<sup>107</sup> with a relatively large number of parallel deliveries (or sub-contracts) all present on the final tier-0 level (on-site) and mostly with opaque upstream sub-deliveries (on tier 4 to tier 1). Furthermore, even if zooming in on these sub-deliveries, only few of them are nested upstream into more integrated product deliveries (tier 2 and 1). The bulk of deliveries is rather brought directly into tier 0-deliveries as relatively simple tier 4-materials or tier 3-components nested on-site. An explanation of this apparently quite traditional system structure can, as mentioned above, be found in NCC's focus on process rather than on product(s). As contractor, NCC works mostly with the implementation of (design) ideas of others and is less concerned with a complete reframing of the

constituent elements of these ideas. In turnkey contracts, NCC bids on already established designs and subsequently divides them into a number of subcontracts corresponding to their usual (domestic) subcontractors. Although NCC within the office concept tries to bridge between idea and its execution (construction), they do not move out of the established subdivision even if other initiatives within the firm actually support this i.e. the development of e.g. the prefabricated configurable installation shaft. The reason should probably again be found in the process focus where the development and test of the dynamic scheduling tool (BIPLU) has been pivotal. However AK points out that when working on the design aspects of such concepts as the DKH, the product view – as e.g. expressed in a system structure - become interesting:

” *‘Where I find this [system structure] interesting for us is in relation to the design of such concepts and on a planning level. [It is] when we start - not on a single project but as here – on a building as a product. How would we like the model to be?’*

(AK/1/76)

The system structure coded for this case expresses the need for considerable on-site coordination between the different parallel deliveries. By furthermore displaying (traditional) trade based divisions rather than functional or performance based (integrated) divisions many of these deliveries are highly distributed and thus integrated into the building as a whole rather than into clearly delimited functional modules. This structure inhibits sub-contractor incentive for enhanced prefabrication by producing an immense amount of on-site interfaces between dominating deliveries i.e. plumbing (VVS), electrical installation (EL), flooring (GUL) and painting (MAL) instead of establishing alternative delivery divisions like e.g. fully fitted toilet units, technical rooms, installation shafts or kitchen modules that each of them integrate several of the former trades. However, some generally established integrated deliveries as Concrete Panel Assembly (ELM), Cladding & Glazing (FAC) and the lift (ELV) does show the general but slow market based tendency towards new divisions. NCC’s idea of concepts leading to products rather than projects could, among others, strengthen this market tendency by demanding new more commoditised sub-deliveries divided along new contractual divisions. In present case examples, the contractual structure rather sustains traditional trade divisions. NCC’s focus on process is primarily company internal and consequently runs the risk of sub-optimisation seen in a wider perspective.

108 In Denmark, contractor responsibility normally runs five years from project handover.

One could say that, by having all sub-contractors delivering and installing on-site, the service level is apparently relatively high. This, however, is opposed by the low preparation and standardisation levels of these deliveries that lead to very project specific solutions that are hard to warrant as products. As buildings are seldom designed down to each single detail and interface the innumerable and fuzzy contract interfaces on-site leave the turnkey contractor with much of the quality control and responsibility – and this on a *project* basis. Warranty periods of more than a few years are unusual within construction projects even though buildings are often built to last virtually for ever.<sup>108</sup> Fewer assemblers on-site through earlier serial nesting into integrated product deliveries produced off-site would enhance possibilities of proper *product* warranty.

## IV.6 ARUP ASSOCIATES

System structure of the Ropemaker Place project

### INTRO

The following analysis is based on a study at Arup Associates in London in October 2010. Particular focus is put on the external façade cladding that is used as a main example for discussion of different issues concerning the system structure of the analysed case. After a short description of the case, the company, and the case study and data collection procedure the system structure model is sought established for this case and its particular attributes subsequently discussed. In a final paragraph the explanative power of the model applied to this particular case is discussed.

### PROJECT TYPE – DESCRIPTION OF THE CASE(S)

The project type in this case is a bespoke high end 22 storey office building erected in a centrally located business area in London. The building, Ropemaker Place, was finished in 2009 and was commissioned by British Land, one of the largest property companies in the UK that develops, owns and manages retail and office properties. It was delivered to British Land as a so-called ‘shell & core’-project where reception, lobbies, infrastructural and other common areas are fully finished while the individual office decks are passed over to the tenants without any preliminary fit-out. Although Arup Associates provides the necessary general documentation needed for the tenants to accomplish the individual fit-out of the decks, they are not directly involved in this part that runs on separate contracts with the developer and landlord, British Land. The scale of the project and the budget for this kind of development combined with a demand for short and precisely scheduled construction time in order to hit the market at the right moment address a special category of contractors and suppliers which often have only few equals on the European or even on the World market.

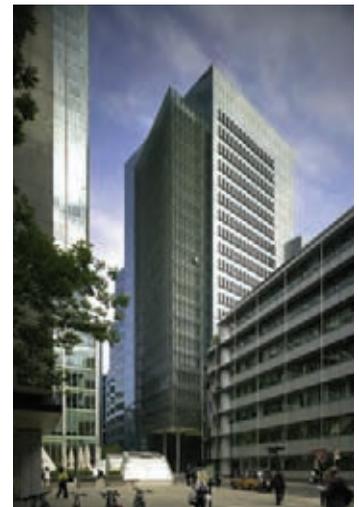


FIGURE IV.6.1  
ROPEMAKER PLACE, LONDON BY  
ARUP ASSOCIATES



FIGURE IV.6.2  
SECTION, ROPEMAKER PLACE



FIGURE IV.6.3  
THE ROPEMAKER PLACE BUILDING  
SCALES DOWN TOWARDS CHISWELL  
STREET ADAPTING TO THE CONTEXT

- 109 See <http://www.arupassociates.com> accessed on April 2, 2011
- 110 See <http://www.arupassociates.com>: “Total Architecture” implies that all relevant design decisions have been considered together and have been integrated into a whole by a well organised team. This is an ideal which is well worth striving for, for artistic wholeness or excellence depends on it.’ (Accessed on April 2, 2011)
- 111 At the time of the study as by October 2010
- 112 An explanation of the *construction management* approach will follow below.

## THE COMPANY AND THE ‘ZOOM’ OF THE ANALYSIS

The building, Ropemaker Place, and the coding of the corresponding system structure model is in this case seen from the perspective of Arup Associates who designed the project and as consultant in construction integrates architecture, structural engineering, environmental engineering, cost consultancy, urban design and product design within one studio.<sup>109</sup> As a subsidiary to Arup that was originally founded as an engineering consultancy in London in 1946, Arup Associates have been formed as exclusively dedicated to what they themselves term ‘Total Architecture’. The idea is that an integrated multidisciplinary design approach enhances the ability to work with the building as a whole from the start.<sup>110</sup> This makes it possible even on an early design stage to work closer with the question of how the building is procured, produced and erected and to let this impact directly on these early design decisions. Arup Associates, as opposed to Arup en general, only engages in projects where they are responsible for all consultancy disciplines. One could say they act as a kind of ‘total consultants’. Their project portfolio encompasses mainly corporate architecture, cultural institutions and university buildings. Arup Associates currently holds approximately 150 employees.<sup>111</sup>

The ‘zoom’ or perspective of this analysis is thus that of the consultant but not limited to the architectural consultant which in this case forms part of a larger team that coordinates internally. As subsidiary of Arup, the company also draws on a huge amount of technical knowledge and experience within construction in general. Particularly relevant here is Arup’s expertise and experience with the building envelope seen as a separate and highly prefabricated delivery. The building envelope was the most expensive single delivery (contract) of the Ropemaker Place building. The choice of a procurement route for the Ropemaker Place, following a so-called *construction management* approach, puts keen emphasis on the contractual divisions that in the British system seem to be more open for negotiation or at least different from a Danish context.<sup>112</sup>

The present analysis of the system structure for the Ropemaker Place deals with these different contractual divisions as pointers towards emerging integrated products and their interfaces.

113 Interview transcriptions (Interviews AA-1-3) are located in the Appendix . VI.6.D

## SPECIFIC DESIGN OF THIS STUDY – CONTRIBUTORS, PERIOD OF TIME, LOCAL CIRCUMSTANCES

The case study at Arup Associates was carried out as a four day study in the office in London. The choice of Ropemaker Place as a case was made from introductory conversations with Mikkel Kragh, Associate at Arup's Milan Office. Preliminary meetings had been set up with three key individuals in the London office involved in the project: Project Director, Paul Dickenson (PD), Architectural Director, Mick Brundle (MB) and Project Architect for the latter project stages, James Ward (JW). An introductory meeting upon arrival was held with PD and JW in order to focus the study and clear access to project material. Subsequent individual interviews were held with all three (PD, JW & MB) focussing on their specific role in and knowledge about the project. The four interviews will be referenced with the initials of the person, the interview number and the corresponding line number in the format (initials/interview #/line #).<sup>113</sup> In parallel to the interviews, time was used to scrutinise the office's project folders as well as the project web shared with the construction manager, Mace, and the client, British Land. The following analysis equally draws on this material. Finally a check-out meeting was held with PD in order to clear out proprietary issues of the material collected and the information obtained throughout the study.

## SYSTEM STRUCTURE – CODING AND SPECIAL PROJECT SPECIFIC FEATURES

Ropemaker Place was organised around a relatively large amount of individual trade contracts directly between the client, British Land, and different contractors. This particular project specific split was established already during the design development stage (PD/2/70) within the Arup Associates' design team in collaboration with Mace, the construction manager of the project who controlled the bidding process/procurement and the later management and coordination of these different contractors each delivering their particular bit

FIGURE IV.6.4  
SYSTEM STRUCTURE OF ROPEMAKER PLACE, PARALLEL TRADE BASED CONTRACTS

T4	T3	T2	T1	T0
	1. Work Package/#			
	1. Enabling Works/2030			
	1. Concrete Structure & Core/2300			
	1. Steelwork/2800			
	1. External Cladding/3200			
	1. Special Ceiling/3530			
	1. Roofing/3600			
	1. Brickwork & Blockwork/3700			
	1. Dry Lining & Fire Stopping/3800			
	1. House Management Fit Out/4100			
	1. Joinery/4150			
	1. Toilet Core Fit out/4250			
	1. Media Wall & Vitrine Artwork/4270			
	1. Stone Flooring/4300			
	1. Reception Desk/4400			
	1. General Metal Work/4500			
	1. Architectural Glass & Metal Work/4550			
	1. Decoration & Painting/4950			
	1. Signage/5200			
	1. Access & Maintenance/5500			
	1. Sprinklers & Wet Risers/6200			
	1. Mechanical/6300			
	1. Ductwork/6500			
	1. Building Management System/6700			
	1. Electrical Installation/7000			
	1. Fire Alarm Services/7050			
	1. Lifts & Escalators/7400			
	1. Security/7500			
	1. External Hard Landscape/8100			
	1. Soft Landscape & Terraces			
	1. Fire Extinguishers			

of the building (PD/1/127). This form of procurement is called *construction management* and the individual contracts are called trade contract packages or simply: *work packages*. The principal difference between the traditional (British) system of procurement and construction management is that in the former the final building design is divided into sub-contracts by a contracting body (a main or turnkey contractor) often using own sub-contractors without involving the designers and consultants (i.e. Arup Associates) in the choice and divisions whereas the latter, construction management, from the start is procured as these different work packages. This gives in this case Arup Associates as well as the client, British Land, enhanced control over the specific division into contracts and the choice of individual contractors, who engage in a direct contractual relation with the client. The contract manager, Mace, does not control this division – they manage it.<sup>114</sup>

The interesting thing about this in a discussion of system structure (which is dealt with here) is that it facilitates a way of splitting up the construction job in new ways that does not necessarily follow a specific turnkey contractor's internal organisation and/or traditions in the building sector. As opposed to traditional craft based divisions these work packages are in some instances delimited as modularised performance based deliveries that simultaneously transgresses and encompasses several of these traditional crafts<sup>115</sup>. In this analysis these work packages become the primary elements of construction – the elements of this particular system structure. Apart from facilitating new divisions these elements are as mentioned introduced already in the architectural and technical design phase thus bringing closer the way architecture is conceived and the way it is subsequently produced.

### Work packages

I have in the current analysis, in line with my definition of deliveries forming a system structure, limited the scope of work packages exclusively to encompass contracts containing some kind of physical delivery that forms part of the final building.<sup>116</sup> This means that some of the actual work packages found in the project fall outside this system structure analysis. Specific examples are introductory site investigations and archaeology, movement monitoring or logistic features on site as tower cranes. Work packages seen as system elements (deliveries) can have varying degree of focus on *thought*, *process* and *matter*.<sup>117</sup> Most will contain shares of all three, but in order to be reflected in the system structure they *need* as a minimum to figure in the final building as a physical entity.

114 Compared to a Danish context the construction management approach resembles traditional craft and trade based procurement (as opposed to turnkey contracting) with the difference of the construction manager which would here normally be the architect.

115 Or skillsets/trades

116 See *Systems terminology*, II.5

117 The distinction between systems of thought, process and matter is introduced in *General systems theory*, II.4 And further elaborated for (integrated product) deliveries in III.2

- 118 *'There is no kind of view that we would have on Schneider's, the cladding contractor's, supply chain and the coordination in terms of how they manage it. [...] It is quite opaque to us how they actually manage it. All we can see is the kind of new result.'* (JW/1/138)
- 119 General on 'Scope of Works' cited from Arup Associates's project material on Ropemaker Place

In the Ropemaker Place project this definition brings out 30 different work packages that together make up the entire shell & core building. Individual office deck fit out is, as mentioned earlier, not part of the construction project. From Arup Associates the work packages are prepared as a specification and a 'scope of work' description (PD/1/131).

The work packages behind the trade contracts are system structure wise thought as parallel, as opposed to serial, in the way that they generally all deliver physical matter installed *on-site* in the building itself. Within each work package and based on the project elaborated by Arup Associates the trade contractor is responsible for the entire supply chain from design to commissioning. This 'internal' supply chain can contain various suppliers, manufacturers and subcontractors and may consist of elements of varying integration levels (tiers) with varying preparation, standardisation and service levels. This sub-structure of the individual work packages is however in most cases opaque to the consultant and the client and thus not reflected in the system structure.<sup>118</sup> The deliveries in all work packages span from and include any sub-delivery from tier 4 (T4) to tier 0 (T0). Arup Associates describes the work packages in the following way:

*'The Works to be undertaken by the Trade Contractor shall be the design, co-ordination, procurement, supply, fabrication, manufacturing, delivery to site, assembly, installation, supervision, inspection, testing and commissioning of the Works. The Works shall be deemed to include all materials, components, assemblies and finishes together with all associated fixing devices, fittings and fixtures required to complete the Works in compliance with the Trade Contract.'*<sup>119</sup>

This underlines that the system structure is always a focussed view seen from a specific position – in this case from Arup Associates working as a 'total consultant'. This perspective combined with the Construction Management Approach creates the specific system structure of parallel deliveries spanning various tier levels (See figure IV.6.4). This structure is thus the system structure seen from Arup Associates' point of view.

However these parallel work packages also express that interfaces *between* the system elements (= the different deliveries of the system structure) are primarily found in Tier 0 (T0) – the building site. Here (on-site, T0) the deliveries are no



longer parallel in the sense that some deliveries evidently depend on the prior execution of or the simultaneous coordination with other work packages. The concrete sub-structure (WP 2300) comes before the steelwork (WP 2800), the reception desk (WP 4400) comes after and upon the stone flooring (WP 4300), the security system (WP7500) has to be coordinated with the access doors of the cladding contract (WP 3200) etc. The system structure of Ropemaker Place becomes a series of specific contractual interfaces that are all present as processes onsite and only interface physically here.

### *Divisions and Interfaces*

Although the (sub) supply chain of each work package in principle is opaque to Arup Associates certain ways to control their execution is indirectly introduced through several means: The initial breakdown structure,<sup>120</sup> their descriptions (i.e. interfaces, performance, available production time etc.) and through the selection criteria of each sub-contractor which is not exclusively based on the question of cost. Through the descriptions and in order to comply with the requested performance, the trade contractors of each of the work packages are encouraged to use techniques of off-site production as much as possible although in some cases restrained by the assembly sequence on-site and the coordination with the other work packages: The concrete substructure (WP 2300) and the structural steel structure (WP 2800) e.g. set up constraints on the size of prefab elements that can be lifted in. Likewise the scheduling of the façade cladding montage is decisive for the delivery of larger elements or ‘flatpacks’ to decks by the tower crane. Some work packages still follow quite traditional lines of division corresponding to old crafts or fragments of these. An example could be the ‘Brickwork and Blockwork’ package (WP 3700) or the ‘General Metalwork’ package (WP 4500). Others like the ‘Toilet Core Fit-out’ package (WP 4250) or the ‘House Management Fit-out’ package (WP 3530) transcend these traditional divisions – in the first case as a mainly off-site produced integrated and modularised kit-of-parts solutions, in the second case as a primarily site based adaptation and joining of lower integration level items. Both packages contain elements and processes stemming from many different trades or skillsets/crafts. Thus, a work package that does not follow traditional divisions along crafts or well established trades does not necessarily result in more integrated products or more off-site fabrication. If the work package encompasses building parts that are physically and/or functionally clearly delimited either as single parts (as e.g. a bathpod) or modularised systems (as e.g. façade cladding panels) it is however more likely that integration and off-site fabrication will

FIGURE IV.6.5  
THE ROOF TERRACE LANDSCAPING  
WAS A SEPARATE WORK PACKAGE  
(SOFT LANDSCAPING)

120 In the production industry *work breakdown structure* describes the way the production of a product is split into different elements.

take place. If, on the other hand, they are distributed and interface with many other packages it is less likely. However, the structure of parallel deliveries can provide for high levels of the service dimension thus compensating for low preparation levels. I will go more into detail with some of the specific integrated product deliveries found in the work packages in a later paragraph.

#### *Changes or negotiations of interfaces*

As mentioned above, the division into work packages of the Ropemaker Place is project specific. That is however not the same as saying that it has been made from scratch for this particular project. Arup Associates has developed the base for an internally used standard division of construction works into work packages about thirty years ago from a specific factory construction project developed together with the big construction company, Bovis. (PD 2/109). A general (work) breakdown structure was established assigning four digit numbers to each work package. The number of different work packages has decreased since then due to the fact that construction managers, as Mace in this case, prefer a reduced number of contracts that require less coordination between the packages (which is the construction manager's responsibility) and more coordination within the packages (which is the trade contractor's responsibility) (PD/2/133). Mostly, the original packages are simply merged i.e. piling, concrete basement construction and 20 floors concrete core (WP 2300) or external cladding, entrance doors and atrium (WP 3200) in the case of Ropemaker Place. Parts of some of the original work packages are in some instances put into several different work packages; Although Ropemaker Place still contains an 'Electrical Installation' work package (WP 7000), many of the other packages equally contain electrician work. The 'Electrical Installation' work package contains the general installation and is distributed all over the building while the electrician tasks moved to other packages are either physically clearly delimited as in the 'Toilet Core Fit-out' package (WP 4250) or the 'Reception Desk' package (WP 4400) or functionally clearly delimited as in the 'Security' package (WP 7500) or the 'Access and Maintenance' package (WP 5500).

In a way the 'ideal' number of work packages is a weighing of control vs. integrated complexity. A reduced amount of packages also reduces the control of the construction process seen from the point of view of the client and Arup Associates as consultant. In the extreme, as with the traditional (turnkey contract) model, one contractor is in charge of all construction work. The project is handed over from the consultant (Arup Associates) as one package that the

contractor himself then splits up beyond the control of the consultant. On the other hand, the complexity to be coordinated increases with a high number of packages. This coordination is the job of the Contract Manager, here Mace, that would evidently like to reduce this to a minimum.

#### *The external cladding work package – an example*

Although work package divisions and the resulting interfaces tend to follow a semi standardised internal system defined by Arup Associates themselves there are however always project specific negotiations of the interfaces between the packages. Apart from the physical and functional delimitation as well as the coordination issues, as mentioned above, reasons can also have to do with economy. The external cladding delivered by Schneider (WP 3200) is an example of various aspects at a time pointing out both expediency and problems. The cladding contract was the highest value work package of the project (JW/3/16). The building type (both high end office and green building) demands a high emphasis on the façade solution allocating a considerable percentage of the total budget to get this right. This means that the primary focus here is not the price, but rather the capability of the contractor to combine high quality and smooth installation. Only few suppliers in the world are able to meet the requirements for this kind of contract.

