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Multi-Scalar Modelling for Free-form Timber Structures

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Abstract

This paper describes a new conceptual and computational framework that employs Multi-Scalar Modelling techniques (Weinan [22]) in order to overcome the problem of big data management and to enable a more integrative digital workflow during the geometrical discretization of spatial structures.
The research explores the design probe of free-form structures composed of glue-laminated timber beams and looks at the different types of data that need to be shared among each discipline and across multiple scales from which different levels of resolution can be defined.
A particular focus lies in the segmentation strategy of glue-laminated timber structures that depend on structural requirements and the different types of constraints related to fabrication, transportation and assembly. Where current working practices decouple segmentation processes within a discrete digital workflow, this research aims to integrate and negotiate the different parameters that drive the same segmentation strategy within a continuous environment.
The research is developed in close collaboration with two industry partners – Buro Happold and DesignToProduction – and focuses on the implementation of Multi-Scalar Modelling concepts and techniques as a means to work within a continuous design environment in which an abstract network of timber beams is iteratively updated through geometrical and structural optimizations at different levels of resolution.

Keywords: conceptual design, Multi-Scalar Modelling, Building Information Modelling, graph theory, data management, glue-laminated timber beams, multi-objective optimization

1. Introduction

The present research is associated to a larger investigation led through the four year Complex Modelling Project developed at CITA (Centre for Information Technology and Architecture). This research agenda examines the computational modelling of structural systems under different scopes, from self-organizing performance to modelling interdependency and Multi-Scalar Modelling strategy. The latter aims to set-up specific hierarchies (or infrastructure) of information through different models and scales, as well as to understand complex feedback loops between the different levels of material organizations that are defined. In the present research, graph theory is investigated and used as the main digital tool for constructing and organizing those hierarchies through seamless abstract networks that can enable the spreading of information from and through multiple scales.

2. Context: from existing modelling methods to Multi-Scalar Modelling

The following section describes the main modelling methods used for architectural conception in current working practices – with examples from the industry partner DesignToProduction – and the respective issues that relate to data management across the different scales considered within an architectural project. Multi-Scalar Modelling is then introduced as a possible novel practice and explores how to solve those problems.

2.1. The current modelling paradigm in architecture

Where the modelling paradigm within the building industry remains scattered through the production of different plans and sections at different scales, architectural firms aiming to improve their digital workflow are progressively integrating the use of the "Industry Foundation Classes" (IFC) – an exchange format allowing the practice of "Building Information Modelling" (BIM) – within their practice. IFC/BIM intends to integrate all the information necessary to the completion of an architectural project into a holistic and unique environment. When the geometrical complexity of an architectural project drastically increases, this strategy becomes computationally expensive (Shelden [19]) and thus difficult to handle when the same project generates a very large amount of data across all scales and resolutions. The digital chain (or workflow) also tends to become discontinuous when each partner of the building industry involved in the construction of large scale and intricate spatial structures needs to access the precise fabrication data of each component. Indeed, new detailed models derived from the master file have to be created in order to encode additional information necessary for the fabrication of every single architectural component (Scheurer et al. [17]). In order to overcome this issue, modelling softwares such as Digital Project and Rhinoceros make it possible to set up the hierarchies of information through separate files (e.g. respectively the .CATPart extentions and the worksession files). In this approach, sub-models are integrated into a master file without being linked to other existing sub-models. Therefore, the overall design workflow remains discontinuous since the dependencies and feedback across scales (or sub-models) do not exist. If one wants to modify a detail that might affect the overall design of a complex structure, the current modelling paradigm only offers the possibility to redraw everything according to the new chosen detail.

2.2. Existing modelling methods in advanced timber constructions

DesignToProduction – one of the industrial partners of this research project – has developed very strong expertise on the segmentation of free-form timber structures (e.g. the Centre Pompidou-Metz and the Haesley Nine Bridges Country Club by Shigeru Ban Architects) and their complex digital workflow from conception to fabrication (Scheurer et al. [17]). During the post-tender phase of those projects, DesignToProduction employs modelling methods enabling the storage of information in parallel to the generated geometry. The hierarchy between children geometries (e.g. beam segments) and their respective parents (e.g. crossing beams) is secured by defining different notational systems, such as layers and attributes. However, the segmentation process remains discontinuous and does not allow a flexible flow of information between the different industrial partners involved in the project. This discontinuity is often due to the large amount of data treated that cannot be handled within a unique file and other software compatibility issues (Scheurer [15]). Indeed, the use of worksession files keeps the design process fragmented and a change in a specific environment does not affect the related geometries that are present in a parent model.

