Simulation in Complex Modelling

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ABSTRACT
This paper will discuss the role of simulation in extended architectural design modelling. As a framing paper, the aim is to present and discuss the role of integrated design simulation and feedback between design and simulation in a series of projects under the Complex Modelling framework. Complex Modelling examining how methods from the parallel disciplines engineering and computer science can broaden our practices and transfer central information modelling concepts and tools. With special focus on new hybrid structural morphologies and material fabrication, we ask how to integrate material performance, engage with high degrees of interdependency and allow the emergence of design agency and feedback between the multiple scales of architectural construction.

This paper presents examples for integrated design simulation from a series of projects including Lace Wall, A Bridge Too Far and Inflated Restraint developed for the research exhibition Complex Modelling, Meldahls Smedie Gallery, Copenhagen in 2016. Where the direct project aims and outcomes have been reported elsewhere, the aim for this paper is to discuss overarching strategies for working with design integrated simulation.

Author Keywords
Complex Modelling; lightweight simulation; design integration; Finite Element analysis

ACM Classification Keywords
Design.; Algorithms; Performance

1 INTRODUCTION
The current forming of a shared digital design practice has led to the emergence of new methods in which simulation both acts as a means by which to enable feedback in the design chain by informing early design decisions, corroborating intuition and rectification of design decisions. In this sense this new practice has employed multiple understandings of simulation; lightweight simulation using fast and less exact methods for early stage design integration and heavyweight simulation using more verifiable and exact calculation method for final design evaluation [1]. This paper examines how this dual practice has traditionally paired particular kinds of simulation tools to either of these practices and how new advances in the way simulation is undertaken challenge this otherwise simple separation.

The paper aims to understand the fundamental differences introduced into architectural design, as we enter an expanded digital design chain equally concerned with design at the scale of the material, the element and the structure. Rather than understanding simulation as duality between lightweight and heavyweight, simulation here becomes a recurrent and distributed event occurring across the modelling environment bringing together different scales of design agency and employing varying levels of precision as well as different tools of calculation. By using examples from the research investigation Complex Modelling [2], the paper will examine how the advancing of digital design practice, the contemporary evolution of our design tools and the stronger understanding of our problems spaces allow us to reconceive how simulation can become part of design strategy.

2 SIMULATION IN DESIGN
Architectural design practice is facing increasing demands in terms of predictability and performance of its outcomes. Simulation lies at the core of this emerging practice of performative architecture [3], as it allows for the quantitative evaluation of a project’s performance. Today, different means of simulation cover a broad range of architectural concerns, from design to construction and operation, including the simulation of a design’s environmental, structural and material performance and its fabrication and assembly. This means for the new practice, that simulation is understood as an integrated part of the whole chain from design to production and as bridging different disciplines including architects themselves. The incorporation of simulation potentially disrupts traditional design practice by introducing feedback and cyclical thinking in a process that is otherwise characterised by an ideal of linear progression and division of labour separating design generation and analysis.

Design integrated simulation produces computational workflows, which grant simulation models different degrees of design agency [4]. In an analytical track, simulation models are used to investigate the performance of a proposal post design. This approach is exemplified in the Dermoid project [5]. The project utilises the bending
behavior of short plywood elements to form larger trusses arrayed in a reciprocal open topology. The overall structural behaviour of the design in terms of deformation and bending stresses in the trusses is simulated with Finite Element Analysis (FEA). The results are used in turn Explored by the designer, who takes decisions on how to alter the design, if design goals are not met yet. In a generative track, simulation is a part of an autonomous design process. This approach is exemplified in The Rise [6]. Here, the 6m high bending active structure is developed in a computational design system based on the simulation of a growth system and built from bundled strands of rattan. The simulation is devised as an artificial energy metabolism, in which a first set of branches are “grown” according to locally available “energy”. The performance of the grown branches is then analysed with an integrated and calibrated particle spring system and a new energy level is locally distributed based on the results, before the process restarts.

Computational design workflows on the generative track are generally linked to lightweight simulations, as only these can provide the necessary amount of iterations. The analytical track on the other side is characterised by fewer feedback cycles, in which heavyweight simulation is used to provide accurate and precise answers - at the cost of higher processing time. The question is how to overcome the tie of the generative track to fast, but inaccurate lightweight types of simulation and the analytical track to heavyweight but slow types, when complex architectural problems necessitate generative approaches and a general demand for more frequent and better feedback cycles exists in the profession.