The German façade construction company Schneider was chosen for the job. Schneider both plan, manufacture and install bespoke façade solutions and have specialised in off-site produced unitised systems.<sup>121</sup> The ‘External Cladding’ work package (WP 3200) included in this case all vertical external cladding on all facades including recessed main entrance doors and ground floor retail facades. It included furthermore external soffits (over ground floor recess), an internal glass vitrine for ventilation and artwork in the reception area and internal and roof glazing for an atrium. However, the external cladding for the roof plant on the top roof was, with exception of the louvers, transferred to the ‘Roofing’ work package (WP 3600). This transfer was apart from advantages in sequence and interface coordination issues also an economical disposition considering that the conventional skillset of the roofing contractor was far sufficient to solve that task and thus avoiding to pay Schneider a premium as over-qualified for ‘a bit of tin cladding’ (PD/2/151) which is not even their speciality. As PD expresses it: ‘If it is separated from or different in the timing or complexity you would look for the most economic way to buy that’ (PD/2/156). In this case both of these circumstances were present.

121 The specific system will be discussed more in detail under the ‘Integrated Product Delivery’ paragraph below.

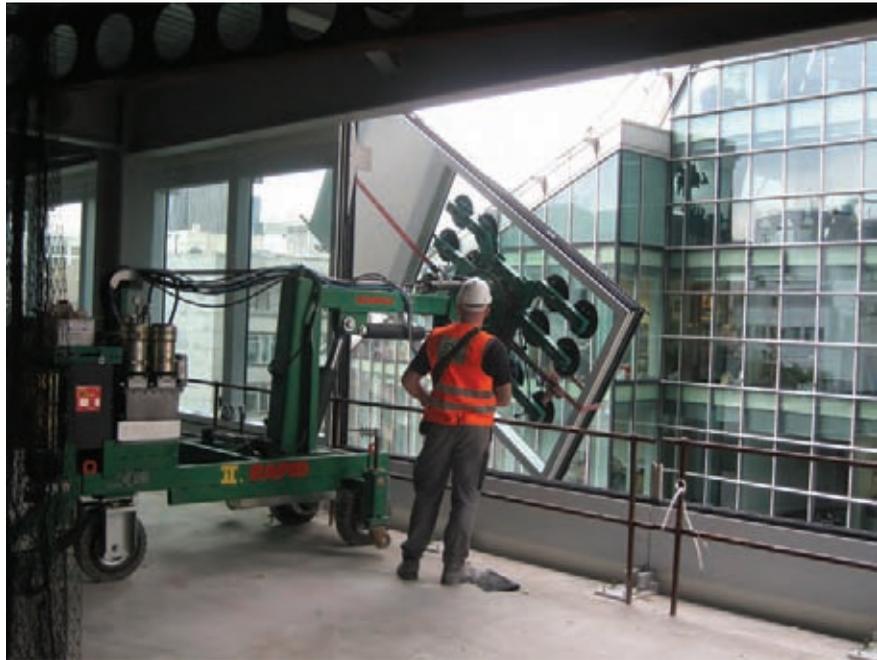


FIGURE IV.6.6  
FACADE CLADDING ASSEMBLY PRO-  
CESS

Other tasks should, according to JW, probably have been moved to other packages as well. Unitised solutions, the speciality of Schneider, are very common for buildings with larger glass facades as Ropemaker Place. These prefabricated façade units are easy to lift onto the decks on tall buildings by tower crane and are subsequently installed by the use of a special robot that moves around on the floors, takes the glass out, rotate it, lift it and drop it into position (JW/3/245). The on-deck robot further streamlines the process by saving tower crane time thus being released for other tasks (See Figure IV.6.6). However, ground floor cladding, atrium glazing and in particular the main entrance doors are not equally suited for unitised systems, that tend to be less slim than stick based systems. Schneider ended up with a hybrid solution of unitised and stick based for these parts. The result was fine but they struggled a lot with it and, as it only constitutes a minor part of their total contract, they had much lesser focus on it than if Arup Associates had placed this work in a separate package suited for a smaller contractor specialised in stick-built solutions. In the case of the main entrance doors a further complication was the electrical controls interface. Schneider are strong in engineering but they are not electricians and the electricians don't understand the cladding business (JW/3/284). An alternative would have been a separate work package – and delivery – for the access doors taken home by a contractor specialised particularly in these issues thus displacing the interface to the physical border of the entrance doors and letting Schneider concentrate on what they do best – unitised façade cladding.

#### *Whose fault is it and/or who can fix it?*

An important point when discussing the interfaces between different deliveries – or in this case – the work packages is what to do when faults occur or when things fall 'between two stools'. It is essential to have clear interfaces in order to know who is doing what. This is not just in order to be able to place responsibility but – and perhaps more important – equally in order to be able to finish the construction work. When interfaces are not clear the probability

of making faults increases. However these interfaces are not just physically defined. They have equally to do with process flow – one process can depend on or impede others and it can be quite a challenge to see through this web of dependencies – in particular if things change during the process. In the case of Ropemaker Place the ‘External Cladding’ package (WP 3200) depends evidently on the base building represented by the ‘Concrete structure & Core’ and the ‘Steelwork’ packages (WP 2300 & 2800). The steel structure was built upon a concrete substructure and core which again was built on a concrete raft. Apart from the fact that the steel is slightly over dimensioned in order to take up compression due to the weight of the tall structure the concrete substructure and core progressively move into position as the building comes up (JW/3/52). The cladding manufacturer uses datums from the core to dimension and produce the unitised façade elements. However instead of following the originally planned sequence of onion ring installation (one storey at a time) the cladding contractor was asked first to close vertically around the cores in order to provide weather protection and make it possible to start the core-fit-out represented by the ‘Dry Lining & Fire Stopping’ and the ‘Toilet Core Fit-out’ packages (WP 3800 & 4250) and others. As the building moved downward into position these datums were moving down relatively and the cladding guy realised that beyond a certain point the cladding units would no longer fit (JW/3/76). Responsibility for this problem is very difficult to determine. However, the only contractor that can *solve* the problem is the cladding contractor. According to JW, there seems to be a movement and a will in this kind of high end jobs to look for the person who can fix the problem instead of finding the one to blame (JW/3/79). This requires some level of mutual understanding and team spirit that can be hard to achieve if the relation is strictly ad hoc project oriented where economy is tight.

## INTEGRATED PRODUCT DELIVERIES – EXAMPLES & INNOVATION IN COMMODITISATION

Due to the work package focus of Arup Associates, selected as viewpoint in this analysis, mostly the system structure does, as mentioned, not display any sub-deliveries within the work packages. Generally Arup Associates do not have direct focus on these upstream tier levels; they divide and describe the content of the work packages through the scope-of-work and the description and thus only indirectly control how each package is actually produced by each

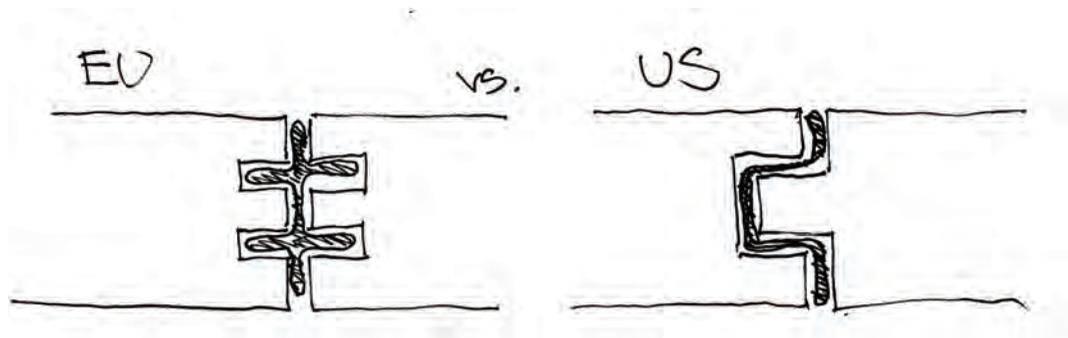


FIGURE IV.6.7  
EUROPEAN VS. AMERICAN FAÇADE  
CLADDING – AUTHOR'S SKETCH



FIGURE IV.6.8  
FAÇADE CLADDING MOCK-UP AT  
SCHNEIDER'S FACTORY

122 On component level many facade products exist as simple standardised plates or sheets with or without matching systems for attachment. Even though standardisation level might be high they oppositely often represent low preparation and service levels

of the contractors before they deliver on-site. Still, Ropemaker Place contains several examples of different degrees of integrated products. A manufacturer focus, as in the Scandi Byg-case, within each of the work packages would alternatively have revealed the detailed system structure of the many parallel supply-chains. This paragraph brings in some of the more integrated sub-deliveries 'hidden' within the opaque work packages.

#### *Unitised façade cladding*

The unitised façade cladding used from first floor and upwards is an example of a bespoke high end industrialised solution where the client is ready to pay a premium to get the best possible quality on the market. The specialisation in façade cladding crosses various traditional crafts and skillsets and has gradually become established as a separate discipline based on considerably specialised knowledge drawn from several fields. In the present system structure terminology the unitised façade delivery represents a tier 2-delivery – an assembly 'by system'. However, the degree of commoditisation – the façade solution seen as a product – is so far low or not very developed for solutions with this degree of sophistication and customisation. While the preparation and service level might be high, standardisation is low.<sup>122</sup> Although Schneider, as cladding manufacturer, in the specific solution draw on several standardised products, i.e. the Schüco-produced gaskets, each solution is rather a *project* delivery than a *product* delivery. Most of it is specifically designed and produced to the building project and not (simply) based on configuration of an already existing system (product). It is however Schneider, and not Arup Associates, that designs all junctions (MB/4/159) and follows what JW terms as the European school of cladding as opposed to the American school of cladding. In the European system, mainly developed by Schüco, the profiles of each façade unit (assembly) are structurally independent and are only connected by the rubber gaskets in between that create the weather seal (JW/3/161). In the American system the profiles from each unit (assembly) interlock and become one structural entity with the rubber gaskets only as sealants – not connectors. (see figure IV.6.7)

“The fundamental [difference] is that the [European] is a symmetrical profile with a non-structural link where [the American] is a metal to metal link and an asymmetric profile”

(JW/3/164)



Although the American system is structurally the most efficient because the connected profiles can borrow structural capabilities from each other, the European system is so tied into Schneider's supply chain that Arup Associates, by choosing them, do not have influence on the choice of cladding school. The Shüco produced gaskets define the solution space of the profiles but also ensure that by following the prescriptions of use for these gaskets the product liability can be placed with Schüco.

#### **Toilet core fit-out**

When toilets or bathrooms are made for residential units it often makes good sense to produce them as tier 1 deliveries (T1) – chunks or 'assemblies by zone' – even if the rest of the building is produced as conventional on-site processes or partly as flatpack prefabricated deliveries based on planar tier 2-elements (T2). This has partly to do with the limited size of private bathrooms. In the case of Ropemaker Place, the toilet cores on each floor were much larger and furthermore divided into ladies', men's and handicap spaces. The manufacturer and contractor, Swift Horsman, chosen for the 'Toilet Core Fit-out' work package (WP 4250) market a specific product under the brand 'Podwall'. According to their homepage Podwall *'is a fully prefabricated modular walling system incorporating finishes and services all of which are manufactured completely off-site in a dedicated controlled environment'*<sup>123</sup>. The modules (or assemblies) are brought to site as a tier 2 delivery (T2) and are literally plugged together and into the building with minor on-site preparation. Swift Horsman is according to PD one of the few companies able to deliver the required quality. Generally the companies who deliver prefabricated toilets originate from the joinery business rather than being grounded in skills around the services as plumbing, ductwork or electrical installation. Off-site joinery is generally good but the quality often fails in the service systems. The origin of a company is not irrelevant. It defines the basic skillset and somehow even the fundamental mindset they work from. Swift Horsman comes out joinery but has as one of the few developed a sophisticated product that is not just a matter of 'putting some stuff together in a factory' (PD/2/194). As a made-to-order (M2O) kit-of-parts of assemblies with a high service level the Podwall represents a highly industrialised integrated product delivery. One of its major qualifications in this sense is the fact of being both functionally and spatially clearly delimited. Still here there are some interface issues: Due to the requirement of a unified solution in order to test certify the systems of the 'Fire alarm services' and 'Security' work packages (WP 7050 & 7500) Swift Horsman had to coordinate with these packages doing their part of the installation onsite.

FIGURE IV.6.9  
SWIFT HORSMAN'S PODWALL PRODUCT DURING AND AFTER INSTALLATION

123 <http://www.swifthorsman.co.uk/companies/swift-horsman/products/podwall> accessed on April 1, 2011

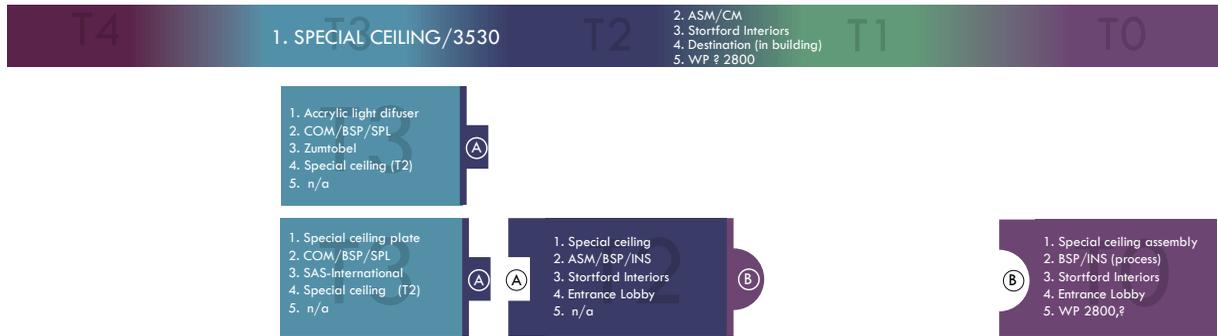


FIGURE IV.6.10  
FOR THE 'SPECIAL CEILING'- WORK  
PACKAGE ARUP COORDINATED NE-  
STED SUBSYSTEMS



FIGURE IV.6.11  
INTEGRATED SPECIAL CEILING PREPA-  
RED FOR SERVICE ACCESS

### Special ceiling

Also the 'Special Ceiling' work package (WP 3530) integrates various trades or crafts delivering a clearly delimited part of the building both physically and functionally speaking – a special ceiling in the entrance and lobby area, that apart from integrating the lighting solution for this area also facilitates easy service access to lighting fixtures and to the technical installations above. In this package, delivered by Stortford Interiors, Arup Associates did have focus on some of the underlying supply chain. (See figure IV.6.10) The solution was designed as a bespoke solution (BSP) by Arup Associates and produced as a combination of bended perforated metal, produced as a sub-delivery by SAS-ceilings and sockets and special acrylic diffusers produced as a sub-delivery by the German lamp manufacturer Zumtobel. The sub-deliveries were assembled off-site as ceiling assemblies (ASM) and later installed and connected on-site (T0) – both steps by Stortford. (MB/4/296). After installation each of these 'gullwing'-shaped modules can be flipped down for service access (See figure IV.6.11). The ceiling solution brings two tier 3 deliveries (T3) together in a tier 2 delivery (T2) modular system that could perfectly be marketed as an integrated suspended ceiling solution. This is however not the case so far. A similar although not identical solution has later been applied in the reception area of Arup's main office in London. The creation of a solution like this is a typical expression of the course of product development in the building industry. A specific project with enough budget to develop a bespoke solution (BSP) become the launch pad for a new commoditised product. A condition for a successful implementation as a more standardised product (either OTS or M2O) is a business setup where the involved parties either engage in a consortium or where one of the stakeholders takes on the role as owner of system – possibly through buying the others out or by paying them royalties. Many well known industrial design objects have been established this way.

### Other integrated product deliveries

The 'Stone Flooring' work package (WP 4300) delivered by Grants of Shoreditch ltd., actually covers a slightly more sophisticated product than just the work of a tiler on-site. As stated by MB, Arup Associates strive towards prefabrication and dry construction (MB/4/220). In this context advanced office flooring has developed into integrated systems that preserve the aesthetics and durability of traditional stone flooring that is the background of Grants of Shoreditch. The installed 'Technik Floor' is, as a tier 2 (T2) delivery, a prefabricated screedless raised dry assembly product that furthermore integrates func-



FIGURE IV.6.12  
TECHNIK FLOOR SUPPLIED BY GRANTS  
OF SHOREDITCH AS A TIER 2-ASSEMBLY

tions as underfloor heating and in-floor lighting. The floors were installed in the entrance lobby, the atrium and in the lift lobbies all the way up the building (see figure IV.6.12) According to PD there are probably only three companies in the UK that can deliver a solution on that level and only the scale of the Ropemaker Place project makes it possible to choose one of these (PD/2/173). Apart from quick installation and reinstallation the cavity below the raised floor makes it possible to run supplementary or later added cabling in a flexible way and without having to hack up the floors. Flooring in the toilet cores and in the house management area were extracted from the ‘Stone Flooring’ work package and installed under these fit-out work packages.

The vertical service risers are often, in projects of the scale of Ropemaker Place, delivered as complete volumetric tier 1 (T1) solutions that sometimes span several floors and include all vertical service routing as sprinkling, water supply, ductwork, cable trays and man access for later re-servicing and supplementary installation. These assemblies are simply dropped into place as the building goes up and secondary pipework and cabling are connected from here.<sup>124</sup> However, in Ropemaker Place this vertical riser work package lacks and pipework and cabling were instead located together with the secondary installation under the different more craft rooted packages as ‘Sprinklers & Wet Risers’ (WP 6200) ‘Mechanical’ (WP 6300), Ductwork (WP 6500), ‘Electrical Installation’ (WP 7000) etc. Ropemaker’s a little unusual design with the many setbacks of the roof terraces made the volumetric prefab strategy untenable because of the enhanced need for transfers. Instead a whole series of tier 3 (T3) flatpack components were brought and hooked into an equally flatpack delivered steel carcass. (PD/2/254 & MB/4/235)

#### **Ropemaker deliveries as ‘haute couture’**

In some way the façade cladding, the toilet cores, the ceiling system and the stone flooring in the Ropemaker Place project, can be seen as a kind of ‘haute couture’ or ‘formula 1’ that, as in the clothing or the car industry, points out certain tendencies that subsequently diffuse into the more conventional commodity market (read: become commoditised). The construction industry has, apart from materials and smaller components, only sparsely been able to develop well established building products. The enhanced complexity to handle in contemporary construction, as pointed out elsewhere<sup>125</sup>, combined with the demand for short installation time however seem to push the general development towards more advanced system solutions with high levels of standardisation, preparation as well as service.<sup>126</sup> ‘Haute couture’ markets like external



FIGURE IV.6.13  
PIPEWORK AND CABLING IS MADE AS  
DIFFERENT CRAFT BASED DELIVERIES

124 On the Danish market NCC Danmark recently launched a configurable installation shaft for residential construction. The product has also been adapted to a pharmatech project. See e.g. III.3 and <http://www.ncc.dk/da/Materialer-og-services/Installation/Skakt/> accessed on May 28, 2011

125 See e.g. *Introduction to problem area*, I.3

126 These three dimensions are explained in the *Systems terminology*, II.5

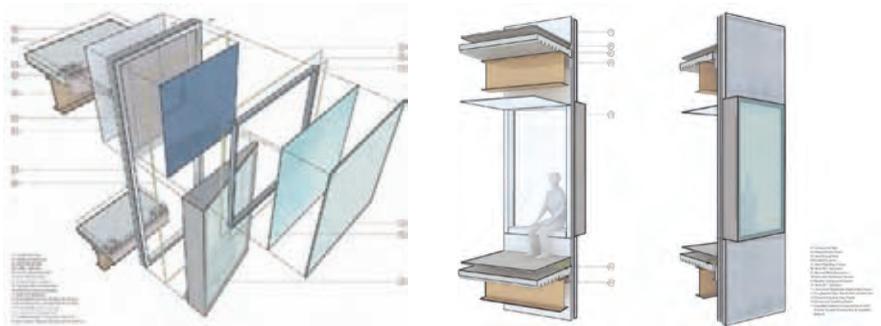


FIGURE IV.6.14  
THE FAÇADE CLADDING OF ROPE-  
MAKER PLACE IS NOT A STANDARD  
PRODUCT

127 Many now standardised and marketed building components are originally developed for a specific purpose in a specific building project and are subsequently established as product due to their general applicability.

cladding of office buildings or some of the other examples given above could show the way for development of new ‘off-the-shelf’ or ‘made-to-order’ (OTS/M2O) products in the building industry. In that sense product development within the building industry, as pointed out under the ceiling paragraph above, still, as it has always been the case, takes place on project basis and is not, as in the product industry in general, an activity detached from the production itself.<sup>127</sup> The new aspects here, however, are that product development, as in the case of the façade cladding, is on the one hand more integrated than simple materials or building components and, on the other hand, that it points towards the emergence of a new product *type* through the redefinition of the contractual, physical and functional interfaces expressed in the work packages. New integrated product deliveries do not just come out of a good (design) idea; they are equally tied to the way construction is organised.