3. Multi-Scalar Modelling: precedents and potential impact in the building industry

Multi-Scalar Modelling presents here an opportunity to overcome the discontinuous modelling paradigm during conception by reconsidering the notions of representation, scale and resolution early in the decision making stages so the access to high-resolution data related to fabrication, transport and assembly is eased at a later stage in the project. The following section describes the interdisciplinary usage of Multi-Scalar Modelling, the advantages it offers, and its possible consequences within the building industry.

3.1. A well-known interdisciplinary concept

The concept of Multi-Scalar Modelling has been largely used in many different scientific domains – e.g. computational fluid dynamics (Chen [4]) – that encounter the problem of modelling and transferring information across multiple scales.

It is recognized that the conceptual development of Multi-Scalar Modelling comes from the realization that the full behavior of a system cannot be represented within one single model since the level of detail differs from one scale to another: maintaining full detailed resolution through all the levels of the system becomes most of the time inefficient and computationally expensive (Nicholas [12]). Alternatively and ultimately, Multi-Scalar Modelling allows the consideration of coupling and interfacing models (or frameworks) at different scales, so we can arrive at an approach that shares the efficiency of the macroscopic models as well as the accuracy of the microscopic models (Weinan [22]).

3.2. Multi-Scalar Modelling: precedents in architectural design research

The coupling of computational design and material science have opened-up a new research field within the architectural practice that argues for the emergence of architectural systems at a global scale through the specification of the material at a very refined scale.
At CITA, the concept of Multi-Scalar Modelling has been specifically introduced through the realization of different design probes and physical demonstrators. The architectural research projects *Composite Territories*, *The Faraday Pavilion*, *The Social Weavers* and *Stressed-Skins* (Nicholas et al. [10], [11], [12]) introduce Multi-Scalar Modelling strategies enabling a direct communication between multiple scales, from material specifications at high resolution to the global design environment. In order to communicate between those different frameworks, bridging or "handshaking" techniques (Winsberg [23]) have been investigated within architectural design research, allowing the translation of information between different models through coarsening and uncoarsening strategies (Nicholas [12]).

3.3. The potential impact of Multi-Scalar Modelling in the building industry

Multi-Scalar Modelling could (re-)unify the fragmented information space of a complex architectural project through the linkage of parallel design frameworks in which models with differentiated objectives can interact between themselves through different scales and resolutions. This definition could challenge on the current shattered domain of the building industry. Instead of being engaged at different moments in time after the final decision of the design, all disciplines would need to negotiate at a very early stage all the constraints together. Only then, the design team can define a Multi-Scalar Model that will take those constraints into account during conception process before distributing particular information – required at different scales – to each specialized team at a later stage during the fabrication process. Such a design framework would enable much more flexibility and ease the data exchange between the different trades involved in the project.

4. Design methods: abstract networks and graph theory

The present design probe uses the process of abstracting complex geometries into simple networks or 2D drawings which serves as a point of departure for setting up a Multi-Scalar Modelling environment for free-form timber structures. Two-dimensional networks can be easily analyzed and manipulated using graph theory, which allows the establishment of connections between nodes through edges. Specific related algorithms enable the user to navigate within a graph, access and manipulate its particular data sets (dividing a graph into subgraphs, checking the number of connections at each node, asking for all the existing closed polygons within it, etc.).
The following design probe investigating the making of a glue-laminated timber structure has been designed through the use of two-dimensional abstract networks in order to map specified dependencies between objects:

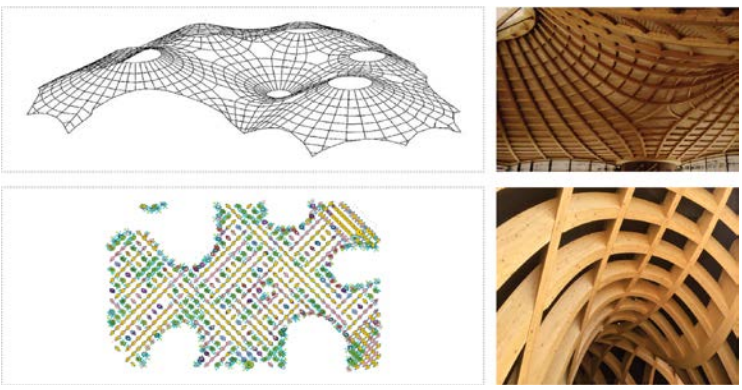

Figure 1: Solemar Therme health spa in Bad Dürrheim (right) and French Pavilion at the EXPO 2015 (bottom)

- During the form-finding process of the Solemar Therme health spa in Bad Dürrheim (Germany) the shell surface was discretized into a network of straight center lines (Figure 1 - top), which represented abstractly the solid geometries that were later needed for fabrication purposes (Linkwitz and Veenendaal [8]).
- During the post-tender phase of the French Pavilion exhibited at the EXPO 2015 in Milan, information exchange between the trades often relied on two-dimensional representations of the timber structure. Excel-tables or simple diagrams (Figure 1 - bottom) eased the access of complex data for both the engineer and the fabricator (Scheurer *et al.* [17]).

Graph theory is seen here as the core concept of parametric/associative modelling (Alexander [1]). Generative Components, CATIA or the Grasshopper environment are all based on directed acyclic constraint graphs (or data-tree structures) that enable the user to specify dependencies between objects. However, the focus in these modelling strategies lies only on the creation of geometry and therefore the graphs themselves and their inherent hierarchies are generally not (or not enough) considered. Thus, traceability between parents and children is often difficult to keep along the continuous modelling actions of the user.

At CITA, the interest in graphs and data-tree structures as methods of modelling and representation has informed different architectural design research projects in order to obtain a better understanding of the relationships between the different structural elements and to ease afterwards the fabrication process. The research project *The Tower* (Deleuran et al. [5]) features a modelling environment that allows the user to directly interact with simulated bending active glass fiber rods that are continuously aggregated and activated by additional strings. When changes occur, a graph is constantly (re-)generated and displays the current assembly logic between all the objects. For the conception process of the *Stressed-Skins* prototype, traceability features have been implemented through adaptive meshing techniques, which allowed the direct transfer of information – from the manipulation of the global design at a macro scale to the calculation of forming strains and material thinning at a micro scale. This particular design framework also allows retroactive feedback – or bi-directional information flows (Nicholas *et al.* [12]) – from high resolution simulations to the global design (and vice versa). In this case, the vertical integration of design and fabrication through directed acyclic graphs is replaced by an interactive and horizontal integration of the design process itself where nodes can communicate and exchange back and forth between each other (Carpo [3]). In the present research, graphs are used to map the specific dependencies between objects existing in free-form timber structures.

5. Design research development: a Multi-Scalar Model for Free-form Timber Structures

The following section describes a speculative design probe that aims to apply Multi-Scalar Modelling techniques using graph theory and data-tree structures as generative and analytical design tools at early stage in the conception of a free-form timber structure. The latter is defined through an aggregation of glue-laminated timber beams that support glass panel elements.

Taking as a starting point the digital workflow existing within the practice of DesignToProduction, this case study tries to enable a new modelling paradigm were a continuous hierarchy is defined across scales within a graph, from an abstract network of lines to the complete fabrication data set of each architectural component.

The sub-section 5.3 extends the defined dependencies by introducing different simulation and optimization methods that can inform and steer the position of each node across the multiple resolutions of the graph – from the material behavior of a particular timber beam to global the structural analysis – in order to inform the overall segmentation strategy by fulfilling particular constraints. The outlook speculates on the introduction of multi-optimization strategies that could enable direct interaction between the different sub-models present within the graph.

5.1 Defining the dependencies across scales and resolutions

The next subsections present the hierarchy of information – from the most abstract to the most detailed level – and the dependencies that exist between the different objects across scales and resolutions (Figure 2), from the conception process to the fabrication data of each component present within the free-form timber structure.