3 THE CURRENT DIVISION INTO LIGHTWEIGHT AND HEAVYWEIGHT SIMULATION

To separate different kinds of simulation we introduce a division into lightweight and heavyweight simulation (Fig. 1). The term lightweight is rooted in computer science, where it describes an algorithm or language, which has a small memory footprint or impact on the overall performance of a computational system. In our field lightweight simulations are similarly characterised by a minimal use of computational power. This allows them to be directly integrated into the generative track and workflows of early design stages. Here, they provide a level of accuracy and precision, that is ‘good enough’ for design decisions, while operating on high levels of abstractions, assumptions and generalisations. The algorithms that underly lightweight simulations are often so general in scope, that they can encompass a wide range of concerns and solve simultaneously questions related to geometry, structure, assembly and fabrication of a design.

In contrast heavyweight simulation is understood as more accurate and precise, but as well computationally heavy, specialised in scope and demanding in terms of knowledge about a design. Typical representatives of lightweight simulations are particle/spring systems commonly used in physics systems. In contrast to FEA, which employs a matrix based method for the solution of the equations of equilibrium and the associated stresses of the structural members as a result of forces, boundary conditions and material properties, particle-spring systems operate on a simplified vector representation of forces and solve the equilibrium of the system iteratively. This reduced approach allows to form find structures [7] or simulate realistic physical behaviour directly in the design environment; for instance with tools like the Nucleus solver within Autodesk Maya™ or the Kangaroo plugin for Grasshopper/Rhino.

![Figure 1. Diagram in which the integration of simulation moves along a time based unfolding from lightweight to heavyweight](image)

In CITA the exploration of how to integrate simulation in design has been undertaken across an extensible range of projects employing different material systems and different scales of material interaction [8]. The design of CITA’s pavilion at Roskilde [9] exemplifies this workflow. In the design of this bending active gridshell structure, an initial series of particle-spring simulation models supported the connection between a limited number of critical material behaviours and limits to key design parameters within a generative process. These models included numeric calculation of minimum bending radius and utilisation, so that the natural minimum energy bending behavior of tubular elements could be attracted to a non-standard target geometry, connections established to other elements within the structure, and element lengths maintained. At each iteration, bending was calculated for each element and those forces acting on the elements applied only when the bending was deemed within the limits of the material. After a design was established, it was then evaluated using a different software environment. A non-linear FEA model defined with the FEA software Sofistik AG was used to analyse the resulting geometry and bending stresses after the shaping of the gridshell.

A second example is the Tower [10] a 9m tall bending form-active hybrid structure, in which bend 10mm glass fibre reinforced plastic (GFRP) rods are stacked in layers and inserted into a constraining bespoke CNC knitted surface. The implementation of the K2 physics solver into the computational design model in Rhino/Grasshopper allowed here for a real-time interaction between the designer and the form-finding of the structure. The ability to quickly customise the K2 simulation engine granted the necessary fluid design process. The general nature of the K2 engine allowed furthermore to represent and solve the many layers of design constraints in one modelling environment. This allows us to consider during the design
process simultaneously parameters of shape, structure, production, assembly and to some extent material behaviour, as the light weight simulation provides feedback on the utilisation of the GFRP rods in terms of bending forces. An accurate analysis of the design in terms of stresses in all building elements and the behaviour of the overall structure under external loads took again part in Sofistik (Fig. 2).

The division of the simulation process into an initial lightweight model for design exploration and a later heavyweight model for validation and verification, sets a focus on interfacing ‘handshaking’ between the often very different levels of description used in the models. The challenge is to identify and extract information from one model and to port it directly into another as input parameter. Handshaking can here be uni- or bidirectional. It can take place sequentially, as in Dermoid, where the form found design was analysed in FEA and the resulting dimension of elements fed back into the lightweight simulation, or in parallel, when multiple simulation models produce information for other models [4]. The interface between the often mutually inconsistent frameworks of simulation has to be carefully curated and reconciled in overall fitness functions, artificial metabolisms, Hamiltonians or other weighting methods [11].

The previous section between one set of methods for more abstract behavioural descriptions, and another set for more highly specified behavioural descriptions, can be replaced by the use of both methods across varying levels of material and geometric description. The recognition and exploitation of this overlap – and the extension of domains to which projection-based dynamic relaxation and FEA can be applied - initiates new possibilities for moving between, or combining, simulations - either to become increasingly accurate and precise over a set of investigations, or to simultaneously calculate and combine results drawn from different levels of resolution (Fig. 3).