## NEW DIVISIONS EQUAL NEW ELEMENTS IN CONSTRUCTION

The Ropemaker Place project and some of its work packages as e.g. the ‘External Cladding’ package (WP 3200), the ‘Toilet Core Fit-out’ package (WP 4250) and others point, at least seen from a Danish perspective, towards new divisions between the elements of construction that could have its logical counterpart in the way the architecture is conceived in the first place. Through (design) demands for highly flexible integrated and commoditised building products along these new lines of division, architectural creation and conception could come closer to the way these ideas are later actually produced thus decreasing the need for tedious and cost intensive translation into the construction of these ideas – a translation often resulting in simplification or degradation of the concept. Integrated products are knowledge intensive and thus not necessarily cheap compared to conventional upstream and on-site construction solutions. Through the architect’s active use and constant development of such more commoditised systems they can however potentially reduce translation and complexity issues thus displacing resources and focussing attention towards quality issues rather than cost reduction.

The construction management approach used by Arup Associates in the Ropemaker Place project brings them, as consultants, quite close to a contractor perspective but still with point of departure in the architectural design rather

than the later production of it. The partly project specific division into work packages is not only driven, it seems, by construction issues. The architectural design also plays a role here. By already on design development stage bringing in the division and by this also the form of procurement and indirectly even the way particular parts of the building will be produced, the distance between the architectural design as idea and the way it is produced seems to decrease. The way Arup Associates practises what they themselves call ‘Total Architecture’ somehow suggests *one* way – not necessarily the only way – to bridge the gap between architectural idea and the way it is actually realised or produced.

The procurement procedure with (parallel) work packages spanning from design over supply, manufacturing, assembly, delivery, and installation to testing and commissioning where one group of people takes full responsibility for the entire sub-supply chain makes liability issues much clearer and strongly facilitates the provision of warranties (= high service levels) which are rarely seen in conventional construction. The encouragement towards prefabricated solutions and the resulting nascent tendency of commoditisation of more integrated building products corresponding to tier 1 & 2 (T1 & T2) deliveries in the system structure model seem to reinforce this development.

## EXPLANATIVE POWER OF THE MODEL

The coding of Ropemaker Place as system structure is considerably different from e.g. the KieranTimberlake case(s) or the Scandi Byg examples. This is mostly due to the structure of a large number of parallel deliveries (the work packages) that each of them at least potentially span all of the different tiers while ending as tier 0 deliveries (T0). In the previous cases, these ‘supply-chains’ are divided serially into subdeliveries on the different tiers, that in the case of Ropemaker Place however become opaque from the analysed viewpoint of Arup Associates. The general system structure model has, as it is thought, two functions that are however closely related: One is to show how the final outcome, the building, production wise is constructed or assembled by different elements. Another is how these elements sometimes are embedded in each other forming supply chains that lead to more or less integrated product deliveries to be installed or nested into the building.

128 See *M' Model presentation*, IV.1

Compared to the theoretical model scenarios introduced in the model presentation, Ropemaker Place seen from the selected viewpoint is actually closest to the scenarios of 'traditional on-site construction' or 'contemporary on-site construction' by having these parallel lines of delivery from upstream tier levels (T4 & T3) to onsite delivery (T0) and many 'assemblers' on-site.<sup>128</sup> This is however, as mentioned above, partly explained by the general opacity of the supply chains within each work package as seen from the viewpoint of Arup Associates but could also be seen as a weakness of the model regarding the ability to express the actual system structure. These 'internal' supply chains and subsequently a much more detailed system structure could have been established through a more intensive in-depth study of the individual work packages. This would possibly show a (system) structural picture closer to the scenario of 'future industrialised architecture' with a tendency towards more tier 1 & 2 deliveries. The complexity of the model would have been high. However, in order to fulfil the overall goal of helping to reduce the complexity of the design process it is not necessarily the aim to establish a view of the entire supply chain. It is rather a question of showing the architectural design complexity *in focus* and equally to show where this complexity in focus has been reduced through the integration into 'opaque' work packages or deliveries, where each contractor is directly responsible for the complete delivery and installation according to the description, the scope-of-work and the drawing material elaborated by Arup Associates. This project material can of course be very complex in itself, but the point is that the internal coordination of the production of each work package is mostly outside the focus and attention of Arup Associates, the client and Mace, the construction manager that is hired to coordinate between work packages. Furthermore, the early introduction of these work packages already in the design development phase and Arup Associates' internal 'total consultancy' work facilitates better correspondence between 'project-as-thought' and 'project-as-built'. As mentioned above: contractors are only indirectly encouraged to use techniques of off-site production through means such as the overall work package division, the choice of work package contractors, the project material and its performance requirements. This strategy does not in itself guarantee but can potentially lead to an enhanced commoditisation of construction solutions and the emergence of more integrated product deliveries in construction. New work package divisions along lines that cross traditional craft based tasks that are typically distributed all over a building and towards divisions of simultaneously physically and functionally well defined entities – as here the façade cladding or the toilet core

fit out packages – present an interesting way of promoting new specialised contractors and manufacturers that develop integrated deliveries encompassing the entire supply chain. These new as well as traditional divisions are reflected in the system structure analysis of Ropemaker Place. Equally it points out the particular work packages where Arup Associates as architects or ‘total consultant’ have had special focus on the supply chain in order to get the right solution. These more focussed views correspond to the focussed discussion of system structure changes in the Scandi Byg analysis.

A disadvantage of the specific system structure for Ropemaker Place, as e.g. compared to the theoretical scenarios of ‘future industrialised architecture’ as well as of ‘conventional customised prefab’ or ‘conventional standardised prefab’, is the relatively high amount of tier 0-suppliers that furthermore also install on-site. This requires a different kind of coordination than if only one or few assemblers did the on-site job. Additionally, the tier 1 dominated prefab scenarios, as in the Scandi Byg case facilitate an earlier integration and give more time or possibilities to correct possible faults in the upstream sub-deliveries. The advantage on the other hand is the high service level in terms of the enhanced possibility of product guarantee and later servicing provided by the supplier which after all ought to be the expert within a particular field as opposed to a general assembler.



# PART V

# REFLECTION

V.1 FINDINGS

V.2 METHODOLOGICAL EXPERIENCE

V.3 CONCLUSIONS IN SHORT

- 1 See *Definition of Scope*, I.4, p. 18
- 2 See second part of *Systems in Architectural Theory*, II.1, p. 56-64

## V.1 FINDINGS

### - discussion of perspectives of system structure and use of the model

The present thesis has as the main contribution to knowledge suggested the introduction and use of the notion of *system structure* in architectural design as a way to conceptualise a systemic level in architecture and construction that lies between general construction techniques and specific architectural results. In order to make such a system structure operational, the principal and essential outcome has been the elaboration of an analytical tool in the form of a *system structure model* that seeks on the one hand to strategically grasp and on the other hand to make it possible to practically work with system structures as part of architectural design. Such endeavour has roots in the main question of the thesis about bridging an apparent and continuously increasing gap between architectural ideation and the way these ideas are brought to life as real physical manifestations of our built environment.<sup>1</sup> Although this split between idea and execution historically, as showed in the theoretical exploration of the the thesis,<sup>2</sup> can be traced all the way back to the Renaissance, the pronounced specialisation of the industrial era as well as the recently emerging and fast developing information technology has further accentuated this tendency.. Architectural design and construction have become a hugely complex matter and fragmentation of the knowledge needed to comply with the task produces risk of incoherent results. At the same time, however, this information technology has also strongly enhanced the ability to deal with complexity through data processing in quantities that were unimaginable just a few decades ago. New advanced management tools within all fields based on information technology are introduced on a daily basis and both processing speed and storage capacity are doubled within only a few years – while the devices that run these software based tools gets smaller and smaller. The notion of system structure and the proposed system structure model is *not* an attempt to keep up with this development and follow this track. On a much more basic level – partly defined by the limited scope of a single doctoral thesis – it is offering a qualitatively new way to look as this complex reality of construction and architectural design through a different kind of lens that detects and describes coherent wholes of interdependent elements rather than seeking to describe each of these in their outmost detail. In line with the so-called systems sciences the present thesis rejects the prevalent scientific view that the degree of detail ‘automatically’ enhances understanding and explanative power. Pivotal in the present research endeavour is that

the concept and the model of system structure seek to establish the idea of a *systems view* on buildings and architectural design that through the use of flexible constituent elements facilitates discussion about how architectural wholes are appropriately put together as assemblages of what the current and future building industry is capable of producing. Such a systems view has – it has been asserted – the potential of reducing design complexity in focus by enabling more qualified decision making concerning where to apply the ‘*precious and limited inventive power*’ or resources available in a building project.<sup>3</sup>

3 ‘*Precious and limited inventive power*’ alludes to the present stage of design as expressed in an initial citation by Chermayeff & Alexander. See Introduction to the problem area, I.3, p. 11

Furthermore it is asserted that by conceptually as well as practically drawing on existing and emerging *integrated product deliveries* when conceiving and realising buildings, design work – and thus design complexity – can strategically be outsourced an individual project and/or even reused over several projects. In the present thesis this has been termed *integrated complexity* and its use and related concepts are considered a second pivotal contribution to knowledge within the field of architectural creation in a contemporary industrialised context. This is not a reinvention of architecture and architectural creation – it is not an attempt to establish a new architectural paradigm or a different style. It does however represent a new way to *look* at what is already there – an industrially produced architecture – and argues that this new view and methodological approach can help facilitating a more active practical use of the present and future building industry in order to create *architecture* – not just construction – that is specifically attached to time, place and cultural context – not just the expression of smooth processes or cost efficient solutions. Important to note is that such a systems view is epistemological rather than ontological: A system as e.g. the proposed system structure with its constituent elements is – in the author’s opinion – in itself always an abstraction chosen or unconsciously adapted with the emphasis on either structural or functional aspects that can be associated with, not identified with the real world physical embodiment of the phenomenon it seeks to describe – in this case buildings or physical structures.

The current section should be seen as an attempt firstly to evaluate on the result of this endeavour and secondly as well presenting a selection from the more general findings about industrially produced architecture and construction – which to some extent comprise all architectural creation today – that has been produced throughout the work with the research and the thesis. Much of the relevant discussion in this thesis is located in the earlier sections of the different parts. Particularly the four case studies contain many points that can-

- 4 See sections IV.3 to IV.6
- 5 See *Definition of scope*, I.4, p. 28
- 6 See *Method and scientific approach*, I.5, p. 23
- 7 See *Method and scientific approach*, I.5, p. 25

not just be summed up here shortly in any meaningful way.<sup>4</sup> The ambition is, however, that the present section should pick up the most important of these in relation to the main question, as referred above, and to the stated goal of the thesis about proposing ‘*an analytical structure [...] for clarifying the potential of industrialised construction as positively enabling rather than limiting the architectural solution space*’.<sup>5</sup> A hope is that this will invite to dive deeper into the preceding parts and sections. Even here, the first two of the following paragraphs concerning the *system structure model* and the *integrated complexity* are primary for understanding the main contribution to knowledge of the thesis. A particular attention is also given to a discussion of the role of the architect in a traditional vs. an industrialised context. Subsequent paragraphs recapitulates on the inherent tension between *industrial* and *architectural* expressed in the notion of *flexible solution space* as well as on the problem of clearly distinguishing *product*, *process* and *project* – or the closely related triad of *thought*, *process* and *matter* which has led to the use of *delivery* as the embracing system entity in the proposed system structure model. The final paragraph points out some of the future perspectives of working with system structures in architectural creation.

## THE SYSTEM STRUCTURE MODEL

So what does the proposed system structure model actually show at the present stage of development? What are its limitations? And can qualitatively (new) knowledge about architecture and architectural creation, as suggested in the initial methodological hypothesis, be produced through creative development and use of an intermediary model as this system structure model?<sup>6</sup>

### *Limitations of the model*

The model at its present stage is – despite constituting the principal outcome of the research – not meant as definitive in the way that in order to become a directly applicable proactive tool in the process of architectural design it still needs considerable elaboration and preferably more external qualification and further tests. The reiterative abductive nature of its conception dictates successive approximation towards a satisfactory explanation.<sup>7</sup> This process exceeds the framework and time available of the present research and thesis and the model is in this sense only satisfactory seen as a step on the way. Another potentially limiting issue would, as mentioned in *Definition of scope*, be whether it

would have benefitted from being turned into a digital piece of software.<sup>8</sup> This equally lies outside the scope of the present thesis – a choice that however does limit the model's actual capacity for handling real world complex scenarios on a directly operational project level. Still, on the strategic level, the model in its present state can actually be used for analytical purposes as it is suggested and performed in the previous four case-analyses. However, comparability between different system structures is still limited as will be resumed further below.

<sup>8</sup> See *Definition of Scope*, I.4, p20f

#### *Chains of physical deliveries as a system view*

On the strategic level, the system structure model provides a possible definition of systems in a building as physical systems and their related processes as they are delivered and inserted into a building (deliveries) which inherently also touches upon the organisational setup. The coding of the different cases display considerable differences in system structures that can be explained in – or can itself be used to explain – both the different viewpoints chosen for the cases and the different characteristics of the particular projects that have been analysed. The model does have explanative power in this sense and seem to support the value of the notion of system structure as applied to industrialised architecture in particular as well as to architectural creation in general. The case-studies generate and facilitate through the model discussions about the way the particular architectural solutions have been conceived and subsequently produced and constructed as buildings and touches important issues about the means of production, the contractual setup as well as their combination and the resulting pros and cons. The angle and sub concepts around the system structure seem to provide qualitatively new knowledge in the form of a supplementary systems view on architecture and construction. This view can be used to talk about and regard the process of architectural creation as *chains of physical deliveries that are nested into each other on various tiers with different levels of integrated complexity* all ending on the building site where the building is assembled and constructed as combinations of these different integration levels. The model is particularly useful for explaining and analysing industrialised production scenarios that are based on a considerable share of off-site produced products. Integrated product deliveries as a new emerging type of delivery in construction has been described and are in the model clearly distinguished from more conventional material or component deliveries while the idea of integration is nuanced through the three dimensions of preparation, standardisation and service. One of the main points of using and discussing integration in architectural design which is facilitated by the system structure

- 9 By opaque is as earlier referred to integrated deliveries where nested upstream deliveries are not visible in the system structure.

model is in its sense of integrated complexity – i.e. the capacity of reducing and handling design complexity in focus. Integrated complexity as the second pivotal conceptual contribution of the thesis will be discussed further below.

### *Comparability and objectivity*

Important to point out is that the fact that the model displays considerable variance in system structures when applied to the different case studies in this thesis does not automatically mean that the cases are directly mutually comparable as system structures. Each system structure with its division into a number of deliveries is – at least at present stage of the model – an interpretation that depends highly on both the particular viewpoint (architect, contractor, manufacturer etc.) as well as the choice of detail when it comes to e.g. nested subsystems of the more integrated deliveries in the structure. This means that the discussion of a particular system structure presently is mainly project specific and can be used e.g. for a comparison of different possible production scenarios for that project rather than fitting into non-ambiguous universal categories of scenarios to pick from and align along. This is e.g. seen in the Scandi Byg case, where several project changes result in different changes to the system structure that can be compared. On the other hand, the previous establishment of a collection of theoretical scenarios has served as a base for some degree of comparison also between cases particularly when it comes to the contractual issues. Overall contractual issues have considerable influence on the system structure – and for the possibilities of changing a system structure if used as the pro-active design tool it potentially could become. All four cases represent different contractual setups which have more or less resemblance with one or several of the theoretical scenarios and, as the analyses show, the contractual setups can provide for new as well as it can fix the traditional organisation that, as pointed out, seem out of step with the current means of production of the building industry. In the case of NCC, the development of a streamlined internal process seem to remove focus from its possible mismatch with external efficiency that through a more appropriate selection of sub contractors perhaps could deliver more integrated solutions thus reducing complex onsite coordination. The Arup case shows a more conscious use of contractual divisions as a driver towards new integrated construction entities but has, with the parallel and relatively opaque work-packages, still a distinct trade and process focus that does not necessarily provide for the development of products of a more commoditised character and the resulting economical as well as qualitative advantages of enabling a more industrialised approach.<sup>9</sup> This will be also

discussed below. The Scandi Byg case, as being seen from the viewpoint of an off-site manufacturer, naturally expresses the wish for industrialised off-site production where the superior (lean production) goal of a steady flow of the production line encourages for new ways of balancing bottlenecks and over-capacity through outsourcing and product sale. This can give incentives for development more clearly delimited and discrete integrated product deliveries made of serially nested subsystems and support the establishment of new market niches. Finally, the KieranTimberlake case show how the same development can be substantiated ideologically through projects that are on the one hand *discursively* constructed as assemblages of integrated product deliveries and on the other hand *operationally* both makes use of existing as well as seeking to develop new products within this category. As the primary case constituting the initial inspiration – or *abduction* - for the system structure model, this case comes closest to the theoretical scenarios of a *future industrialised architecture* as presented in the model presentation.<sup>10</sup>

#### **Feedback from industrial participants**

Direct feedback from the contributors during the case studies has worked as *one* of the means of iteratively modifying the system structure model and the related concepts and thus potentially also for improving its practical applicability. As for the primary case study (at KieranTimberlake), the relatively long and ‘stretched’ duration of the study has provided the possibility for an extensive but continuous feedback on the initial elaboration of the basic concepts and the earliest abductions of the model. Feedback was received from the various persons involved through the performed interviews, the two formal presentation sessions (kick-off and wrap-up) as well as during informal discussions during the work day. Having point of departure in KieranTimberlake’s own theoretical as well as practical work with supply chains and integrated products in construction,<sup>11</sup> the system structure model (at its early stages) was generally received as relatively easy to understand among most of the people who got involved. Both the idea of enhancing the number of tiers as well as of mirroring the model for displaying disassembly scenarios were considered as useful elaborations of the office’s own theoretical work. However, in order to further improve the practical applicability questions were raised about how the model could equally encompass parameters as e.g. time and economy.

The secondary case studies have, as described, been conducted in a much more condensed format and were posterior to the primary.<sup>12</sup> In these cases, the model

10 See *Model Presentation*, IV.1

11 See *Model Presentation*, IV.1, p. 199

12 See *System structure analysis*, IV.2, p. 210

13 See also p. 318

at its stage of development at the time of the studies was presented initially as the author's approach to the main question of the thesis and as the suggested way of examining the selected cases. This provided a better initial understanding of what material was needed in order to conduct the analysis. The 'best match' was clearly found in the Scandi Byg case, where the manufacturer's perspective with focus on production rather than construction made the model an excellent basis for communication during the stay and e.g. provided useful feedback concerning the conceptual division lines and overlaps between the different tiers in the model. As for NCC and Arup, the more trade based system structures – as opposed to more product based system structures in the former cases – made it harder to get the relevant delivery information and led to the abduction of the *parallel* as opposed to *serial* system structures.<sup>13</sup> The distinction was partly conceived through dialogue with participants e.g. concerning available project material. All analyses have passed through review and acceptance by the industrial participants and so far two out of four presentation sessions are planned posterior to the thesis in order to continue the dialogue, the feedback, and the model iteration towards practical application.