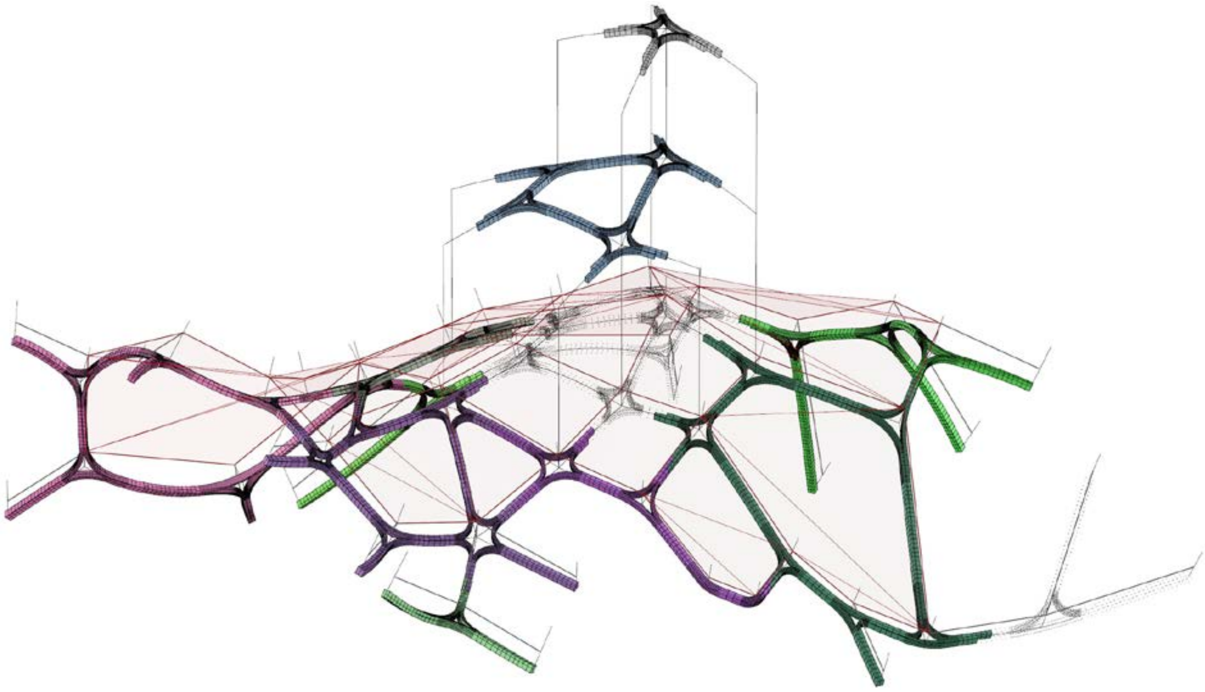

Figure 2: From the joint condition to the global network: defining dependencies across scales and resolutions

5.1.1. Resolution 1: Initializing the network

First, an initial abstract network of lines is defined and interpreted as an aggregation of glue-laminated timber beams.

- If the global design is understood as a continuous shell, the network is projected onto a NURBS master surface that can be controlled by the designer.
- If interpreted as a branching structure, the network does not depend on any master surface and can be freely manipulated in space. In this case, the resulted geometry is truly tridimensional.

For clarification and simplicity purposes, the Multi-Scalar Model described here will not exceed 2.5 dimensions and will therefore rely on a master surface. However, complete three-dimensionality will be introduced and discussed in section 5.2.

Using the python library NetworkX, the abstract network is analyzed as a graph (Figure 3) providing specific information for further geometrical refinement. The user is able to access an ordered list of nodes (and corresponding indices), an ordered list of edges (and corresponding nodes indices at both ends) and the number of connected edges at each node. This strategy enables the construction of a Multi-Scalar Model that generates and links data by the only means of nodes and edges, and thus presents itself as a very lightweight format in the context of 3D modelling for architectural conception.