In the Complex Modelling project we explore alternative models for intersecting and interfacing different modes of simulation in the design model.

4 PROPOSING A NEW MODEL: INTERFACING SIMULATIONS OF DIFFERENT LEVELS OF FIDELITY

Changes in simulation practice now open the door to less linear differentiations and progressions between lightweight and heavyweight simulation. The separation described in the previous section between one set of methods for more abstract behavioural descriptions, and another set for more highly specified behavioural descriptions, can be replaced by the use of both methods across varying levels of material and geometric description. The recognition and exploitation of this overlap – and the extension of domains to which projection-based dynamic relaxation and FEA can be applied - initiates new possibilities for moving between, or combining, simulations - either to become increasingly accurate and precise over a set of investigations, or to simultaneously calculate and combine results drawn from different levels of resolution (Fig. 3).

The research experiments Lace Wall, A Bridge Too Far, and Inflated Restraint develop and demonstrate this extended ability to specify - at varying degrees of accuracy and precision - material systems within design integrated dynamic relaxation and FEA simulation. Limits around the methods for dynamic relaxation, particularly the capacity to incorporate material information such as Young's Modulus,
have previously restricted its capacity to contribute to higher level quantitative understandings of behaviour. But new approaches using projection based dynamic relaxation extend to include this information: In Lace Wall, the goal solver Kangaroo2 is implemented both for describing form-finding behaviours, used during exploratory design where topology and dimensions are free, and for describing mechanically calibrated behaviours used during accurate structural analysis. The Kangaroo2 API enables designers and developers to integrate the solver and write custom goals with great freedom. Enabling both the development of the K2Engineering plugin [12, 13] and the interactive Lace Wall modelling pipeline [14] where designers are free to handshake between the exploratory and structurally accurate modes of modelling at any time.

In contrast, the limits around FEA tools have been in the other direction: a traditional separation from design tools has implied slow iteration time and encouraged use only in the validation of high-resolution geometries. Current integrations of FEA into the design environment are exploited in A Bridge Too Far to enable fast and iterative feedback, but also to develop more nuanced relationships between the FEA model and the design model – simulations that act on scalar subsets of the model to ask partial questions, and which exploit the fact that often, appropriate answers only require a minimum of information, rather than the whole. In A Bridge Too Far, the integrated FEA tool Karamba is implemented within the design process as part of a search and optimisation loop. Its integration within the 3D modelling environment Rhinoceros allows structural simulation to be informed but also then combined with other considerations in a form-finding and optimisation process.

With the ability to specify the models at varying levels of accuracy and precision, new workflows are enabled. While the simulation methods differ between the projects, the workflows share a common approach that partitions models into networks of sub-models functioning at different levels of resolution, and the curating of connections between these models (Fig. 4). This involves identifying appropriate models, tailoring the specificity of material information and the resolution of geometric definition to those models, at the appropriate resolution, and distributing multiple such models across the workflow. Connections might support a sequential progression of material and design specification from low to high, or one to many: In the case of Lace Wall sub-models are organised by feedback loops. Where upstream models generate topology, geometry and behaviours, central models solve these behaviours, and downstream models generate analysis data to re-inform the upstream models. Enabling a continuous and interactive search loop, where resolution is automatically defined on the fly. Allowing humans or search algorithms to generate fit candidates without having to continuously adjust parameters that do not affect design. Alternatively, connections might support also support the progressive generation of design detail across multiple scales, as in the case of the research structure Stressed Skins [15]. Lastly, connections might extract information in parallel from multiple models and combine this within a single energy descriptor to steer design generation, as implemented in A Bridge Too Far.

Our initial exploration of these workflows has led us to change the way we conceptualise the relationship between methods, and the spectrum on which they sit. When both simulation methods can be employed with greater or lesser quantities of information, lightweight and heavyweight is not the best characterisation anymore. With an increased degree of freedom in how we computationally describe both pseudo behaviours (the description of place-hold behaviours that estimate material performance) and accurate physical behaviours, we are now afforded direct

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**Figure 4:** Flowchart of the interactive Lace Wall modelling pipeline, defining different modelling stages and expressing the integrated feedback loops.
control of how we define modelling accuracy (i.e. qualitative properties of the underlying model) and precision (i.e. quantitative properties, such as resolution). As such, the simulation spectrum is perhaps better described as being one of fidelity. Rather than arranging these as an incremental process of refinement we can employ these differing means of reproducing behaviour with different degrees of resolution strategically within the design workflow.