## REDUCTION OF DESIGN COMPLEXITY IN FOCUS – INTEGRATED COMPLEXITY

As the second main contribution to knowledge of the thesis, and as stated in the introduction of the problem area, a main concern of present thesis has been the question of handling increased complexity and knowledge fragmentation that seem to further widen the claimed gap between architectural ideation and the way it is realised thus causing translation problems and incoherence of the final architectural result. The atomistic knowledge paradigm of the dominating scientific tradition has not provided good answers to this problem and clashes with the general integrative character of architectural design concerned with the creation of wholes. The system structure model seeks to introduce a systems view where wholes and relations *between* entities can be considered while (temporarily) disregarding their individual characteristics. Choice of different viewpoints and complexity in focus keep parts of the model opaque according to the purpose of the modelling. This is necessary in order not to get lost in the abundance of e.g. technical, legislative and economical detail that – although not irrelevant – can blur the conception of the whole and result in suboptimisation according to more or less arbitrary parameters. The thesis

suggests that fragmented knowledge can be gathered around new – and preferably flexible – constituent elements of construction that are serially nested into gradually more integrated deliveries. In this way a levelled complexity can arise where each nested delivery while contributing to the overall complexity and integration of the whole (building) it forms part of simultaneously reduces the complexity that is needed to be handled design wise at the level of the whole. On delivery level this *integrated complexity* has tentatively been expressed along three dimensions of respectively preparation, standardisation and service that can be seen as qualitatively different means of integrating complexity. Preparation is close to what often in construction is termed as prefabrication – although here it is more nuanced as various levels that correspond to the different tiers of the system structure model. Standardisation integrates complexity through deliberate (or forced) limitation of a broader solution space while service compensates for complex processes of supply, installation or maintenance by including these as integral parts of a delivery.<sup>14</sup> This means that even an only loosely prepared delivery can have a relatively high degree of integrated complexity. Acknowledging that products are more than just the physical substance delivered, integrated complexity expressed as a combination of the three dimensions thus gives an overall valuation of the delivery as a commodity. The total integrated complexity value is parallel to what we could call the degree of commoditisation of a delivery.

Important to point out here is, that present thesis does not agitate for a highly commoditised building industry on building level which, while it would heavily reduce complexity in focus by limiting design choices, would equally reduce the ability to respond to single and context specific design tasks. Through the levelled integrated complexity of series of nested deliveries an overall context specific complexity of a unique architectural solution can – if market choices of the subsystems are sufficiently manifold – be created through combinations of existing more or less mass customised products thus combining the advantages of economies of scale with those of economies of scope. The levelled complexity can furthermore provide the basis for industrial ecologies by clearly distributing knowledge (and responsibility) of material cycles over a range of sufficiently simple subsystems and suppliers while maintaining these as disassemblable elements. However, while common data standards within information technology aims at reducing translation work between systems thus simplifying the process of data processing and facilitating more complex results, the standard and prefabrication attempts in construction has so far mainly simpli-

- 14 Forced standardisation is e.g. building code or established industry standard performances and interfaces. The establishment of standards exclude others and integrate the complexity implied in their definition.

15 See *Classification systems in construction*, II.2

fied the architectural result.<sup>15</sup> These systems have not been made for handling the complexity of unique context specific solutions – they are not properly translating between systems of thought (ideation) and systems of matter (result) but rather reduce the former to already existing categories (products) of the latter. Like the classification systems in construction introduced in the theoretical part, industrialised construction has tended towards an over determination that freeze the division of constituent elements rather than setting it free through the enhanced capacity of handling complexity by the introduction of a systems view – a general level to mediate between the specific idea and the specific realisation of it. Many new design drivers have joined the cacophony of parameters to consider and integrate as e.g. energy performance, design-for-disassembly, energy and life-cycle assessment, indoor climate and health or user involvement. All these make obsolete the traditional or fixed divisions into constituent architectural elements by dealing with the overall performance of the whole rather than the constituent parts. If these are to be included in early design phases, oscillation between the whole and (its) flexible constituent parts is necessary. The system structural view and the concept of integrated complexity of wholes potentially provides for such a process.

### ***Bridging the gap***

The point furthered here is that we *should* use the existing industry and its products as more active design drivers already from the early design phases. This is not the same as a subsequent translation of an architectural concept into existing standard elements. By thinking upfront how to build but simultaneously – and through the levelled complexity – choosing where to respectively locate design attention and where to maximise integrated complexity through the choice of integrated solutions, the architectural solution space can be negotiated on project basis while still making use of highly industrialised solutions. Through what has been called *flexible structuration* the system structure model can (potentially) support the elaboration of project specific balances between opaque highly integrated parallel deliveries, specifically designed or mass customised serial nesting of different subsystems and simple building materials and components delivered directly to and installed on the building site. Again it should be stated that the model in its present state is not a finished design supporting tool. However, even used as the present stage analytical tool it enhances as a minimum the understanding of this interweaving of systems on different integration levels and nuances the stereotypical picture of buildings being either off-site produced (prefabricated) or on-site constructed (traditional

construction). Any building – and any of its subsystems or deliveries - is a specific combination of these two poles and the understanding of this can, it is asserted, help bridging the gap between architectural ideation and building production. The idea of integrated complexity as a means of actively controlling this balance and focussing design attention points towards several new roles of the architect. These will be treated in the following paragraph.

## THE (NEW) ROLES OF THE ARCHITECT

Drawing on design knowledge and design work already imbedded in industrialised systems that are delivered as parts of buildings seem to challenge the traditionally perceived role of the architect as the central ‘auteur’ in the architectural design process. However, the architect seen as a specifier in detail has perhaps only been present for a short and possibly transitory period of time while moving from established crafts into new integrated but yet more flexible partitions of the deliveries in a building project – the integrated product deliveries as they have been sketched and exemplified in the present thesis. The traditional crafts embedded huge amounts of (tacit) knowledge of materials and their connections in local vernacular building styles. The internationalisation of building styles and techniques combined with the explosion in the number of available building materials has, as mentioned among other factors, distorted the coherence of these knowledge systems. In this context an industrialised architecture based on knowledge partly embedded in integrated product deliveries as sketched above seems a more plausible path for handling the complexity of contemporary construction and for providing a more holistic approach for creating integrated architectural wholes. Much valuable material knowledge from the crafts (e.g. on material properties and jointing) can and should be reused in industrialised systems but as bits from many disciplines simultaneously in each product.<sup>16</sup> An important issue becomes how to transfer and integrate this often tacit knowledge from crafts to industry – if it is not already lost! This will need further treatment elsewhere.

In the scenario sketched above the architect can still be seen as an important and central, though not exclusive, creator of a building.<sup>17</sup> However, in order to make this creation possible today it is here argued that architects *need*, to rely on knowledge integrated in industrialised systems – as they equally relied on knowledge integrated in the crafts. A future industrialised architecture based

- 16 The bathpod e.g. integrates mason, plumber, electrician, glazier and other traditional and more recent trades into one discrete industrialised delivery
- 17 The scenario corresponds that of a future industrialised architecture presented under theoretical scenarios found in Model presentation – IV.1

18 See the KieranTimberlake case study IV.2

on assemblages or configurations of discrete integrated product deliveries could represent an opportunity of getting out of the work overload of overspecification and (again) rather concentrate on architectural wholes. Architectural design focus is moved towards interfaces and interaction between systems (performance) rather than the detailed design of the systems themselves. The architect would to some extent, but not solely, become a configuration manager of existing systems. As KieranTimberlake state: Architecture is rather the employment of collective than singular intelligence and the architect is (just) one of the stakeholders in a dynamic interplay of forces and competencies. The architect in this role does not represent a detached creative force but work in a team particularly concerned with the creative selection, organisation, integration and articulation of systems.<sup>18</sup>

#### *Architects on various integration levels*

But this is not the only possible role of the future architect. As more integrated solutions probably will become commoditised as integrated product deliveries, architects can equally work with or within companies delivering these upstream deliveries – just as industrial designers today work with product development within the product industry. While architects in an architectural office perhaps today would sketch on and even fully design a balcony solution, a bathroom plan and a kitchen layout, this design work could be outsourced to companies specialised in these assemblies or chunks of a building but could still be designed by in-house architects of these companies. Alternatively – and perhaps in some cases more architecturally viable – such in-house architects could be in charge of developing, defining and qualifying the architectural solutions space of such integrated product deliveries thus introducing a system level with a flexible solution space that could be applied for configuration by the architect working with the building as a whole and choosing the particular product as a means of integrating complexity. Even companies delivering further upstream systems i.e. building materials and components could make use of architects for the development of their products. Such in-house architects could be concerned with product development both concerning the possible preparation for nesting of these deliveries into other industrialised subsystems as well as into final buildings and – as architects – still have the particular training concerned with architectural wholes that makes them capable of qualifying such products beyond their mere technical performance. Although architects today are not only found working in architectural offices, they are only seldom found in such building product companies. Combined with the fact that the architectural

offices is often one of the smaller companies involved in a building project, this has diminished the overall role of the architect in construction process whereas as large consulting companies with roots in engineering, large turnkey contractors also heavily founded in engineering and construction management, and huge investor and developer companies form the core stakeholders in present day construction projects – at least seen from an economical point of view. If this picture is to change it will probably have to be addressed already at the level of educational training programs which are today mostly directed towards the traditionally perceived role of the architect as the central ‘auteur’ of buildings and furthermore often support a generalist approach that excludes specialisation already at university level. Such a specialisation could broaden out the scope of new roles of the architect and contribute to the development of coherent solutions over several tiers or integration levels and facilitating the active use of such subsystems during the architectural design process. A stance in the present thesis is that both the ‘black-box’ design process represented by the traditionally perceived role of the architect as well as the turnkey contractors’ traditional internally controlled tender process is problematic for the coherence of the final architectural result. Both can be seen as kinds of sub-optimisation that do not bring in all relevant factors. What Simon calls ‘satisficing’ as opposed to optimising, and which is the true goal of architectural design, requires KieranTimbelake’s collective intelligence.

19 See *Systems in architectural theory*, II.1

## THE NEED FOR FLEXIBLE SOLUTION SPACE

As it has been shown, already in the renaissance Alberti pointed out the importance of variety (*varietas*) in architecture.<sup>19</sup> Although he – as Vitruvius – sought to establish clear guidelines for the design of our built environment, his directions were rather prescriptions than demands; they were not meant to lead to a specific solution but sought to establish a frame within which architectural alternatives should be kept open. Architecture was not to be seen as a free art, but neither was it to become a mechanical application of rules leading directly to a solution. The newly established architectural createur extracted and detached from the craftsman was a man of thought and creation – not a technician. Only he could combine (divine) prescriptions and context specific conditions and requirements thus introducing *concinntas* into buildings. Although our ‘rules’ of building today are not ascribed to any divine force but rather have roots in the mechanical sciences and their breakthrough in the nineteenth century, the

- 20 See Systems in architectural theory, II.1
- 21 See introductory citation I.3

balance between constraining rule application and artistic interpretation and synthesis is basically the same. The negotiation of such a balance become even clearer when architecture is partly produced through industrialised means of production. The need for a flexible solution space needs to be (re)considered.

The notion of industrialised architecture should, as stated in the introduction to the problem area, not be seen as a direct promotion of organisation, processes and results falling within this category as being particularly conducive for the architectural result. Industrialised architecture as it has been treated particularly within the framework of CINARK – Centre for Industrialised Architecture – as well as within the current thesis has rather concentrated on the critical discussion of developments and tendencies which are already there. As the gap in society in general, in Frampton's Arendt inspired version, is enhanced between the *what* and the *how* – the thought or idea is removed from the task of its realisation.<sup>20</sup> For architecture this means that its meaning loses the connection to culture and society it earlier had through its physical embodiment in the building. Although pessimistic, Frampton however, as mentioned, sees conscious architectural practice as a potential resistance that can mediate between *work* and *labour* (the *what* and the *how*) by sustaining a combination of rationalised production and more traditional craft based practice. This is the core message of his so-called *critical regionalism*. Using this idea of a hybrid situation in the present context, an industrialised architecture as summarised above could – as opposed to mere industrialised *construction* – represent such a combination of rationalised production and craft based practice. In other words: in order to become true architecture and (re)claim the connection between thought and process/matter – between idea and its cultural manifestation, an industrialised architecture needs to provide space for this mediation thus resisting '*being totally absorbed by forms of optimised production and consumption*' (Frampton IN Hays 2000:359). This somehow resembles what is tentatively suggested in this thesis through the concepts of flexible structuration and levelled complexity that by means of industrially produced integrated product deliveries integrate complexity while simultaneously keeping open the possibility to decide where to focus the architectural design attention – or using Chermayeff and Alexander's words: '*just where to apply the precious and limited inventive power*'.<sup>21</sup> The industrialised means of production used in the right way, it is here proposed, can actually contribute to the solution of singular and context specific architectural design tasks by freeing resources and directing design attention towards selected parts of the whole.

An example: When NCC as described in the NCC-case study integrates the different roles of architectural designer, technical consultancy and turnkey contracting within one single company it provides a good outset for bringing the idea and its realisation together and in a way bridges the gap that has been pointed out as a main problem in present day architectural creation. Crucial, however, is that the architectural solution space is kept sufficiently flexible and that the architect is constantly able to challenge the highly pragmatic approach of e.g. the particular office concept that obviously has roots in contracting (read: execution) rather than architectural ideation. The design work (or thought) should seek to make use of the logic and efficiency of NCC's process system as an active design driver but not become subordinate to it. A company internal system like NCC's produces risk of suboptimisation both concerning (process) *labour* over (result/idea) *work* as well as concerning internal over general efficiency.

- 22 See e.g. the description of the Omniclass tables 22 and 23, II.2
- 23 See *Customisable Architectural Subsystems*, III.2

## PRODUCT/PROCESS/PROJECT

The thesis has in the first place drawn up a theoretical division between systems of thought, process and matter. However, it has also been shown that this distinction is used purely theoretically or epistemologically in the sense that it might help to describe different aspects of a continuum while the architectural result or its constituent elements mostly are a mix of all three. The different classification systems introduced in the theoretical part express different attempts to establish clear divisions between processes and products but get into the same problem of distinguishing e.g. between a product delivered to a construction project and the work results on the building site implying work processes.<sup>22</sup> A product is, as discussed in the introduction to the different types of integrated product deliveries, not just a physical entity but can equally encompass elements of process (supply, installation, maintenance) and even thought being all the (design) knowledge integrated into such a product.<sup>23</sup> The system structure model elaborated within the present thesis seeks to integrate the three types of systems into one single system entity, the *delivery*. Although in the first place, for simplifying reasons, concentrating on deliveries that contain some kind of physical matter to be inserted into the final building, deliveries without physical content can equally potentially be included into the model. The process software tool, *U\_build* was used as an example that points out a potential need for integrating pure systems of process into the system structure.

### *Product vs. project (deliveries)*

The lines between thought, process and matter become particularly blurred when introducing more complex deliveries as the integrated product deliveries. As mentioned in the Arup case-study, some of the high end solutions used in the Ropemaker Place building are almost completely bespoke solutions (BSP) although delivered as discrete work packages by a sub-contractor specialised in delivering this particular kind of solution. The façade cladding is a prime example where the system level – or commodity aspect – of such a delivery physically is reduced to patented gasket and bracket solutions while procedural and knowledge wise drawing heavily on experience from earlier similar deliveries. Such deliveries are equally *projects* in themselves as well as they are general *products*. As introduced earlier, such bespoke integrated *product* deliveries should perhaps rather be termed integrated *project* deliveries. However, acknowledging that products equally encompass knowledge and process makes it easier to see deliveries as the façade cladding as a product as well. Using the three dimensions of (complexity) integration from the taxonomy, the high preparation and service level of the façade cladding compensates for the lower standardisation level and the result (the ‘sum’) still is a relatively high value of total integrated complexity. Another aspect is, as mentioned, that such high end bespoke solutions very well can turn out to work as the haute-couture or formula 1 of integrated product deliveries thus pointing out new market niches for development of more standardised or mass-customised integrated product deliveries. These can be marketed for more main stream architectural projects and contribute to the provision of a flexible solution space for these kinds of projects by making it possible to focus the limited design attention available on other aspects that perhaps are considered more important in a particular project context. They can reduce complexity in focus without necessarily reducing the complexity of the final result itself by integrating complexity into the (opaque) product solution. The development of such established integrated product deliveries requires engagement from the industry as well as from architects – the latter perhaps, as mentioned above, being employed directly in the industry as integrated product developers.

### *Off-site fabrication is context specific*

An important statement of present thesis is that maximising off-site fabrication is not necessarily the same as optimising the use of it. Off-site fabrication – or prefabrication as it is often termed – vs. site built tends to be regarded as an either/or choice. Typically when an architectural office addresses CINARK for

consultancy they say: ‘We want to do prefabrication. How can we do that?’ However, at the previous case-analyses show, there are many versions and degrees of such off-site fabrication and any building project is *always* a context specific combination of off-site and on-site processes. Any product made offsite has at some point to meet the site and here lies some of its complexity.<sup>24</sup> The service dimension of the elaborated taxonomy grasps some of this complexity by showing that integrated service as supply, installation and maintenance (SPL, INS and MNT) equally (to preparation and standardisation) reduce complexity around the application of an integrated product delivery. One could say that while the preparation dimension has to do with the physical interface of the delivery towards its surroundings, the service dimension has to do with the procedural interface of the delivery: Is the delivery simply handed over at ‘factory gate’ or dealer, is it delivered onsite but handed over to an assembler – or is the supplier responsible for the entire installation and perhaps even later servicing? The standardisation dimension has to do with internal organisation of the delivery or a company’s production line or product family but can also be about interfacing with legislative demands, national or international standards.

#### ***By zone and by system – chunks and assemblies***

Finding the right interfaces (of constituent elements) and optimising the use of off-site fabrication is a design task in itself and can – as suggested in the present thesis – become an integrated part of the architectural design already from early design phases. The system structure model with its different tiers and the individual deliveries with their respective dimensions form (so far) a conceptual framework for the system structure as a complementary design driver – particularly when the design intention is to move towards a higher degree of offsite produced or integrated product deliveries as theoretically reflected in the scenario of a future industrialised architecture.<sup>25</sup> The system structure model is meant to reduce complexity in focus rather than augmenting it.

The integrated product deliveries are, as explained in the model presentation, divided into two basic categories each representing a tier in the system structure model: The assemblies and the chunks (respectively tier 2 and tier 1). A fundamental difference between these is that whereas the chunks are always volumetric spatial deliveries thus constituting actual finished space of the final buildings, the assemblies are a singular or an integration of various systems that rather serves these finished spaces; a wall assembly closes and supports, a kitchen assembly provide for cooking etc. Assemblies are functional ‘by sys-

24 See e.g. the Kieran Timberlake analysis IV.3

25 See the theoretical scenarios in *Model presentation*, IV.1

26 See the NCC-case, IV.5

tem'-deliveries whereas chunks are spatial 'by zone'-deliveries. In some chunks, as e.g. a bathpod or a lift, 'by zone' and 'by system' widely coincide thus making the system boundary definition clearer than in other cases. Assemblies can form part of the more integrated chunks whereas the opposite is not the case. In some cases, a smaller chunk – as e.g. a bathpod – can form part of a larger chunk as e.g. an entire apartment floor. A single assembly can constitute an entire system as e.g. a one storey staircase but often these 'by system' deliveries are modularised into a number of assemblies and delivered as a kit-of- parts that can be plugged together on-site – or off-site as nested into chunks. However, as partly reflected in the cases, off-site strategies tend to be either 'by system' or 'by zone'. As expressed by the theoretical scenario of *conventional prefabrication* many manufacturers offering off-site solutions maximise offsite fabrication by producing volumetric chunks but these are often produced predominantly as conventional construction under roof where simple building materials and components are joined together by use of manual labour and relatively simple power tools as circular saws and nail guns. Others again produce assemblies as e.g. wall, floor and roof panels, façade systems, finished attics, or installation walls (e.g. *Podwall*) that are mostly delivered for site installation and only seldom become nested subsystems of the chunks. Exceptions exist and the development described in the Scandi Byg case points towards a more nuanced evaluation and use of the pros and cons of each of these two integrated delivery types and their possible combination as a hybrid strategy of 'by zone' and 'by system' deliveries. Such a strategy in a more elaborated form could e.g. combine relatively simple volumetric chunk frames with modularised system assemblies comprising both local and distributed systems of a building. Another rationale behind a combination of assemblies 'by system' and chunks 'by zone' could, as pointed out in the NCC-case, be that when the chunks get bigger and installation 'intensity' pr m2 gets relatively lower, tier 2-assemblies can be a wiser solution both cost and quality wise.<sup>26</sup>

#### *Higher standardisation level*

Off the shelf (OTS) or cut-to-fit (C2F) products are only seldom found on higher integration levels as the integrated product deliveries (assemblies and chunks). The use of more standardised products in general requires earlier integration in the architectural design process in order to avoid expensive on-site adaptation. Particularly standardised versions of the more complex integrated product deliveries will, as mentioned e.g. in the Kieran Timberlake analyses, often have considerable impact on the selection and location of other elements

or features as plan solutions of the rest of the building. If markets are to be created for more standardised integrated product deliveries it calls for changes in the architectural design process as practiced in most offices. Early procurement where some of the (detail) design work is moved to sub-consultant, suppliers or manufacturers representing such deliveries is a possibility that however often is inhibited by the contractual setup. Early procurement blurs the linear logic of most existing stage models used in the construction sector where conceptual design and design development stages and stakeholders normally are located prior to production and execution stages and stakeholders.<sup>27</sup> Scenarios based on such blurred stages are in the present thesis estimated to potentially benefit hugely from the use of the notion of system structure and a design process supported by a system structure model. The system structure integrates the way the product is produced and assembled from its constituent elements – sub-systems and components – into the way the product is designed. The system entities are not connected to particular stages of a process model but to tiers (of integration) that rather express their degree of integrated complexity.