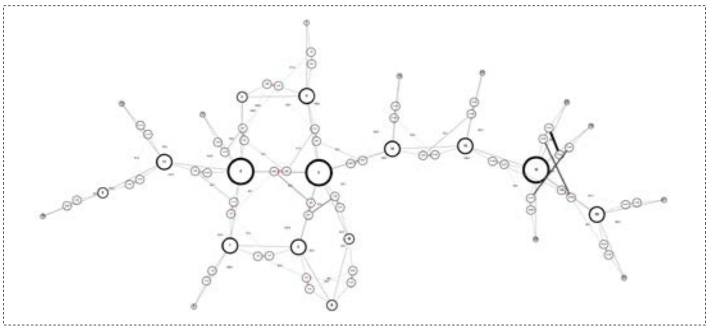

Figure 3: Graph modelling of an aggregated network of timber beam elements

5.1.2. Resolution 2: Subgraphs

Using cycle basis algorithms (Kavitha *et al.* [7]), it is possible to detect all closed polygons present within a graph. This results as a set of subgraphs that can be used for different purposes, from rationalizing façade panels to defining modules for prefabrication strategies.
Each closed polygon of the graph is analyzed and treated as a single element of the cladding system. Glass manufacturing techniques present various typologies: planar, cold bent, single curved and double curved. Depending on the planarity, the size of the polygon and its number of edges, different subdivision strategies enable the generation of the appropriate typology.
Each polygon can also be interpreted as prefabricated modules of aggregated timber beam elements. A collection of multiple polygons can generate larger modules. Transportation and on-site assembly constraints would directly define the maximum size allowed for each module.

5.1.3. Resolution 3: Defining an assembly method through branching strategies

Figure 4: Solemar Therme health spa in Bad Dürrheim

At an architectural scale, branching techniques have been used for centuries in timber structures, and more specifically in the context of bracing work: *"Probably the oldest and most common way of bracing a structure is to use kneebraces, which can take on a wide variety of forms."* (Herzog *et al.* [6]). More recent projects have been using branching systems without any secondary orthogonal elements for supporting roof structures. The Solemar Therme health spa in Bad Dürrheim (Germany) consists of five tree-like columns that branch until they connect to the roof acting as a suspended gridshell (Figure 4).
In the present research, a specific type of joint that can branch and adapt to different valence conditions has been chosen. Contrary to traditional joint techniques where the node complexity increases by the number of elements connected to it, the segmentation location has been displaced at the center of each edge. From this strategy results a specific type of node (Figure 5) where all the connected beams bifurcate along a specified radius in order to meet their respective neighbors (n). Thus, each glue-laminated timber beam splits and bifurcates in n directions. The radius of each bifurcation is calculated by generating the best fit between the largest possible fillet allowed at the angle between two neighboring beams and the minimum bending radius defined by the material behavior of the chosen wooden species.

5.1.4. Resolution 4: Generating the refined geometry of each architectural component

Where the integration of fabrication data within the same computational environment is a well established research enquiry in the context of architectural design research (Aish and Woodbury [2]), this paper explores Multi-Scalar Modelling strategies enabling the integration of meshes or sub-graphs (that carry specific fabrication data sets) within the global graph (or abstract network).
Each glue-laminated timber beam is represented through meshing techniques, as the resulted geometry – additionally to its light format – can be shared within a large number of platforms and softwares related to digital fabrication. Because of its discrete nature, a mesh can be interpreted as a graph which could be integrated within the initial abstract network of edges that substituted so far the geometrical representation of every timber element. Each mesh is therefore a local refinement (or sub-graph) of the global graph. Furthermore, the meshing refinement can adapt to the local curvature and torsion of each beam, so the

generated amount of data does not become excessive or superfluous where it is not particularly needed during simulations and optimizations.
Considering all the established connections that link the global model to the full resolution of a component, it is therefore possible to extract one node that contains all the graph information necessary to regenerate within a parallel environment a refined level of the timber's geometrical representation.

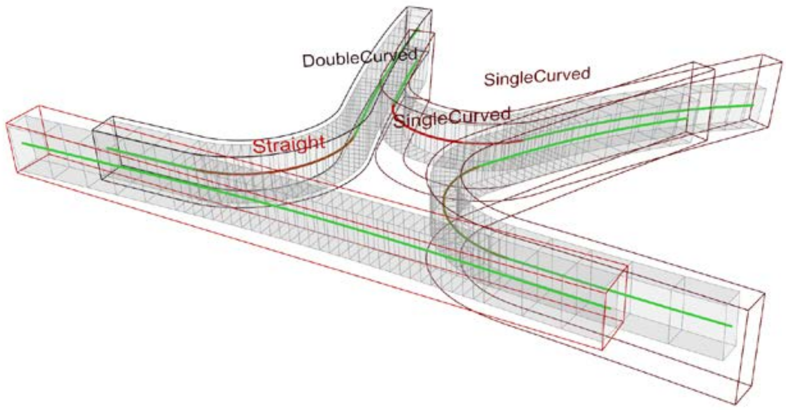

Figure 5: A branching joint and the blank typology of each glue-laminated timber beam