5 EXAMPLES OF WORKFLOWS IN COMPLEX MODELLING

These workflows are prototyped and developed through three Complex Modelling projects: Lace Wall, A Bridge Too Far and Inflated Restraint. Where each project finds local means of implementing simulation, then the strategies have in common the partitioning of the model into a network of models, the distributed and recurrent utilisation of different kinds of simulation across the design chain with varying degrees of fidelity, the external verification and validation of the simulations and the establishing of different kinds of handshake operations within the modelling workflow.

5.1 Simulation in the Lace Wall workflow

Lace Wall belongs to the family of form-active hybrid structures and is a generic and modular space frame-like system, that can be extended in a spatial array to construct large enclosures such as walls, roofs, domes and more complex macro shapes. The material system consists of a minimal inventory of elements: 8mm GFRP rods, textile cables and custom designed high-density polyethylene joints. The rods are bent and joined into 80 discrete units, each stabilised by an internal three-dimensional cable network. While the dimension and topology of the GFRP units are identical, the cable networks are differentiated so as to allow the single units to withstand different local strains in the structure and to constrain each unit into bespoke geometries, that allow them to fit into a desired overall macro shape [16].

Lace Wall investigates computational strategies to design with material systems, that are characterised by a high degree of interdependence of elements and scales. This reciprocal relation limits for Lace Wall the traditional use of small scale physical models for design exploration. Designers get quickly fatigue by the necessary level of accuracy to develop form-active hybrid structures, which are highly sensitive to the smallest imprecision and changes. On computational level the simulation of single units and large arrays of interacting bending active units is similarly challenging, as the final shape emerges only as a result of the interacting forces in the bending active element and the tensioning wires. These can not be captured precisely enough by lightweight simulations and the sheer amount of interacting elements prohibits a handshake to FEA. For Lace Wall it was furthermore of high importance, that the design environment is not restricted to iterations within fixed topologies, as it was the case in Tower [10], but that topologies could be openly explored.

The computational workflow (Fig. 4) of Lace Wall employs, an approach in which a low fidelity simulation, for an initial and approximate form finding, can at any time be exchanged with a high fidelity simulation, for precise determination of the resulting shape and stresses (Fig. 6). The speed of the K2 simulation enables not only a direct interaction of the designer with the bending active structure and immediate feedback on the expected shape and through the K2 loop on the expected performance, but as well to employ generative workflows. Herein topologies for the constraining cable networks can be automatically generated and form found, which provides the means to analyse and qualify the fitness of a candidate. These are collected alongside their fitness parameters in a database for further design iteration. Promising candidates can undergo a more precise analysis with the K2E engine in a second loop.

The models in the workflow share a common data model, where topologies, properties and their performance are encoded in an Object oriented way. This way of representation enables a handshake between the very
different modelling frameworks, within the Lace Wall pipeline.

Core to the development of the workflow, is the constant verification of the computational model against established structural and computational models and theories, as well as the validation of the results against physical probes and prototypes.

**Figure 7. A Bridge Too Far in the Complex Modelling exhibition.**

### 5.2 Simulation in the A Bridge Too Far workflow

A Bridge Too Far is an asymmetric bridge, spanning 3 meters and weighing 40kg excluding buttresses. The structure consists of 51 unique planar, hexagonal panels, arranged without framing into an inner and outer skin. The thickness of each panel varies locally, and at maximum is 1mm thick. The project explores an extension to the capacities of thin panelised metallic skins through the use of rigidisation (the selective movement of local areas of the sheet out of plane to increase structural depth) as means to enable novel lightweight and frameless structures, and the improved understanding of underlying processes [17].

The modelling approach seeks to counter and evaluate buckling at the scale of the structure, the panel and the material. The integrated FEA tool Karamba is used to predict behavior and deflections of the entire structure. This design-integrated simulation is validated against simulation using Sofistik as well as empirical load testing of prototypes. A k-means clustering algorithm is used to determine panel outlines, a low fidelity representation that supports evaluation of the coincidence of seams on upper and lower surfaces. An interference model generates high fidelity rigidisation geometries, from which a precise calculation of material properties is made using circle projection. This is done to incorporate the implications of fabrication within the modelling process. All geometric features in the bridge, including those for resisting local footfall, buckling within each panel, and also the structural connections that manage shear forces across upper and lower skins, are fabricated using Robotic Dual Point Incremental Forming (DPIF). The effects of this fabrication process are both geometrically and materially transformative, where stretching and a local increase in surface area corresponds to thinning and a change of yield strength, according to the angle of forming. The impact within the simulation is to add significant variation to information that would more usually be simplified and made uniform.