<sup>27</sup> See *Classification systems in construction*, II.2

Whether using stage models, classification systems, data interchange standards or the suggested concept of system structure it is, as also pointed out in the Arup case, essential to have clearly defined interfaces (between different entities comprising thought, process and matter) in order to know who is doing what. When interfaces are not clearly defined – as they were between the traditional crafts – things fall between stools and the resources used to fix these misfits are most probably out of proportion with the size or amount of what is missing. However, as illustrated e.g. in the Scandi Byg case, it is (almost) impossible to plan for any unforeseen problem that can occur – even if the final result is completely defined before the production and/or construction process starts. Solutions and products change, production plans and delivery times are rescheduled and all of this cause changes that can – at least partially – be picked up and visualised by use of a dynamic system structure model.

### ***Parallel and serial structures***

Apart from more or less resemblance to the theoretical scenarios introduced in the model presentation, another significant system structural feature has been revealed through the application of the system structure model to the four casestudies. While the KieranTimberlake and the Scandi Byg cases display what has been termed as serial system structures, the NCC and the Arup cases rather display what has been termed as parallel system structures. The serial system

structure is characterised by series of upstream subsystems often nested into other more integrated downstream subsystems before these (of varying levels of integration) are installed in the final building. This corresponds closely to the theoretical scenario of *future industrialised architecture*. The parallel system structure on the other hand is characterised by so-called opaque deliveries (called work packages in the Arup cases), where a number of subcontractors deliver finished solutions – often as installed (INS) directly into the final building. By opaque is meant, that the viewpoint of the system structure does not reveal possible nested subsystems of these deliveries and is rather concerned with the parallel division and coordination of these deliveries on-site. Superficially seen this corresponds to the theoretical scenarios of traditional or contemporary on-site construction thus representing a division along (traditional) crafts or trades that each with their particular tools, materials and processes deliver an often distributed solution in the final building. In both the NCC and the Arup case, this is partly correct. Several of the old crafts as plumbing, masonry and carpentry can be found as separate (parallel) deliveries. However, particularly in the Arup case several of these parallel deliveries also represent new more performance based entities such as e.g. external cladding, toilet cores, reception desk, house management fit-out or special ceiling that cross over and incorporate elements and processes from several of the traditional trades within one single delivery (or work package). Such deliveries, although their specific internal supply chain and production method remain predominantly opaque, can – equal to the tier 1 and tier 2 integrated product deliveries, be seen as highly integrated deliveries that considerably reduce the complexity of the design task by e.g. having clear physical and functional interfaces to other deliveries while internally integrating the coordination of many different materials, tools and processes formerly belonging under traditional crafts distributed as deliveries over the building as a whole. This last special kind of integrated product delivery is tentatively termed a Tier 0-integrated product delivery as it is assembled on-site (low preparation level) but still to some extent can be standardised and often represent a high service level i.e. installation (INS) or maintenance (MNT).

The parallel tier-0 integrated product delivery is a different way to comply with the demand of variation while still maintaining a delivery around a clearly defined product – a part of a building - and not as earlier around trade or craft and its related tools and processes. As well as the development of industrialised assemblies and chunks requires engagement from both industry and architects (the latter as specifiers), this is also equally the case for this particular strategy

of industrialisation. There needs to be companies like e.g. Arup Associates in collaboration with e.g. construction managers like Mace that specify in alternative ways, that do not follow the traditional divisions thus establishing the basis for new more performance based deliveries (or work packages). Working with what Arup themselves term as *total architecture* and being able to exclusively choose high end projects where they can furthermore do all consultancy work put Arup Associates in a special position for influencing the building industry towards the development of this special kind of integrated product deliveries. The system structure of NCC reflects, as mentioned earlier, a much more traditional division of trades and somehow fixes this craft/trade based culture among their subcontractors. Their innovation stays company internal and consequently probably has much less impact on the sector as a whole. A weakness of the system structure model in its present state is its inability to show visual difference between on the one hand a predominantly traditional division into parallel deliveries and on the other hand a more innovative division around new more performance based deliveries. The model has to be interpreted in detail in order to make such differences perceivable.

## A FUTURE INDUSTRIALISED BUILDING INDUSTRY

The point of departure and the main problem treated in the present thesis was that an apparent growing gap between how architecture is conceived and how it subsequently is or can be produced. This combined with a pronounced specialisation of the society in general and the construction sector in particular result in fragmentation of knowledge and in problems of handling the increased complexity related to the integration of relevant design knowledge into architectural wholes. Contemporary creation and modification of our built physical environment seem to be in lack of adequate tools to handle this integrative task. The stance of the present thesis is that a more systematic and conscious but also critically well balanced application of industrial logic in construction and architecture potentially can influence the building industry. This requires – it has been argued – that architects more actively use the possibilities of the industry and through the insight in this field can make qualified demands on how the industry should be able to perform in the future.

### *Inspiration from the product industry*

As has been presented in earlier sections, the product industry has been

- 28 Modular clusters are groups of firms and markets that “play host” to the evolution of a set of modular designs. See *Industrial production theory*, II.3
- 29 See Arup case, IV.6

through a development that could be of inspiration for the building industry. The introduction of modular design and the subsequent forming of modular industrial clusters from the 1970’s and on, as described by e.g. Baldwin & Clark, has led to the establishment of completely new industries and products which again subsequently become the building blocks or constituent elements of new integrated products.<sup>28</sup> The microchip and the LED-technology could be examples. The building industry has so far only experienced true product development on building material and component level but the appearance of a number of gradually more commoditised integrated product deliveries points towards possible new areas for industrialisation that does not – as the first wave of industrialisation in construction in the 1960’s and early 1970’s – subordinate architectural creation and inventiveness to the straitjacket of all-encompassing closed industrialised building systems with roots in efficient technical execution and cost optimisation rather than in softer architectural parameters as well-being, comfort, experience and self-realisation. As mentioned earlier, more complex systems as e.g. bathroom pods and façade cladding are beginning to form networks of sub suppliers but they can so far not be characterised as modular clusters.

An open question – too big for the scope of this thesis to answer – remains whether such a new product-by-product structure of the built environment can be created to replace the fainting traditional trade-by-trade structure of the crafts formerly involved in construction. The issue of creating sufficient market volume for such new products is probably one of the most important obstacles for a further commoditisation of integrated product deliveries today. National and even regional differences of both geographical/climatic as well as legislative character today seriously limit the possibility of forming stable markets that can provide sufficient critical mass for a true industrialised production. The international ‘haute-couture’ of construction can perhaps to some extent lead the way. Equally, as pointed out in the Arup case, the (trade) origin of a company engaged in development of more integrated product deliveries is not irrelevant. It defines the basic skillset and somehow even the fundamental mindset they work from.<sup>29</sup>

### **System structures**

On the operational level the present thesis has set out to examine how architecture and construction can be seen – and possibly conceived as – a system of processes and/or products that better match the means of production that currently produces our built environment while simultaneously taking into ac-

count architecture's specific attachment to time, place and cultural context. The system structure model, its systems view and its related concepts constitute the practical contribution in this regard. As mentioned, the scope and the applied methods of the research carried out throughout the work with the thesis have permitted to iteratively test, modify and qualify the model. However, although the explanative power of the system structure model has been substantiated by the case-analyses much work still remains in order to make it a fully functional proactive tool for use in the process of architectural design. If the model, as intended, should truly bridge the inexpedient distinction between product and process – or even between matter, process and thought – and effectively handle the complexity of a contemporary industrialised architecture, it will probably need extension of the current system boundary definition that as a start and for simplifying reasons has been set to include only deliveries with some kind of physical elements to be inserted in the final building.

### *Industrial Ecology*

In the section *Commoditisation of architectural construction* it is suggested that integrated product deliveries can provide for better controlled material cycles in construction.<sup>30</sup> Through a commoditisation of these more integrated deliveries the information and documentation needed about the building materials applied as well as the establishment of an infrastructure to recollect them into closed material cycles can move from a project level into a product level that as a non-project specific system level can benefit from economies of scale that do not exist on project basis for each singular building. The economies of scale – the economical benefit made from repetition – can in the first place make elaboration of such documentation and infrastructure economically plausible. If commoditised integrated product deliveries are furthermore put together by series of subsystems, a hierarchy of nested deliveries each with their particular material cycles controlled and documented by each supplier can bring the issue down to a scale that seem manageable. It is however hard to see how such an initiative should come from the industry itself. It will most probably need legislative backup and official national or international support. The construction industry is one of the most resource and energy intensive industries – both concerning the production and construction of buildings as well as their later operation. The increasing demand for environmentally sustainable solutions makes it of outmost importance to control resource use and material cycles and here is perhaps the heaviest argument for introducing the system structure as an integrated part of the architectural design process as

30 See the paragraph Industrial ecology – a strategy for discrete controlled products in III.2

will as for the design of the following disassembly and recycling of the same system entities. As suggested in the KieranTimberlake case, the system structure is equally suited to describe and analyse the disintegration of buildings into their constituent components on various levels of integration reusable in other specific contexts – as materials, as components or as recycled integrated product deliveries.

## V.2 METHODOLOGICAL EXPERIENCE

### - research method and procedural approach

31 See (Jensen & Beim 2006)

#### INTRODUCTION

The current section is a smaller excursus on the different methodological experiences collected throughout the work with the present thesis. The section is partly ordered according to the main parts of the thesis – ‘Frame’, ‘System’, ‘Product’, and ‘Model’ but additional themes crossing these parts have also been included. Apart from seeking to reflect and be critical to the methods and methodology applied and discuss what might have been alternatives the current section also is a summation with regard to the more general lessons learned. As in the preceding section the most pivotal discussions are located in the early paragraphs . A PhD-project as represented by the present thesis should both be a process of learning for the candidate as well as a useful piece of research of general applicability. It is education while also producing qualitatively new knowledge.

#### ‘FRAME’ – DEVISING THE SCOPE AND RESEARCH DESIGN

Inspiration and backdrop for the present work of research naturally has roots in author’s earlier work and research experience. Particularly the idea of creative model development and the proposed use of abductive inference for this purpose have been explored in several occasions e.g. in the author’s research into architectural design strategies.<sup>31</sup> However, the present work seeks more intensively also to pursue and discuss the specific *methodological* implications of such an approach. A little unusual in the present research was that the study did not have a precise scope, project description, or timeline at the outset. Normally such a frame would have been a prerequisite for getting the grant in the first place. As the project and PhD-grant was taken over from another person with only short notice, the usual application and recruitment procedure was not followed and the preparation was rather formal than academic. Furthermore, present project has been conducted over a slightly shorter period than usual thus representing the work of 30 months rather than the normally stipulated 36 months. However, the project grant description used for the

- 32 See *Project grant description*, VI.4 (in Danish) in Part VI – 'Appendix' on enclosed CD
- 33 For examples of author's major earlier research work see (Beim, Nielsen & Vibæk 2010, Beim, Vibæk & Jørgensen 2007, and Jensen & Beim 2006)
- 34 See *Method and scientific approach*, I.5

original call and for funding applications was quite in line with the themes the author had been working with previously in CINARK.<sup>32</sup> It was consequently estimated that this earlier work to some extent could serve as part of the initial work and combined with author's previous research experience thus compensate for the shorter project period available.<sup>33</sup> Still, it meant that introductory work concentrated on the formulation of a main problem to examine and the elaboration of an initial research design in order to start up the project.

#### ***Methodological development***

As mentioned in *Method and scientific approach*, architectural research is not as methodologically established a discipline as many other fields of science.<sup>34</sup> This can be interpreted as making it both easier and more difficult to conduct architectural research; Easier because you are more free to choose what suits your particular project without necessarily having to acquire larger theoretical and methodological complexes. Harder because this freedom provides less precedent and model for the carrying out of such architectural research. While acknowledging the risk of working on too many levels at a time, in the present project this apparent freedom was used to direct part of the scope of the thesis towards *methodological development* within the field of architectural research in general while using the present study as test bed for a particular research approach that could subsequently be discussed and evaluated. By introducing the concept of abduction, the creative aspect of research work was provocatively brought in as an important aspect meant to match the character of the object of research itself – architectural design as thought, process and result (matter). Turning the methodological approach itself equally into an object of examination and creative development during the project did evidently challenge the rigidity of the subsequent research plan. Furthermore, inherent in abductive reasoning and inference lies the idea of successive approximation through iteration which means that it is difficult to apply a linear logic for building up the elements of the thesis, that constantly interact with and influence each other throughout the project course. This also challenges the ability subsequently to account for the procedural approach in a sufficiently transparent way thus to some extent problematising the issue of reliability of the research. The openness and interdependency between different phases of the research as well as the parts of the final thesis has equally produced certain inconsistency e.g. concerning the use of specific terms and, as will be discussed below, in the format of the model that is considered the main outcome or contribution of the thesis.

### *Hypotheses and their relation to the whole*

The thesis presents a total of five hypotheses – one methodological in *Method and scientific approach*<sup>35</sup> and four theoretical corresponding to the four first sections of Part II – ‘System’.<sup>36</sup> As for the methodological hypothesis it was inferred abductively with basis in the author’s earlier experience with architectural research, methodology and model development as well as with inspiration and literary input from a PhD-course dealing with the specificity of architectural research through practice.<sup>37</sup> The methodological hypothesis suggests that analytical models in architectural research – as e.g. the system structure model – can be created in creative ways similar to architectural creation itself. They can in other words be abducted from initial ideas and assumptions e.g. from the primary case study of the present research into an intuitive synthetic guess<sup>38</sup> and can subsequently through successive approximation (here facilitated by the theoretical and the practical exploration) lead to a satisfactory explanation – a useful model. That this is actually possible – that the hypothesis is true – can only be determined by the usefulness of the model in its present or future states. As stated earlier, this abductive leap causes problems both concerning validity as well as reliability seen within a traditional scientific paradigm based on deduction and induction as the only valid forms of inference. However, using Pierce and Kirkeby it has been made plausible that any qualitatively new scientific knowledge initially does seem to require some sort of creativity falling outside this traditional paradigm and thus introduces abduction as a supplementary non exclusive but yet independent way of inference with slightly different criteria for both validity and reliability.<sup>39</sup> In the present model development, the ideal and iterative sequence of abduction – deduction – induction suggested by Kirkeby has been followed as explained in the methodological section and as such served as procedural inspiration.<sup>40</sup>

As for the four theoretical hypotheses related to the theoretical exploration of Part II – ‘System’, they are in the first place, as explained in the introduction, derived from the main question of the thesis but with regard for the respective fields, i.e. architectural theory, classification systems in construction, industrial production theory and general systems theory.<sup>41</sup> The four fields of theoretical exploration that successively broaden in their focus were chosen – or inferred abductively - from a combination of initial scanning, supervision meetings and recommendations from the advisory group following the research project.<sup>42</sup> Potentially other fields could have been relevant but have been omitted due to either time constraints, extent, or simply because they were not brought into

35 See *Method and scientific approach*, I.5, p. 23

36 See Part II – ‘System’, pp 42, 65, 78 and 100

37 The ph.d.-course *The role of material evidence in architectural research* was attended in November 2010. See Appendix, VI.7.F – course description and programme

38 See *Method and scientific approach*, I.5, p 26

39 See *Method and scientific approach*, I.5, p. 34f

40 See *Method and scientific approach*, I.5, p. 30

41 See Part II – ‘System’, p. 41

42 See *Acknowledgements*, I.2, p. 9

- 43 See *Definition of Scope*, I.4, p. 18
- 44 See *Conclusions in short*, V.3
- 45 Papers, articles, and book chapters produced during the project course can be found in VI.5 in the Appendix – 'Part VI' (on CD)

play in the fora mentioned above. The theoretical hypotheses are all accompanied by research questions that as a kind of operationalisation of each hypothesis initiate a directed theoretical exploration within each field. These subordinate research questions are not aiming at specific answers nor at validation of the hypotheses but should be seen as exploratory with the aim of producing short ideographic contributions within each field that have served as inspiration for the iterative model development. The model development and the theoretical hypotheses are connected through the main problem and goal as stated in the definition of scope.<sup>43</sup> Again, the reiterative nature of the abductive model development makes it difficult to draw a 1:1 relation back to the theoretical exploration and challenges the issue of reliability within a traditional scientific paradigm as mentioned above.

The exploration of architectural theory relates to the apparent gap between architectural ideation and its subsequent realisation expressed in the main problem. The exploration of classification systems in construction relates rather to the expressed increased complexity of specialisation and technical development. As for the industrial production theory, the link is how systems thinking (in industry) can help bridging the expressed gap and finally the exploration of general systems theory equally relates to the increased complexity of specialisation from the main problem and combine this with the idea of intermediary models from the methodological hypothesis (see above). An attempt to conclude on the specific findings related to the main problem, as well as each of the derived hypotheses and research questions can be found in the final section, *Conclusions in short*, of the present part.<sup>44</sup>

#### ***Paper collection vs. monograph***

Taking into account this character of work in progress, an initial idea was to structure the final thesis around papers, articles and book chapters elaborated during the project and used for external dissemination purposes instead of elaborating a more traditional monograph at the end of the project period. In this way the process and the development of e.g. model and concepts could be reflected in a logical way that would furthermore distribute peak workloads more evenly over the entire project course while simultaneously getting more feedback from outside sources. In the collected final version these texts were meant to be held together by smaller connecting sections and rounded off by a general discussion of the process and the findings placed in their context.<sup>45</sup> Although a considerable amount of such dissemination texts have been produced

within the current project frame, the author was dissuaded to use this idea of collected papers during a feedback session with an external panel approximately 8 months prior to hand-in. On the basis of the then available material it was estimated that such a format would have too much repetition and that the fluctuation of concepts and model over time would be too confusing if they were not to some extent integrated in a more coherent whole. Consequently, all the material produced has been restructured, rewritten where necessary and integrated in to the present monographical format. Still, the open trial character of the research method itself inevitably counteracts the static character of such a monograph.

## ‘SYSTEM’ – THEORETICAL STUDIES

Acknowledging that systems theory and systematic thought is not a field of knowledge that is particularly strong within architectural theory, the need to transcend the architectural field of knowledge seemed obvious. The theoretical part of the thesis was meant to be an exploration that apart from architectural theory also looked for inspiration and similar problematics within several other fields traditionally more concerned with systems approaches. The idea was – to use some systems terminology – that isomorphisms (similar structures) of thought could be found within several different fields of knowledge and that architectural thought could benefit from the localisation of such isomorphisms. This is actually one of the prime assumptions of the general systems theory itself that claims that particular problems often can be described and solved by looking at their general structures. At the same time, architectural practice – the object of study – is, as it has been mentioned in several occasions in the present thesis, an integrative and synthesising discipline that seeks to combine incommensurable parameters into coherent wholes. With the methodological outset explained above, the intention was also to imitate this typical architectural approach to knowledge in the applied research method.