5.1.5. Resolution 5: Generating the blank – or fabrication data set – of each timber element

Building on the research of DesignToProduction which has identified during its practice five different types of "blanks" (the rough piece that is produced after gluing and bending the wood before finishing), the Multi-Scalar Model integrates this particular knowledge in order to optimize fabrication strategies at early design stage. The classified blank typologies are ordered from the simplest and cheapest to the most complex and expensive type: "straight", "single curved", "single curved arc", "double curved without torsion" and "double curved with torsion" (Scheurer *et al.* [17]).
Within a Multi-Scalar Model, the corresponding blank of a selected beam within the graph can be algorithmically identified and generated according to a given waste percentage that is calculated by the difference between the volume of the blank and the volume of the final geometry after finishing fabrication processes. The results often depends directly on the geometrical complexity of a selected beam.

5.2. From 2.5D to 3D modelling - shifting away from the master surface

The representation of glue-laminated timber elements – composing a typical free-form timber structure – often relies on a master surface, which acts as a target geometry helping the generation of precise geometrical information. Because of its inherent geometrical UV mapping properties, a master surface is typically referred by the machining and graphics industries as two-and-a-half dimensional – a particular dimension type that helps to simplify the representation of more complex models (MacEachren [9]). The Centre Pompidou-Metz, the Haesley Nine Bridges Country Club and the French Pavilion exhibited at the EXPO 2015 all rely on master surfaces or reference geometries (Scheurer *et al.* [16]) that facilitates the generation of the fabrication data of each timber element. However, this particular landscape model limits the design exploration of more complex and spatial typologies: *"Planes, mountains and valleys are all possible features of the landscape, but caves, bridges and overhanging cliffs are not."* (Rutten [14]).
Alternative modelling strategies have been explored at CITA, which enable the generation of more intricate design features within structural frameworks. The research project *The Rise* has shown the architectural potential of a fully three-dimensional branching strategy that allows *"an aggregation of variably sized bundles of rattan core to multiply, bend, branch and recombine into a distributed assembly that manifests an alternative to traditional structural systems."* (Tamke *et al.* [20]).
For the present research, we explore how to integrate the experimental and computational approach developed for *The Rise* with advanced wood processing using CNC technologies in order to produce an

aggregation of glue-laminated wooden elements through branching strategies. Interpreted as a graph, the abstract network composed of glue-laminated timber beams can start to grow iteratively in multiple directions: a custom algorithm has been written in order to generate the full geometry that takes into account the specific splitting condition at each node (Figure 6).

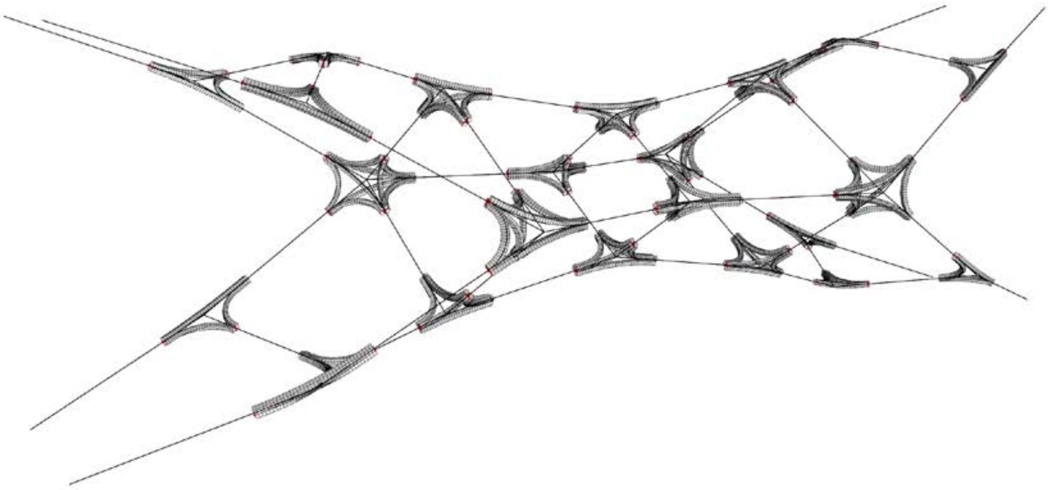

Figure 6: Specific branching joint conditions are generated from a three-dimensional abstract network