**Figure 8. Flowchart of A Bridge Too Far modelling pipeline.**

Where previous research at CITA has explored a sequential approach to the definition of shapes and features at different scales, [18], this project has implemented a parallel approach [11]. A custom tree hierarchy class is used to establish geometry-data coupling and support continuity of information flow [15]. The tree supports information flow between models of different geometric resolution and precision, as well as various upstream and downstream methods of data propagation. This approach to communication between models supports a search and optimization loop. Within the loop, geometric (seams, connection size and shape) and material information (yield strength and material thickness) is generated at geometric resolutions that are both lower and higher than that of the FEA simulation, with information down and up-sampled as required. Deflections calculated using Karamba are integrated with measures coming from these other models and combined into an overall measure of energy, which is minimised during the optimisation loop (Fig. 8).

### 5.3 Simulation in the Inflated Restraint workflow

Inflated Restraint is an air-inflated cable-restrained pneumatic membrane. In this class of structural hybrids the cutting pattern plays a critical role in the scalability,
mechanical performance and resulting aesthetic of the membrane. Architectural membranes are generally characterised by rational patterns with minimal deviation between discrete textile elements. We investigate a method for producing irregular cutting patterns that offer an extension of possible surface languages, achieving defined design volumes with complex surface curvature and the generation of cable restraint topology. To demonstrate this we define a target geometry with areas of pronounced anticlastic curvature. This class of curvature is 'unnatural' to pneumatic systems and embeds an efficacy test for our pattern generation method and fabrication approach. We analyse the mesh curvature of the target geometry to identify and separate regions of synclastic and anticlastic curvature. A k-means clustering algorithm is then used to group mesh faces according to approximate curvature in each of the separated regions. Graph traversal methods (Depth First Search and Dijkstra’s Shortest Path) are then employed to further sub-divide the localised curvature regions into individual patches for fabrication. The naked edges of these patches are then dynamically relaxed to smoothen the boundary edge, ready for laser-cutting and sewing.

The topology model of the cable restraint is also derived from curvature analysis of the design target model. In this case, we firstly identify areas of anticlastic curvature, the ‘lowest’ points of the membrane surface, to establish the primary loops of the net. This ensures that they do not exhibit ‘slippage’ on the membrane when under tension. Further edges are added to the net topology using search criteria that combines finding areas of lowest synclastic curvature (to relieve membrane stress) and being approximately equidistant from each other (to ensure even distribution). In simulation, we ‘inflate’ the membrane model to verify its interaction with the cable restraint model. Here, the measure of success is that the net does not ‘slip’ and the two systems find, and maintain, equilibrium across the operating pressure range. The modelling workflow as a whole is verified by comparison with the physical demonstrator. Here, the measures of success are that the inflated surface achieves the desired curvatures, that the membrane has a smooth transition across patches and that there are no areas of compression resulting in unsightly and underperforming wrinkles (Fig. 11).

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6 CONCLUSION

Complex Modelling takes point of departure in the understanding that the development of architectural design and its material practices is impeded by our inability to comprehend and capture the complexity of more hybrid and more bespoke material systems. If current building practice is optimised through a modus mass production, Complex Modelling asks how future more complex and more hybrid building systems that take advantage of the complex interactions of stress and strain could look and what the logic of the underlying systems of representation and analysis could be.
The modelling workflow presented here seeks to prototype how future design methods can integrate simulation in ways that support the design of complex and highly interdependent material systems. Where the Complex Modelling projects presented in the paper are highly speculative and rarefied, they explore how advanced computational modelling and its strategic integration of different modes of simulation with varying degrees of accuracy and precision allows us to reconsider how architecture is designed, built and understood.

In this workflow simulation is no longer conceived as a simple division between the practices that belong to generative design thinking or analysis and evaluation. Instead, modelling as a whole is understood as the strategic construction of a network of dedicated sub-models in which simulation models for both design generation and analysis appear as distributed and recurrent events across the design chain. The essence of this practice is that:

- That there are multiple sub-models and that they are composed in an overarching modelling network (workflow)
- That the overarching modelling network integrates different kinds of simulation that operate at different levels of fidelity according to locally available information and needs for design accuracy and precision
- That the dedicated sub-models are locally validated and verified in respect to the particular mode of analysis undertaken
- That information is passed between the models through different kinds of handshakes with different levels of sophistication operating within the models

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