### *Knowledge and information*

Retrospectively seen, the ambition of covering four large and established fields of theoretical knowledge and furthermore with the intention to synthesise the findings into a format useful for an architectural context seem like – and to some extent has also been – an insuperable task. While architectural practice is not necessarily bound to demands of justification and documentation when

46 [http://www.ebst.dk/publikationer/rapporter/eksport\\_kontrol\\_system/kap04001.html](http://www.ebst.dk/publikationer/rapporter/eksport_kontrol_system/kap04001.html) accessed on September 1 2011

47 See e.g. [http://en.wikipedia.org/wiki/Linus%27\\_Law](http://en.wikipedia.org/wiki/Linus%27_Law)

drawing on inspiration from several inhomogeneous sources, this is not in the same way a valid procedure for architectural research. While the juxtaposition of different elements in architectural creation can remain an open statement subject to interpretation, this is not normal procedure within the sciences that supposedly produce knowledge that strives to claim some kind of general validity. Architectural research can – in the author’s opinion – not be a detached open artistic statement that lacks a transparent and logical procedural description and an argumentation for the methodological choices made on the way. On the other hand, the nature of knowledge is definitely changing character in the modern information society, where the total amount of knowledge available is said to be doubled in 6-7 years.<sup>46</sup> This means that even if choosing a relatively limited scope for making a scanning or a state-of-the-art of existing knowledge within a certain field, just the task of processing this knowledge would be immense. A split seem to have emerged between what we could call *information* – which is the overall available knowledge – and real *knowledge* which then is a selection and distillation of information into a format useful for the purpose. In other words: No field of knowledge can be described in its whole. It will always be a selection that even though it can be based on certain predefined criteria it will also to some extent represent a somehow arbitrary scan based on preliminary preferences or recommendations. Consequently there is no certain way to acquire a field of knowledge and a considerable risk that you will miss something important. Acknowledging this, there are however certain guidelines that can be followed in order to enhance possibilities of not missing essential points. Here is just a few of them mentioned:

- a) The time factor has significance in order to be able to get around a field of knowledge and draw on several sources. The time factor also enhances the researcher’s understanding of a field and thus facilitates the selection of useful information.
- b) The continuous dissemination of findings in networks that can give feedback, inspiration and further qualify the selection. This can be exemplified by Linus’ Law saying that ‘*given enough eyeballs, all bugs are shallow*’<sup>47</sup> – the knowledge of a critical mass of people working with a particular field reduce the chance of serious lacks – and finally
- c) c) You have to be ready to be surprised and throw away what you already thought you knew. The point is that information only becomes knowledge, if it is useful.

## ‘PRODUCT’ – PRACTICAL EXPLORATION

Although establishing the notion of delivery as a term virtually covering any product or work in the building industry the main focus has from the outset been on the more complex and integrated deliveries termed integrated product deliveries as system entities. The term of integrated product delivery (so far!) is not an official English term – neither is its equivalent in Danish (Systemleverance). This is partly because it covers a relatively new entity in construction – or at least a new way of looking at this kind of entity as a kind of product. English literature on the subject of industrialised construction use related terms as integrated system, system product, integrated component delivery, integrated component assembly, integrated project delivery etc. All of these – which are not particularly established either – have particular connotations or are used in a very narrow context. Risking to add to this cacophony, the choice has been to use a new term – that has however been used at least internally at CINARK for some time. Although words and terms theoretically only designate a phenomenon outside itself, in practice words are also actively contributing to the construction of meaning. I will here not go into a long discussion on structuralist philosophy of language but just conclude that the choice of using a new term also opens up for the freedom to define it – and that the piece of reality it seeks to describe actually starts gathering around it. Subsequently the aim of the practical exploration has been to put explanative pictures on this main system entity in order to discuss its delimitation and to give it practical foundation.

### *State-of-the-art*

In this context, an intent to give a state-of-the-art description of an entity that you are simultaneously trying to define can seem a little strange. This is however what is attempted in a kind of three-step procedure: a) defining the concept of integrated product deliveries in words, b) introducing and discussing practical examples of borderline cases that challenges this definition, and c) listing up practical examples that falls clearly within the defined category while trying to classify them (along the introduced dimensions) as more or less genuine or strong examples. All the practical examples used are based on what the author has found during work and research and is as such mainly a personal selection based on personal experience. Again, when trying to define a new entity or phenomenon that does not have a fixed term yet, chances are big that you will miss something important. The intention has however not been to give an exhaustive overview of what exist but rather a definition in order to know what to look for. The term state-of-the-art has not been explicitly used.

48 See *Method and scientific approach*, I.5

## ‘MODEL’ - BUILDING AND TESTING THE MODEL

As mentioned, the abductive reasoning applied as part of the research method is not directly compatible with a linear logic of description. This problem has been particularly present in the elaboration of the system structure model and has two aspects: The first is when it comes to how to describe the model and its genesis in a clear way that can meet general reliability criteria of research. This issue has already been touched in *Method and scientific approach*<sup>48</sup>. The second aspect is rather a matter of available time and resources: A first model draft was derived from a combination of the theoretical exploration, the practical exploration and the primary KieranTimberlake case study. Subsequently this draft was applied to the secondary case studies – both as a lens for the data collection as well as a framework for the subsequent analyses of this data. Both data collection and analyses challenged and (iteratively) modified the design of the model and particularly all the concepts connected to the use of it as an analytical tool. Theoretically the logic of the successive approximation towards an ideal model would require the entire analysis work to be revised every time the model was changed in order to update layout, terms and conclusions. This however turned out to be immensely time consuming partly due to the quite elaborated case analyses. Consequently – and as recommendations cf. above – was to aim at a coherent whole rather than expressing a work in progress – the model and its concepts has to some degree been updated where the workload has been in proportion with time available and the enhanced clarity obtained. Consistency, however, is not total.

### *Simplicity and explanative power*

Another issue concerning the model has been the ambition of keeping it simple, meant as easy to use and understand, while still giving it sufficient explanative power and sophistication to make it a valuable knowledge contribution serving a useful purpose. This balance between the risk of on the one hand becoming banal and on the other hand becoming too complex and difficult to use has been a challenge. From the outset, the ambition has explicitly excluded the idea of in the first place developing a software tool. However, when dealing explicitly with issues of complexity in construction, a software platform would be an obvious way to combine ‘back-stage’ complexity with a more simple ‘front-stage’ user interface. In present thesis the choice of so far keeping the system structure model as a manual and conceptual tool has apart from the proportions of a single PhD-thesis also been a restrain towards letting technical issues take over before

the basic purpose of such a model was established and some level of explanative power had been confirmed. Included in the wish for both visual and conceptual simplicity was also an intention to make it a manual sketching tool that with minor introduction could be used parallel to other work processes of e.g. the architect. The result, as the present status is, does leave something to wish for in this sense, so a discussion of whether future work effort should be directed towards the visual simplification of a manual tool or a software integration with enhanced complexity based on a simple user interface is still relevant.

<sup>49</sup> The offices were Big, Vandkunsten and NNE-Pharmaplan (all three Danish offices)

## CASE ANALYSES

Much valuable methodological experience of the project has been gained from the part of the research design based on case-studies. When choosing cases for a research study it has to be added that this is never a completely free choice – particularly when cases and the way they are studied can give insight into proprietary information of the involved companies or informants. The choice becomes a combination and weighing of different factors. Often access will be easier through some kind of already established connection in your network. On the other hand one has to be careful about the possible bias which lies in *exclusively* drawing on your already established network.

### *Observational studies*

of real time architectural design processes in early design phases of selected building projects from selected offices. Three attempts were made with three different offices and all had to be turned down due to different reasons.<sup>49</sup> Generally it can be said that the timing is very difficult when such case studies can only be located within a certain limited time span in order to fit the research design of a 30 months' PhD-study. The probability that an office that matches predefined selection criteria will have an adequate project running at the right stage just when it fits the research schedule is little. Furthermore, even if there seems to be a match, the probability that the project schedule will move around before start-up or during the process is high. The day-to-day planning of an architectural office is very different from that of a research project. Another problem is the mentioned question of access to proprietary material. Even if you are able to establish initial contact, negotiations of the specific execution of the study can – and did in one case – result fruitless if the office judge the possible insight gained through the proposed study to be too sensitive. As the

50 One particularly elaborated 3-year anthropological study of a competition project at OMA in Rotterdam is described in (Yaneva 2005). Even here, the realisation of the competition was skipped thus impeding drawing relations between process and final result.

process of architectural design is seldom completely foreseeable it can be difficult for an office too assess such proprietary issues in advance, and the result can be a rejection of the research proposal. Only few real time observational studies of architectural design processes have been published and there are probably reasons for that.<sup>50</sup>

#### *Recently finished projects as alternative*

An alternative design for the case studies had to be elaborated and the KieranTimberlake case became decisive here. Initially the intention was equally to follow the work of an ongoing project but while it resulted difficult to locate an adequate one, the office had a recently finished, the *Cellophane House*<sup>TM</sup> project that in many ways seemed obvious: a) The author had recently and just upon completion visited the building (and the office), b) the office had so far not had any external party doing research on that project, c) the project had a highly industrialised profile with mass customisation as part of the design strategy, and d) most of the design team still worked in the office and finally: there was no problem in timing, as it was a recently finished and not an ongoing project. The specific details of the research design is described in the case-study, but while this came out of necessity and convenience it turned out to be the model for the subsequent three case studies, although in a shorter and much more condensed format. The original idea of being present doing research in the office was maintained while the object of study changed slightly. The presence gave an excellent possibility for direct feedback, smaller ad-hoc adjustments to the research design and well as un-problematic access even to proprietary project material that just had to be cleared when checking out. The presence also deeply enhanced the understanding in the office of what the purpose of the study was and why the access to different parts of the project material was necessary. Even follow-up queries and project material requests have worked out quite well for all the four case studies after having showed face in the office – even when it was just for a very short period of time. Equally, the mere fact of being present in the environment for a while enhances the overall understanding about how things work there on a daily basis. This insight would not have been possible to gain exclusively through interviews and requested project material and in this way the case studies ended up still containing some elements of the initially intended observational study.

### *Qualitative research interviews*

A considerable part of the data used for the case analysis is retrieved through semi-structured qualitative in-depth interviews with key persons that have been involved in the different projects.<sup>51</sup> All interviews were conducted during the stay in the different offices as recorded face-to-face sessions that has later been transcribed in their entirety. The open form of this kind of interview or conversation which is structured around a theme and a number of key words and/or main questions has been used by the author in several earlier research projects with good experience.<sup>52</sup> The quality of this type of data collection is that you do not force answers and understanding into pre-established categories but seek to let the interviewee form the conceptual universe around the subject matter. The downside, on the other hand, is that qualitative in-depth interviews produce a huge amount of often ill-structured information that subsequently has to be processed in order to be condensed into directly applicable data material. Although the idea is to let the interviewee talk freely around a subject matter, it still requires considerable control from the interviewer to produce a useful interview and make the findings between different interviews comparable in wider context. It is often difficult – if not impossible – to generalise findings. It should be said that qualitative interviews are generally most applicable in explorative research phases, where the purpose is to enhance the researcher's (general) understanding of a particular field of research and establish or enhance the conceptual universe around it. Subsequent phases aiming at hard fact data collection will often benefit more from quantitative multiple choice oriented approaches. This particular PhD-project mainly stays in the explorative field, while trying to synthesise different field of knowledge in order to establish a new way of looking at a contemporary industrialised architecture.

### *Reviewing process*

When getting access to potentially proprietary material during the data collection for the cases in the different offices, the normal procedure is to provide the possibility of a reviewing process in order to assure that the information used for the thesis does not compromise proprietary issues for the participating offices. Even when just performing an interview, at least giving this possibility is often the best way to assure that you do not violate such issues. Furthermore such an offer enhances the probability of getting access to the right information: The contributor does not in the first place have to think about what might be problematic or not to provide. On the other hand, by opening up for the possibility that contributors can actually comment on and potentially demand

- 51 An introduction to different forms of interview – and the qualitative interview in particular can be found in (Kvale1997)
- 52 See e.g. (Jensen & Beim 2006, Beim, Vibæk & Jørgensen 2007, and Beim, Nielsen & Vibæk 2010)

changes – potentially even demand the withdrawal of the entire of parts of the contribution does pose certain risk on such a promise. Being too dependant on one single contributor should be considered. A less serious although still important matter is that of getting the produced material out to the contributor and getting feedback and/or accept back in time. Here, author's experience is that offering long time limits is not very expedient. Rather they should contain two steps – a first relatively short deadline that – if it does not yield result – should be followed up by a kind reminder explicating that if you do not get any feedback within a slightly prolonged time limit, you will take that as an accept of what has been forwarded. In this way you keep your promise and simultaneously avoid taking unnecessary time from your project contributors.

### *Network is crucial*

It should be mentioned that in all four cases of the present thesis, the initial contact was established either on the basis of earlier collaboration or through personal recommendation from people that had connections to the offices. Objective and neutral selection of case studies of the kind that has been executed in connection to the present thesis does not seem like a plausible path. There is simply too much work and too low success rate in starting from scratch – particularly when considering the time available. You need a network!

## GOING ABROAD

Both the primary KieranTimberlake case study and the secondary Arup Associates study implied going abroad and have contributed to the international profile of the thesis. For the latter it was basically just a matter of a short travel as the study was condensed to four full days in the office in London. The KieranTimberlake study was different – partly because of the time span which was two days a week during four months but also because it was combined with a visiting scholarship at University of Pennsylvania, Department of Architecture, where the author had the chance to follow relevant courses and receive qualified supervising during the stay. This mix between academic and professional affiliation worked out really well despite the evident fact that two part time 'jobs' is more than full time and that activities occasionally were difficult to combine. The double affiliation also boosted networking possibilities for a newcomer and this was used both for arranging e.g. factory visits and attending academic events in other locations that all contributed positively to the data collection and

the contextual understanding of the thesis. Being abroad for a semester, as it was in this case, was probably the most suitable for a project of the present extent.

## THE TIME

Although three years – or in this case 30 months – might seem a long time for one single research project and was longer than any project the author had been involved in beforehand, you quickly realise that it is extremely important to have a research plan with predefined milestones and work phases in order to keep up the pace of the work and the general progress of the project. Making wrong selections can be very instructive but also very time consuming – as the intention of doing observational studies turned out to be. Without prior experience in doing a project of this size and duration completely on your own, you are surprised about the relatively limited amount of information you are able to process into knowledge during the available period. This is not to say, that without strictly following a predefined plan, you will never reach the goal in time. Rather it is about having a plan and a schedule in order to break loose of it while always being able to fall back on it and revise it according to new insights and experience. Without being in deep water from time to time, you will most probably not discover much that you did not know already beforehand. On the other hand it is also important to know when to focus and narrow down the scope. This is often the most difficult task. Again, today it is not a question about whether the knowledge you are looking for is out there – it most probably is. Rather it is a question of locating it and selecting it from the immense amount of information available.

## MANAGING DATA COMPLEXITY AND WRITING PROCESS

So what is the most efficient – or effective – way of condensing information into relevant knowledge for the project in general and for the final thesis in particular? There is definitely no single response to that question other than that is very personal. Generally regarded, the author has in present project used two parallel ways of writing and collecting data and thoughts. The first one is a log where the text and/or illustrations are ordered by date in a long non-thematised way. The second one is the gradual formation of themes, that later

become chapters in a structure that end up being the final thesis – or smaller articles or papers throughout the project course. These latter texts can also be seen as a third way that enables you to write down a relatively long coherent line of thoughts that fold out one or several of your themes or later chapters – a way of practising the writing and of testing some of your ideas. The idea of the log is that it represents a more free way of thinking and writing that does not necessarily have to be fitted into any context. The log can then regularly be checked for consistent ideas or interesting tracks that perhaps suddenly fit into the more thematised structure of the chapters. Most of the log probably never find its way into the thesis but is still during the process a way to keep up pace and not get stuck.

### *Supplementary tasks*

At the end of the work with the thesis at least if it has the format of a monograph and even if thoroughly planned, you will most probably be heavily concentrating on the writing process. Here the time spent on supplementary tasks should not be underestimated and need to be incorporated in the planning. The final layout is an important issue and although it should not be blown out of proportions – a PhD-thesis is not a book publication – it still takes up considerable time if it should not just be a 200 hundred pages' standard word-format document print without a single illustration where you will most probably lose the reader's attention after the first ten pages. An exception here is perhaps your opponents that are to some extent obliged to get through the entire text, but even here you do them – and yourself – a big favour in adding a bit of scientific knowledge concerning visual perception and ways of facilitating concentrated reading. Proof reading by someone not being yourself should also be considered, but both jobs are extremely expensive if professionally outsourced, so try and use your network again.

Other issues are the use of illustrations and references that also in the present thesis has constituted a considerable workload. To start with the latter, the only thing that really works is to write down the entire reference when you make use of it the first time (during the writing process). If one should miss, the author has in more than one occasion had substantial support by Google Books that especially for English literature often can provide you even with the exact pagenummer. Finding sufficiently high resolution illustrations and clearing copyright issues can equally be a tedious job. However in most cases the copyright rules for PhD-thesis are less strict and with a formulation about

the possibility of putting up a claim, the experience from earlier publications is that you can save a lot of work. Still it is important to remember to credit photographers and other sources if possible, so writing these down from the beginning can be very helpful.

## CONCLUDING REMARKS

The present section has tried to sum up some of the methodological issues that the author has faced during the process of elaborating the present thesis. Some are very simple and practical while others have more theoretical character. Equally some are very project specific while others have general relevance and applicability and can thus hopefully serve as inspiration for others.

53 See *Definition of scope*, I.4, p. 18

## V.3 CONCLUSIONS IN SHORT

- revisiting main problem, hypotheses and research questions

The two previous sections have sought to recapitulate and discuss both the pivotal as well as more secondary findings of the present research on three levels concerning respectively methodological aspects and experience, model development, as well as results from the specific analyses of the case studies in part IV – ‘Model’. The attempt to span all three levels in one single thesis produces a large material that, admittedly, can make it difficult to get an overview and draw out explicit and concise conclusions of the work. This last section is intentioned to sum up the findings in a short format by revisiting the main problem and the hypotheses with their respective research questions as they were formulated in part I – ‘Frame’ and part II – ‘System’. A final paragraph touches upon the issue of further development perspectives and the need for future research.

### MAIN PROBLEM AND GOAL

The main problem was formulated as:<sup>53</sup>

**How can systems thinking help bridging the apparent gap between architectural ideation and its subsequent realisation as process and result in contemporary industrialised construction while simultaneously handling the increased complexity of specialisation and technical development?**

The derived goal then followed as:

*To propose an analytical structure (interpreted as a tool or a model) for clarifying the potential of industrialised construction as positively enabling rather than limiting the architectural solution space.*

The notion of *system structure* and the system structure model, as it has been presented, represent the author’s proposal for an analytical structure – or tool – that can, it is asserted, help clarifying the potential of industrialised construction as positively enabling. This assertion is substantiated by the meaningful results of applying the model in its present stage to four different case studies. By integrating inspirational systemic elements from four different theoretical

fields as well as from a practical exploration of products and commoditisation in architectural construction, the system structure model draws on several sources of systems thinking in order to introduce a systemic level in architecture and construction that lies between general construction techniques and specific architectural results. This level – grasped by the system structure model – seeks to bridge the apparent gap between architectural ideation and its subsequent realisation by establishing a systems view on buildings and architectural design that can facilitate the handling of the increased complexity of both specialisation and technical development. Through the use of flexible constituent elements – termed *deliveries* with varying degrees of *integrated complexity* – the model visualises how architectural wholes (ideas) are appropriately put together as assemblages of what the current and future building industry is capable of producing (realisation as process and matter). A multi dimensional understanding of integrated complexity – an integration taxonomy – has been introduced as a way to nuance what deliveries and in particular integrated product deliveries as an emerging entity in architectural construction are, and how they can contribute to handling complexity in architectural construction through different preparation, standardisation and service levels. The taxonomy does not exclude supplementary dimensions.

54 See *Method and scientific approach*, I.5, p. 23

Used actively, the notions of system structure, integrated complexity and the system structure model potentially bring idea closer to realisation in architectural construction. However, at its present stage, the model stays mainly analytical on the strategic and theoretical level. Still, it enhances understanding and overview concerning industrialised construction in particular and is thus applicable even on a practical level although it will still need further elaboration in order to become a true and effective operational tool for direct use in architectural practice.

## HYPOTHESES

The thesis lines up five hypotheses – one methodological and four theoretical. The latter are derivations of the main question of the thesis but with regard for the respective fields of exploration.

### *Methodological*

The methodological hypothesis was formulated as:<sup>54</sup>

55 See *Systems in architectural theory*, II.1, p. 42

**A particular research method that better matches the way architecture itself is conceived can be used in the development of (intermediary) analytical models that are specifically suited for an architectural frame of reference – a new paradigm for knowledge production in architectural research.**

The abductive research approach and the creative application of a suggested ideal sequence of inference: abduction – deduction – induction have successfully led to the elaboration of a system structure model, that has roots in the object it seeks to examine – architectural creation with particular focus on industrialised construction. *Successful* does here not necessarily refer to the practical application of the model in its present stage but rather to the fact that the system structure model has shown to be coherent as an analytical model that has been conceived specifically for an architectural frame of reference. Furthermore, in its present form, it clearly integrates knowledge from this frame of reference. Abductive inference seems to match important aspects of knowledge production in creative disciplines like architectural creation and is likely to become a part of a more established paradigm for architectural research in the future.

### *Theoretical*

The derived hypothesis for the exploration of *architectural theory* was:<sup>55</sup>

**A gradually growing division has appeared between on the one hand how architecture is conceived as design (conceptual idea and form) and, on the other hand, how it can actually be produced (construction)**

The hypothesis was addressed through the following two research questions:

- a) What are the main constituent ‘elements’ of architecture as expressed in architectural theory?
- b) How can the apparent division between design and production/construction be substantiated and explained through architectural theory?

Much of the classical architectural theory as e.g. Vitruvius deals with the search for universal laws or guidelines for architecture that can prescribe or suggest a certain combination of its constituent elements. These constituent elements seem up until the renaissance to form a coherent whole or continuum from idea to realisation. Alberti’s building types and elements are still closely connected to their realisation but however introduce *angles and lines* as prod-

ucts of thought as opposed to *matter* in the form of building materials. From this point and on conceptual idea/form and construction seem gradually to loose connection. While the former oscillates between pure artistic expression and political ideology the latter becomes consolidated as a separate discipline expressed in the emergence of engineering and culminates (?) in present day industrialised construction techniques and concepts like e.g. lean construction.

The derived hypothesis for the exploration of *classification systems in construction* was:<sup>56</sup>

**The growing complexity of construction both as processes and as objects has produced a variety of classification systems that either split up or transcend the traditional crafts**

The hypothesis was addressed through the following two research questions:

- a) How has the construction sector conceptually systemised building processes and/or physical elements in order to facilitate clear interfaces of responsibility between a growing number of stakeholders and reduce the complexity of the construction process?
- b) Does classification systems used in the construction sector reduce the complexity from the point of view of the architect and what implication does it have for the architectural result?

Different classification systems in construction have emerged as tools exclusively concerned with the execution of buildings. They seldom – if ever – have roots in architectural ideation and mostly work as posterior translations of architectural projects into construction projects thus rather enhancing than reducing complexity of a design task from the point of view of the architect. Classification systems in construction are mostly nationally based thus mirroring the construction sector in general. The introduction of new IT-technology combined with enhanced internationalisation are beginning to trigger universal standards that however still rather *classify* (as ‘type-of’) than *identify* (as ‘part-of’) thus often freezing the constituent elements in fixed and interlocked categories of process, products (matter) or organisation (e.g. trades). This seems to work against the development and use of new more *integrated product deliveries* in construction that potentially could integrate complexity thus reducing design complexity in focus in individual construction projects.

<sup>56</sup> See *Classification systems in construction*, II.2, p. 65f

57 See Industrial production theory, II.3, p. 78

For the exploration of *industrial production theory* the derived hypothesis was:<sup>57</sup>

**Industrialisation within the production industry has moved from standardisation of products towards standardisation of processes thus extending the concept of ‘the product’ to include processes, techniques and business models that are equally applicable within construction – even when it comes to one-off building projects.**

The hypothesis was addressed through the following research question:

- a) Which concepts from industrial production theory are applicable within the context of building projects and architectural design?

While on the one hand the project based construction sector has become more industrialised on the other hand the product industry has directed focus towards standardising processes rather than products. Processes have become products themselves! This enhances potential links between the two fields that intersects in new concepts like e.g. mass customisation and configuration. The somehow – in an architectural context – misleading term of *product architecture* referring to the structural organisation of both physical and non-physical elements seem useful in architectural construction when brought to building *project* level as *system structures* that sustain the whole while simultaneously splitting up this whole into meaningful project specific constituent elements (products, modules, product platforms etc.) that can be designed and produced relatively independently e.g. as outsourced. Combined with the more process oriented concept of *supply chain* and *supply chain management* product architecture/system structures point towards a possible enhanced commoditisation of architectural construction through new splits between a product level of more or less integrated product deliveries (economies of scale) and a project level where these are assembled into unique context specific buildings (economies of scope).

Finally, for the exploration of *general systems theory* the derived hypothesis was:<sup>58</sup>

**Widespread specialisation in construction caused by growing complexity has resulted in fragmentation into isolated fields of knowledge and has produced a need for intermediary models capable of grasping *relations between* these rather than their individual characteristics**

This hypothesis was addressed through the following research questions:

- a) How does (general) systems theory address the balance between specialised knowledge and wholes?
- b) How can (general) systems theory point towards answers to the need for an intermediate model that can help combining specialised knowledge (of architectural construction) into coherent wholes?

58 See *General systems theory*, II.4, p. 100

General systems theory introduces *isomorphism* as a way of conceptualising structural or organisational similarity between systems or coherent wholes with potentially widely different specific content. In architectural construction this can be translated into equal system structures across different projects. On the other hand *equipifinality* expresses structural or organisational difference leading to essentially the same system or coherent whole. Here – in architectural construction – different possible system structures (or construction scenarios) lead to equal end results. Furthermore the notion of *holons* as entities being both parts and wholes depending on the (selected) focus represents a useful input for the understanding of how a model of the constituent elements of architectural construction and its entities – as e.g. the elaborated system structure model and appurtenant *deliveries* – can switch level, scale or focus point according to the specific purpose of modelling such a system structure. This *levelled complexity* of the holons – in the model: the deliveries – facilitates what in the present thesis has been termed a *flexible structuration* that coded into a system structure grasps relations between entities (deliveries) of thought, process and/or matter rather than their complex and specialised individual characteristics. These entities span in the system structure model from raw materials over building materials and system components to assemblies and chunks with a high degree of integrated complexity which then culminates in the final building.

## FUTURE RESEARCH AND DEVELOPMENT PERSPECTIVES

The present research has, as mentioned earlier, intentionally operated on three different levels of development:

- a) a *methodological level* concerning method in architectural research
- b) a *model development level* concerning the development of the system structure model – and

- c) a *practical application level* aiming at using the elaborated model for specific analyses of empirical data

The first and most general is the methodological level where the ambition was to contribute to an ongoing discussion and methodological development within architectural (an artistic) research and its relation to practice. Creative knowledge production through use of abductive inference is not new – and abduction is a relatively well known term within the architectural research community. Present research has – with the earlier mentioned difficulties of representing such an approach in a linear fashion – sought to apply abduction and the suggested sequence of abduction–deduction–induction in a conscious and systematic way which seem to have yielded useful results. However a more thorough examination of the implications of a conscious use of abductive inference for architectural research and knowledge production as well as its relation to the more established forms of inference seem necessary in order to possibly establish a proper (new) research paradigm. Extracts from the discussions of the theme in the present thesis have been selected for publication as part of a special issue of the now reborn architectural research journal of The Nordic Association of Architectural Research. The issue titled *When architects and designers write, draw, build, ?* a PhD is due for publication late 2012. It is the author's hope that this issue will represent one of the fora for a continued discussion and development of these methodological aspects.

The system structure model has, as dictated by the applied methodology, already been through several iterations of successive approximation thus seeking to qualify the initially abductively inferred version through both deductive inference of theoretical scenarios as well as inductive inference through exposure to real world phenomena as expressed in the case studies as well as in the practical exploration of the building industry and its products as described in part III – 'Product'. Although ideally the sequencing back to new abductions of the model was intentioned, the procedure has not always been that straight forward. What hopefully qualifies the model as robust although not definitive is its strong foundation in both theory and practice. However, the model should be seen as an open proposal rather than a finished tool. Future steps will obviously be to bring the model in its present stage back to the contributors of the different case studies in order to discuss and record what it actually shows for them and to what extent this gives new insight in the cases that have already been analysed. Relevant here will equally be to understand what lacks, faults

and problems the contributors can point out in the current model version. This concerns not the least the use of the *delivery* as the system entity with its different degrees of integrated complexity. Direct interest in a model presentation session has so far been taken from two of the four industrial participants.

The future practical application of the model is evidently closely related to the continued model development and iteration as sketched above. Pivotal for a possible successful implementation of the model as a directly operational tool in architectural practice, contracting firms, and/or building manufacturers seems to be to obtain an enhanced understanding about where complexity – here expressed e.g. through workload and resource use – actually is located in the everyday practice of these companies. In order to make it plausible to integrate the use of the model in practice for more than just test purposes, heavy arguments are needed to make probable that it will actually, as suggested, reduce the complexity of the overall design work to be handled – or at least improve the end result to such a degree that resources can be meaningfully allocated for its use. Here is perhaps one of the keys: the resource aspect in a broad sense. As pointed out earlier, the increasing demand for environmentally sustainable solutions makes it of outmost importance to control resource use and material cycles. This is perhaps the heaviest single argument for introducing the use of system structures as an integrated part of the architectural design process which in the future will need to include the later disassembly and recycling design of buildings and their constituent elements. As suggested, system structures are equally suited to describe and analyse the disintegration of buildings. If we are to understand and actively work with buildings as series of systems that can both be nested into each other (as integrated complexity) and disintegrated in order to form part of e.g. closed material cycles of an industrial ecology, we – and the architectural practice – need operational tools that bridges not only idea and realisation but the idea, the realisation as well as the *afterlife* of our built environment. It is the author's hope that the notion of system structure and future iterations of the thoughts around the proposed system structure model will take hold or inspire in the development of such future operational tools.

SYST-AINABILITY could be a new mantra!



# PART VI

# APPENDIX

VI.1 ILLUSTRATION CREDITS

VI.2 BIBLIOGRAPHY & REFERENCES

VI.3 KEYWORD INDEX

- ONLY ON CD

VI.4 PROJECT FRAME DESCRIPTION

VI.5 ARTICLES, PAPERS, AND ABSTRACTS

VI.6 DATA MATERIAL, CASES

VI.7 COURSE MATERIAL

VI.8 OTHER PRESENTATIONS

VI.9 CURRICULUM VITAE

## VI.1 ILLUSTRATION CREDITS

## PART I - FRAME

- I.3.1 Unknown
- I.5.1 © KieranTimberlake  
I.5.2 Author's drawing  
I.5.3 Author's drawing  
I.5.4 Author's drawing

## PART II - SYSTEM

- II.1.1 Author's scheme  
II.1.2 <http://www.mahalo.com/answers/robert-venturi-famous-buildings-architect-what-are-some>  
II.1.3 Vitruvius (1960) *The ten books on architecture*. Translation by Morris Hicky Morgan, Dover Publications, New York, p 85  
II.1.4 CINARK, Johannes Rauff Greisen  
II.1.5 Author's drawing  
II.1.6 Author's drawing  
II.1.7 Hays, K. Michael, ed. (2000) *Architecture Theory Since 1968*. MIT Press, Cambridge/London, p 154  
II.1.8 Ibid, p 155  
II.1.9 Hartoonian, Gevork (1994) *Ontology of Construction – on Nihilism of Technology in Theories of Modern Architecture*. Cambridge University Press, Cambridge, p 21  
II.1.10 Ibid, p 8  
II.1.12 <http://www.all-art.org/Architecture/21-8.htm>  
II.1.13 <http://www.all-art.org/Architecture/21-8.htm>  
II.1.14 [http://en.wikipedia.org/wiki/Beaux-Arts\\_architecture](http://en.wikipedia.org/wiki/Beaux-Arts_architecture)  
II.1.15 <http://www.panoramio.com/photo/1869493>
- II.2.1 <http://www.detdigitalebyggeri.dk/>  
II.2.2 <http://www.detdigitalebyggeri.dk/>  
II.2.3 <http://www.bips.dk/> Introduktion til DBK, Teachers Day 2007-02-27 for Implementeringsnetværket ved Gunnar Friborg, bips (.ppt)
- II.3.1 CINARK, Anne-Mette Manelius  
II.3.2 Ulrich, Karl T. & Steven D. Eppinger (2008) *Product Design and Development* (4th edition), McGraw-Hill, New York, p166  
II.3.3 Pine II, B. Joseph and James H. Gilmore (2000) *The Experience Economy: Work Is Theater & Every Business a Stage*, Harvard Business School Press, Boston  
II.3.4 Baldwin, Carliss Y. & Kim B. Clark (2000) *Design Rules - The Power of Modularity*. Massachusetts Institute of Technology, Cambridge, p 133  
II.3.5 Ibid, p 143  
II.3.6 <http://www.doublecad.com/Products/DoubleCADXTProv3/PROFeatures/ParametricConstraints/tabid/1306/Default.aspx>  
II.3.7 [http://www.velux.dk/private/inspiration/velux\\_ovenlydesigner/](http://www.velux.dk/private/inspiration/velux_ovenlydesigner/)  
II.3.8 Hugos, Michael (2006) *Essentials of Supply Chain Management*. John Wiley & Sons, Hoboken (New Jersey), p 27  
II.3.9 Ibid, p 21  
II.3.10 <http://129.187.108.94/dsmweb/en/understand-dsm/tutorials-overview/descripton-design-structre.html>  
II.3.11 Brand, Stewart (1994) *How buildings learn: What happens after they are built?* Viking Press, New York, p13
- II.4.1 <http://www.successcircuit.com/articles/maslows-hierarchy-of-needs/>  
II.4.2 Author's photo  
II.4.3 <http://barkingrabbits.blogspot.com/2007/06/beauty-from-realm-of-abstract-math.html>  
II.4.4 Bertalanffy, Ludwig von (1968) *General System Theory – Foundations, Development and Applications* (revised edition), George Braziller, New York, p 142  
II.4.5 Checkland, Peter (1990) *Soft Systems Methodology in Action*. John Wiley & Sons, New York, NY, p 38  
II.4.6 Ibid, p 27  
II.4.7 Skyttner, Lars (2005) *General Systems Theory*. World Scientific Publishing, Singapore, p 176  
II.4.8 Author's sketch from Alexander, Christopher (1964) *Notes on the synthesis of form*, Harvard University Press, Cambridge, p 82  
II.4.9 Chermayeff, Serge & Christopher Alexander (1965) *Community and Privacy*, Anchor books, New York, p 158  
II.4.10 Ibid, p 176  
II.4.11 Ibid, p 181  
II.4.12 Author's drawing

- II.5.1 Author's photo
- II.5.2 <http://www.heathrowairport2.com/heathrow-taxi-prices>
- II.5.3 Author's diagram
- II.5.4 Ibid
- II.5.5 Ibid
- II.5.6 Author's drawing
- II.5.7 Ibid
- II.5.8 Ibid

## PART III - PRODUCT

- III.1.1 Pine, Joseph II. From presentation at MCPC2007 – The 2007 World Conference on Mass Customization and Personalization (MPC) – See e.g. <http://www.mass-customization.de/mcpc07/>
- III.1.2 Beim, Anne, Jesper Nielsen & Kasper Sánchez Vibæk (2010) *Three Ways of Assembling a House*, Kunstakademiets Arkitektskoles Forlag, Copenhagen, p 79
- III.1.3 NCC AB, <http://www.ncc.se> (press photo)
- III.1.4 <http://www.vuggetilvugge.dk/>
- III.2.1 <http://www.thebrightsparkblog.com/2011/03/kit-of-parts-doctrine-is-fact-sensitive.html>
- III.2.2 Kullman Offsite Construction, [www.kullman.com](http://www.kullman.com)
- III.2.3 RBE (2009) *Facadeguiden 'Rundt om facaden'*. RBE, Ringsted, p 27
- III.2.4 Ibid, p 38
- III.2.5 ©2011 Lutron Electronics, Inc. - <http://www.lutron.com/Company-Info/News/Media-Pres-sCenter/Pages/ImageLibrary.aspx>
- III.2.6 ©2011 Lutron Electronics, Inc. - <http://www.lutron.com/Service-Support/Service/Pages/ServicePlans.aspx>
- III.2.7 Thabo Lenneiye, Benjamin Callam & Kasper Sánchez Vibæk
- III.2.8 Ibid
- III.2.8 Ibid
- III.2.9 Mutopia - <http://mutopia.dk/>
- III.2.10 Ibid
- III.2.11 Ibid
- III.2.12 Author's photo
- III.3.1 Altan.dk - <http://www.altan.dk/>
- III.3.2 Karsten Pålsons Tegnestue (2003) *X-tension – tilbygningssystem til bygningsrenovering* (X-tension: Extension system for building renovation). Erhvervs- og Boligstyrelsen, Copenhagen
- III.3.3 <http://www.deba.de>
- III.3.4 <http://www.dolle.dk/en-us/products/modularstaircases.aspx>
- III.3.5 Kapfinger, Otto (2001) *Martin Rauch, Rammed Earth*, Birkhäuser, Basel, p130 and <http://www.lehmo.at/> and <http://www.lehmtonerde.at/>
- III.3.6 ©2011 Lutron Electronics, Inc. - <http://www.lutron.com/Company-Info/News/Media-Pres-sCenter/Pages/ImageLibrary.aspx>
- III.3.7 NCC Construction Danmark - <http://www.ncc.dk/>
- III.3.8 <http://stavneblokka.blogspot.com/>
- III.3.9 RBE (2009) *Facadeguiden 'Rundt om facaden'*. RBE, Ringsted
- III.3.10 <http://www.easyvator.dk/>
- III.3.11 <http://www.rucon.dk/gallery/færdigkviste/færdigkviste>
- III.3.12 <http://www.swifthorsman.co.uk/companies/swift-horsman/products/podwall> and Arup Associates (Ropemaker Place)
- III.3.13 [http://www.tatasteelconstruction.com/file\\_source/StaticFiles/Construction/Bi-steel/Corefast%20Brochure%20DPS%20Final%20Approved%20130607%20.pdf](http://www.tatasteelconstruction.com/file_source/StaticFiles/Construction/Bi-steel/Corefast%20Brochure%20DPS%20Final%20Approved%20130607%20.pdf)
- III.3.14 Transwall - <http://www.transwall.com/>
- III.3.15 WindowMaster A/S - <http://www.windowmaster.com/>

## PART IV - MODEL

- IV.1.1 KieranTimberlake
- IV.1.2 Author's drawing
- IV.1.3 Ibid
- IV.1.4 Ibid
- IV.1.5 Ibid
- IV.1.6 Ibid
- IV.1.7 Ibid
- IV.1.8 Ibid
- IV.1.9 Ibid
- IV.1.10 Ibid

- IV.3.1 © Peter Aaron/Esto  
 IV.3.2 © KieranTimberlake  
 IV.3.3 CINARK, Ulrik Stylsvig Madsen  
 IV.3.4 © KieranTimberlake  
 IV.3.5 © KieranTimberlake  
 IV.3.6 Author's drawing  
 IV.3.7 Author's diagram  
 IV.3.8 © Peter Aaron/Esto  
 IV.3.9 © KieranTimberlake  
 IV.3.10 Author's drawing  
 IV.3.11 © KieranTimberlake  
 IV.3.12 [www.eurienta.com/travel/berlin/cite-radieuse.php](http://www.eurienta.com/travel/berlin/cite-radieuse.php)  
 IV.3.13 Author's drawing  
 IV.3.14 © KieranTimberlake + author's sketch  
 IV.3.15 © KieranTimberlake  
 IV.3.16 © KieranTimberlake  
 IV.3.17 Author's photo  
 IV.3.18 © Albert Vecerka/Esto  
 IV.3.19 © Peter Aaron/Esto
- IV.4.1 Author's photo  
 IV.4.2 Scandi Byg A/S - <http://www.scandibyg.dk> and ONV Arkitekter – <http://www.onv.dk/>  
 IV.4.3 Ibid  
 IV.4.4 Author's drawing  
 IV.4.5 Ibid  
 IV.4.6 Ibid  
 IV.4.7 Ibid  
 IV.4.8 Author's photo  
 IV.4.9 Ibid  
 IV.4.10 Ibid  
 IV.4.11 Author's drawing  
 IV.4.12 Scandi Byg A/S - <http://www.scandibyg.dk>  
 IV.4.13 Ibid  
 IV.4.14 Author's photo
- IV.5.1 Ibid  
 IV.5.2 Author's photo and <http://www.ncc.dk/da/Erhvervslokaler/Kontor/Vallensbaek-Company-House/>  
 IV.5.3 NCC Construction Denmark - <http://www.ncc.dk>  
 IV.5.4 Author's drawing  
 IV.5.5 Ibid  
 IV.5.6 Ibid  
 IV.5.7 Ibid  
 IV.5.8 Ibid  
 IV.5.9 Author's photo
- IV.6.1 © Arup Associates/Christian Richters  
 IV.6.2 © Arup Associates  
 IV.6.3 Author's photo  
 IV.6.4 Author's drawing  
 IV.6.5 © Arup Associates/James Ward  
 IV.6.6 © Arup Associates  
 IV.6.7 Author's sketch  
 IV.6.8 © Arup Associates  
 IV.6.9 Ibid  
 IV.6.10 Author's drawing  
 IV.6.11 © Arup Associates  
 IV.6.12 Ibid  
 IV.6.13 Ibid  
 IV.6.14 Ibid

## VI.2 BIBLIOGRAPHY &amp; REFERENCES

BOOKS, CHAPTERS  
AND ARTICLES

- A** Alberti, Leon Battista (1992) *On the Art of Building in Ten Books*. Translation by Joseph Rykwert, Neil Leach & Robert Tavernor. MIT Press, Cambridge/London
- Alexander, Christopher (1964) *Notes on the synthesis of form*, Harvard University Press, Cambridge
- Allenby, B. (2006) *The ontologies of industrial ecology?* IN: *Progress in Industrial Ecology - An International Journal*, Vol 3, Nos 1/2 pp 28-40, Induscience Publishers, Geneva, CH
- Andersen, Heine, Thomas Brante & Olav Korsnes (ed.) (1998) *Leksikon i Sociologi* (Sociological Encyclopedia), Akademisk Forlag, Copenhagen
- Archer, Bruce (1995) *The Nature of Research* IN: *Co-design, Interdisciplinary journal of design*, pp 6-13, Taylor & Francis, January
- Armistead, Colin, A. Harrison & Philip Rowland Armistead (1996) *Business Processes: Lessons from Operations Management* IN: Colin & Philip Rowland (ed.) *Managing Business Processes: BPR and Beyond*, John Wiley & Sons, Chichester
- B** Bachman, Leonard R. (2003) *Integrated Buildings – the systems basis of architecture*, John Wiley & Sons, Hoboken (NJ)
- Baldwin, Carliss Y. & Kim B. Clark (2000) *Design Rules - The Power of Modularity*. Massachusetts Institute of Technology, Cambridge
- Becker-Christensen, Christian (ed.) (2001) *Politikens Nudansk Ordbog med etymologi* (New Danish Dictionary with Etymology). Politikens Forlag. Copenhagen
- Beim, Anne, Jesper Nielsen & Kasper Sánchez Vibæk (2010) *Three Ways of Assembling a House*, Kunstakademiets Arkitektskoles Forlag, Copenhagen
- Beim, Anne, Kasper Sánchez Vibæk & Thomas Ryborg Jørgensen (2007) *Arkitektonisk kvalitet og industrielle byggesystemer* (Architectural Quality and Industrialised Structural Building Systems), The Royal Danish Academy of Fine Arts, School of Architecture, Copenhagen
- Bergdoll, Barry & Peter Christensen (2008) *Home Delivery – Fabricating the Modern Dwelling*, The Museum of Modern Art, New York
- Berlemont, Thierry (2009) *(re)classify - Constructing Architectural Experience* IN: *Architectural Design and Construction Education, Proceedings for ENHSA-EAAE Conference Genoa, June 2009*
- Bertalanffy, Ludwig von (1968) *General System Theory – Foundations, Development and Applications* (revised edition), George Braziller, New York
- Bips (2006) *Det Digitale Byggeri – DBK 2006* (Digital Construction, Denmark), Series of 8 publications about digital building classification in Denmark, Bips, Ballerup, DK
- Braham, William W. & Jonathan A. Hale (2007) *Rethinking Technology – a Reader in Architectural Theory*, Routledge, Oxon
- Brand, Stewart (1994) *How buildings learn: What happens after they are built?* Viking Press, New York
- Boothroyd, Geoffrey, Peter Dewhurst & Winston Knight (1994) *Product Design for Manufacture and Assembly*, Marcel Decker, New York
- Bundgaard, Charlotte (2006) *Montagepositioner – en undersøgelse af montagebegrebet i industrialiseret arkitektur* (Attitudes towards assembly – a study of the notion of assembly in industrialised architecture). Doctoral thesis, Arkitektskolen Aarhus, Århus
- Checkland, Peter (1990) *Soft Systems Methodology in Action*. John Wiley & Sons, New York, NY
- C** Checkland, Peter (1999) *Systems Thinking, Systems Practice*. John Wiley & Sons, New York, NY
- Chermayeff, Serge & Christopher Alexander (1965) *Community and Privacy*, Anchor books, New York
- Cross, Nigel (2006) *Designerly Ways of Knowing*, Springer, London
- Cross, Nigel, ed. (1984) *Developments in Design Methodology*, John Wiley & Sons, New York
- F** Frayling, Christopher (1993) *Research in Art and Design* IN: *Royal College of Arts Research Papers 1*, Royal College of Arts, London
- G** Giddens, Anthony (1990) *The Consequences of Modernity*. Polity Press, Cambridge
- H** Hartoonian, Gevork (1994) *Ontology of Construction – on Nihilism of Technology in Theories of Modern Architecture*. Cambridge University Press, Cambridge
- Hanson, Julianne (1998) *Decoding Homes and Houses*. Cambridge University Press, Cambridge
- Hays, K. Michael, ed. (2000) *Architecture Theory Since 1968*. MIT Press, Cambridge/London
- Hillier, Bill (1996) *Space is the Machine*. Cambridge University Press, Cambridge
- Hillier, Bill & Julianne Hanson (1984) *The Social*

*Logic of Space*. Cambridge University Press, Cambridge

Hugos, Michael (2006) *Essentials of Supply Chain Management*. John Wiley & Sons, Hoboken (New Jersey)

Hvattum, Mari (2004) *Gottfried Semper and the problem of historicism*. Cambridge University Press, Cambridge

**J** Jackson, Scott (2010) *Architecting Resilient Systems*, John Wiley & Sons, Hoboken (NJ)

Jensen, Kasper Vibæk (2003) *Rummet som faktor – en sociomateriel discussion af det byggede miljø* (Space as a factor – a sociomaterial discussion of the built environment). Bachelor thesis. Institute of Sociology, University of Copenhagen, Copenhagen

Jensen, Kasper Vibæk & Anne Beim (2006) *Kvalitetsmål i den arkitektoniske designproces* (Goals and Strategies in the Process of Architectural Design), CINARK (Royal Danish Academy of Fine Arts, School of Architecture), Copenhagen

Jørgensen, Thomas Ryborg (2007) *Arkitektur & Mass Customization* (Architecture & Mass Customization), The Royal Danish Academy of Fine Arts, School of Architecture, Copenhagen

**K** Kapfinger, Otto (2001) *Martin Rauch, Rammed Earth*, Birkhäuser, Basel

Kaspersen, Lars Bo (2005) *Anthony Giddens* IN: Andersen, Heine & Lars Bo Kaspersen, (ed.) *Klassisk og Moderne Samfundsteori* (Classical and Modern Social Studies), p. 430-463, Hans Reitzels Forlag, Copenhagen

Kieran, Stephen & James Timberlake (2004) *Re-fabricating Architecture*, McGraw-Hill, New York

Kieran, Stephen & James Timberlake (2008) *Loblolly House – Elements of a New Architecture*, Princeton Architectural Press, New York

Kim, W. Chan & Renée Mauborgne (2005) *Blue Ocean Strategy*, Harvard Business School Press, Cambridge

Kirkeby, Ole Fogh (1994) *Abduktion* IN: Andersen, Heine (ed.) *Videnskabsteori og metodelære*, Vol. 1 – Introduktion (Philosophy of science and scientific methodology, Vol. 1, Introduction), Samfundslitteratur, Frederiksberg, DK

Kruft, Hanno-Walter (1994) *A History of Architectural Theory – from Vitruvius to the present*. Princeton Architectural Press, New York, NY

Kvale, Steinar (1997) *Interview – En introduktion til det kvalitative forskningsinterview* (Interview – An introduction to the qualitative research interview). Hans Reitzels Forlag, Copenhagen

Kwok, Allison G & Walther T. Grondzik (2007) *The Green Studio Handbook*. Architectural Press/Elsevier, Oxford, UK

Larsen, Esben (ed.) (1993) *Håndbog for Bygningsindustrien*, HFB 27 (Handbook for the Building Industry, HFB 27), Nyt Nordisk Forlag Arnold Busck, Copenhagen, DK

Laszlo, Ervin (1996) *The systems view of the world*. Hampton Press, Cresskill, NJ

Lindemann, Udo, Maik Maurer & Thomas Braun (2010) *Structural Complexity Management – An Approach for the Field of Product Design*. Springer, Berlin/Heidelberg

Lund; Nils-Ole (2001) *Arkitekturteorier siden 1945* (Architectural theory since 1945). Arkitektens Forlag, Copenhagen, DK

Lönberg-Holm, K & C. Theodor Larson (1953) *Development index* University of Michigan, Ann Arbor, MI

Maier, Mark W. (1998) *Architecting Principles for Systems of Systems* IN: *Systems Engineering*, Vol. 1, No. 4, 1998, pp. 267-284, Wiley Periodicals, Wilmington

Maier, Mark W. & Eberhardt Rectin (2009) *The art of systems architecting* (3rd edition), CRC Press, Boca Raton

McDonough, William & Michael Braungart (2002) *Cradle to cradle – Remaking the way we make things*, North Point Press, New York

Meadows, Donella H. (2008) *Thinking in Systems: a primer*, Chelsea Green Publishing, White River Jct.

Meyer, Marc H. & Alvin P. Lehnerd (1997) *The power of product platforms*. The Free Press, New York, NY

Mikkelsen, Hans, Anne Beim, Lars Hvam & Martin Tølle (2005) *SELIA - Systemleverancer i byggeriet – en udredning til arbejdsbrug* (Integrated product deliveries in construction – a preliminary account), Institut for Produktion og Ledelse, DTU, Kgs Lyngby

Mish, Frederick et al. (ed.) (1989) *Webster's Ninth New Collegiate Dictionary*. Merriam-Webster Inc. Springfield, MA

Mutopia (2008) *U\_build - Fremtidens proces- og dialogværktøj* (U\_build. Future tool for process and dialogue). Mutopia, Copenhagen

Nagurney, Anna, (2006) *Supply Chain Network Economics: Dynamics of Prices, Flows, and Profits*. Edward Elgar Publishing, Cheltenham Glos

Nordby, Anne Sigrud (2009) *Salvageability of building materials*. Doctoral thesis, NTNU, Trondheim, NO

Odum, Howard T. (1983) *Systems Ecology: an introduction*, John Wiley & Sons, New York

Odum, Howard T. (1996) *Environmental Accounting: EMERGY and environmental decision making*, John Wiley & Sons, New York, NY

L

M

N

O

- P** Perkins, John B. Ward (1989) *Arquitectura Romana*. Aguilar S.A de Ediciones, Madrid, ES
- Peirce, Charles Sanders (1994) *Semiotik og pragmatisme* (Semiotics and pragmatism). Gyl-dendal, Copenhagen, DK
- Pine II, B. Joseph and James H. Gilmore (2000) *The Experience Economy: Work Is Theater & Every Business a Stage*, Harvard Business School Press, Boston
- Projekt Hus Sekretariatet (2001) *Tæt samarbejde i byggedelen, debathæfte 2, Projekt Hus* (Close collaboration in construction, vol. 2, Project House), By- og Boligministeriet, Copenhagen
- Karsten Pålsons Tegnestue (2003) *X-tension – til-bygningssystem til bygningsrenovering* (X-tension: Extension system for building renovation). Erhvervs- og Boligstyrelsen, Copenhagen
- R** RBE (2009) *Facadeguiden 'Rundt om facaden'* (The facade guide 'Around the facade'). RBE, Ringsted
- Ryn, Sim Van der & Stuart Cowan (2007) *Ecological Design* (10th anniversary edition), Island Press, Washington DC
- S** Schmidt, Robert III, Jason Deamer & Simon Austin (2011) *Understanding adaptability through layer dependencies* IN: Proceedings for International Conference on Engineering Design, ICED11, Technical University of Denmark, Lyngby, DK
- Schön, Donald A. (2001) *Den reflekterende praktiker. Hvordan professionelle tænker, når de arbejder* (The reflective practitioner), Forlaget Klim (and Basic Books), Århus
- Semper, Gottfried (1989) *The Four Elements of Architecture – and other writings*. Translation by Harry Francis Mallgrave & Wolfgang Herrmann. Cambridge University Press, Cambridge, UK
- Simon, Herbert (1979) *Models of Thought*, Yale University Press, New Haven/London
- Simon, Herbert (1989) *Models of Thought – volume II*, Yale University Press, New Haven/London
- Simon, Herbert A. (1996) *The Sciences of the Artificial* (3rd edition). MIT Press, Cambridge
- Skyttner, Lars (2005) *General Systems Theory*. World Scientific Publishing, Singapore
- Smith, Adam (1776) *An Inquiry into the Nature and Causes of the Wealth of Nations*, Strahan & Cadeli, London
- Stacey, Michael (2001) *Component Design*, Architectural Press, Oxford
- Thomassen, Mikkel Andreas (2003) *The economic organisation of building processes*. Doctoral thesis. Technical University of Denmark, Lyngby
- Tjavle, Eskild (1979) *Systematic Design of Industrial Products*, Institute for Product Development, Technical University of Denmark, Lyngby
- Ulrich, Karl T. & Steven D. Eppinger (2008) *Product Design and Development* (4th edition), McGraw-Hill, New York
- T**
- U**
- V**
- Vibæk, Kasper Sánchez (2007) *Flexible Solution Space – Architecture by means of industrialised structural building systems*, Conference Paper, MCPC2007 – Mass Customization and Personalization, MIT, Boston
- Vibæk, Kasper Sánchez (2010) *System Level Design and Nested Systems in Industrialised Architectural Design* (unpublished)
- Vibæk, Kasper Sánchez (2009) *User Involvement as a Configurable Integrated Product Delivery*. Conference paper. MCPC2009 - Mass Matching. Aalto University, Helsinki, FI
- Vind, Bjarne og Mikkel A. Thomassen (ed.) *Byggeriets Innovation – Innovation af byggeriet i teori og praksis* (Buildinglab DK – Innovation in construction in theory and practice). Byggeriets Innovation (Building Lab DK), Copenhagen
- Vitruvius (1960) *The ten books on architecture*. Translation by Morris Hicky Morgan, Dover Publications, New York
- Vitruvio, Marco Lucio (1991) *Los diez libros de arquitectura* (The ten books on architecture). Translation to Spanish by Agustín Blánquez, Editorial Iberia, Barcelona
- Værdibyg.dk (2011) *Perspektiver på faseskift – et debatoplæg* (Perspectives on stage models in construction – a discussion), Brancheinitiativet Værdiskabende Byggeproces, København
- Warszawski, Abraham (1999) *Industrialised and Automated Building Systems*, Taylor & Francis, Oxon
- W**
- Y**
- Yaneva, Albena (2009) *The Making of a Building – a Pragmatist Approach to Architecture*, Peter Lang, Oxford
- Yaneva, Albena (2005) *Scaling Up and Down – Extraction trials in Architectural Design* IN: Social Studies of Science 35/6 (December 2005) Sage Publications, London

## WEBSITES

All websites used are referenced directly in the end notes of the thesis.

## VI.3 KEYWORD INDEX

Allopoietic, heteropoetic	123
Architectural design process	6,16,21,27,37,57,80, <b>107</b> ,110,113,117-18...300
Assemblies	127
Assemblage	120, <b>128-29</b> ,142,152,154-55,167-70,197,205,304,307
Autopoietic/autopoiesis	123
By zone and by system	<b>127</b> ,159,233-34,313-14
Chunks	127, <b>144</b> ,152,167,200,205,308,313-14
Commoditisation	16,84, <b>III.1</b> ,158,202,235,243,255,265,289
Complexity	13-16,18,65,91,96,99-104,118,130, <b>142</b>
Complex systems	20,27,97,99, <b>104</b> , 117,120-24,149-50,208
Configuration, configurator	53,55,57-58,62,77, <b>87-90</b> ,111,114-16,152,307,(341)
Connection joints	28,232,252
Construction management	47,280, <b>283</b> ,294
Cradle to cradle	<b>148-49</b> , 205,(340)
Cybernetics	93,105
Delayed differentiation	<b>80</b> ,90,259
Delivery	<b>125</b>
Design for disassembly	80,90,96, <b>149-51</b> ,205,222-26
Design for X	<b>95-96</b>
Design structure matrix (DSM)	93, <b>94-95</b> ,106,111,113
Early procurement	68,273,314
Embedded knowledge	12, <b>13</b> , 69,97,102,148-51,166,202,274,307
Equifinality	<b>107-8</b> ,119,125,196
Flexible structuration	68,103, <b>119</b> ,124,129,196,246,306,310
General systems theory	19,68,II.4,196,322,(341)
Holarchic structuration	<b>103</b> ,150
Holons	<b>103-4</b> , 111,120-21,150
Industrial ecology	<b>147-50</b> ,319,(339)
Integrated complexity	131, <b>133-35</b> ,154,156,169,304
Integrated product delivery	<b>126</b>
Isomorphism	82, <b>105</b> ,120,124,155,196,322
Levelled complexity	103, <b>119</b> ,123,196,204,304,310
Mass customisation	15,77, <b>87-90</b> ,132,154,174,221
Model	<b>124</b> , IV.1
Modular clusters	<b>84</b> ,174,317-18
Modularity	<b>80-84</b> ,181
Nested commoditisation	<b>150</b>
Nested systems (integration)	72, <b>119-21</b> ,149-50,(341)
Network	84,90, <b>124</b> ,169,318,329
Opaque (deliveries)	97,129,206-8,220,239-40,296,306,315
Parallel and serial deliveries	97,167-68,207-8,240, <b>265</b> ,284, <b>315-17</b>
Parametric design	87,113,148,166,255
Preparation level	<b>131</b> ,146,200
Product-by-product	167,318
Product family	<b>84-86</b>
Product platform	80, <b>84-86</b>

- Service level **132-33,200**  
 Soft and hard systems 108-10(-113),196  
 Soft systems methodology **108-10**  
 Solution space, (flexible) 11,18,21,31,**87-89**,134,142,154,168-69,205,305,**309-12**,(341)  
 Standardisation level **132,200**  
 Structural complexity 31,37,(340)  
 Supply chain 15,28-31,80,**90-93**,97,125,143,199,218-20  
 System boundary definition 159,161,165,313,319  
 System (definition) **122-24**  
 Systems engineering **93-94**,108,113  
 Systems of matter 106,110,174,305  
 Systems of process 106,120,**165**  
 Systems of thought 45,60,120,154,**165-67**,305,311  
 System structure 21,29-31,72,120,**127-30**,152-55,167-69  
 System structure model **196-208**, IV.3-IV.6  
 Technical and biological nutrients **148-50**  
 Tier **28-29**,91,152,199-203  
 Total integrated complexity value 175,202,246  
 Trade-by trade 153,167,318  
 Turnkey 16,**143-47**,169,208,234,246,308-10  
 Upstream and downstream **91**, 125-27,150,199-204,257-60,315
- Alberti, Leon Battista 44,**49-52**,57,63,309,(339)  
 Alexander, Christopher 11,44,95,**110-13**,117,142,163,166,198,204,310,(339)  
 Baldwin, Carliss & Kim Clark **82-84**,317,(339)  
 Bertalanffy, Ludwig von 75,93,**104-7**,118,126,(339)  
 Brand, Steward 95,(339)  
 Hartoonian, Gevork 43,**57-60**,62,93,(339)  
 Hillier, Bill 44,56,**114-17**,(339)  
 Kieran, Stephen & James Timberlake 28,155,168,**IV.3**,307,309,(340)  
 Laszlo, Ervin **101**,103-4,119,150,(340)  
 McDonough, Willian & Michael Braungart 148,(340)  
 Maier, Mark & Eberhardt Rectin 93,**103-4**,142,208,(340)  
 Meadows, Donella 36,**103-4**,149,208,(340)  
 Odum, Howard **118-19**,149,(340)  
 Peirce, Charles Saunders **25-27**,33,35,117  
 Pine (II ), Joseph B. **81-82**,88,140,163,(341)  
 Semper, Gottfried 44,**53-56**,59,128,(340)  
 Simon, Herbert **166**,309,(341)  
 Skyttner, Lars 93,**107-10**,(341)  
 Steward, Donald 94  
 Ulrich, Karl & Steven Eppinger **78-81**,128,(341)  
 Vitruvius 44,**46-49**,57,309,(340)