5.3. Coupling the resolution frameworks through Multi-Scalar Simulations

After having defined and mapped the dependencies between objects through different scales and resolutions within specific design frameworks, simulation algorithms are implemented in order to bridge information across the different scales. This strategy enables the optimization and negotiation of geometrical and structural properties of the overall spatial structure:

5.3.1. Geometrical Optimizations

Dynamic relaxation methods can optimize the global network so it can adapt to specific constraints that relate to the material behavior or design intentions and contextualization. When applying branching or bifurcation at the nodes, a minimum angle between two neighboring edges can be set in order to take into account a specified minimum bending radius across all the timber elements.
Once relaxed, the graph is able to negotiate all angles so the bending radius of all members is maximized through the overall network.

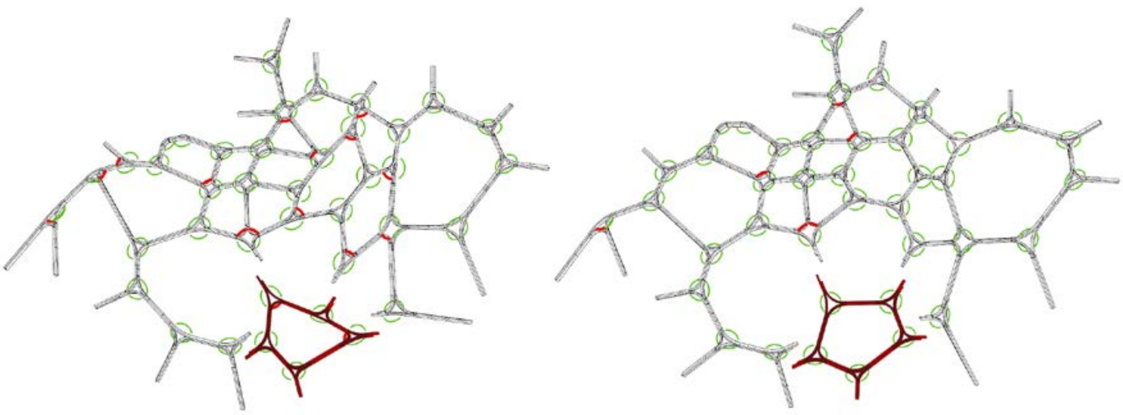

Figure 7: Geometrical optimization of the overall network through the maximization of the radius of each glue-laminated timber element (left: original network, right: optimized network)

5.3.2. Structural Optimizations

If the abstract network relies on a master surface, it is possible to perform multi-objective optimization algorithms allowing the alignment of structural lattices along the principal stress lines generated from the same surface that is considered as a continuous shell (Winslow [24]). Buro Happold has been applying such method by integrating Multi-Scalar strategies and other specific design constraints during the structural optimization in the Design of the Louvre (Shrubshall and Fisher [18]).
Another structural optimization strategy – that does not depend on a master surface – can be applied and propagated across scales. At the finest resolution, single elements can be extracted and analyzed through FE methods. The forces resulted from the global structural optimization can be mapped locally at each connection within a parallel environment. This particular method has been used in order to simulate the local behavior of 2500 complex steelwork connections for the exoskeleton of the City of Dreams hotel designed by Zaha Hadid Architects (Piermarini *et al.* [13]).

6. Outlook: Multi-Objective Optimizations

Ultimately, it would be possible to combine the different optimization methods described above in order to negotiate the user design intents with multiple constraints related to structural and material behavior, fabrication and logistics (e.g. segmentation and assembly).
Different concepts and algorithms can be used to link and transfer information from each simulation frameworks in order to find an equilibrium state that satisfies all conditions.

- Broadly used in computer science, belief propagation (also known as sum-product message passing) allows the communication or interference between multiple nodes within a graph.
- Discreet Event-Based Simulation frameworks borrow mathematical concepts from Discreet Event System Specification (DEVS) and present novel design approach allowing the integration of multiple and autonomous sub-models that inform each other without passing through a centralized model. The overall simulation is split into discrete events that continuously exchange with each other (Tamke *et al.* [21]).

Discreet Event-Based Simulation could be combined with Belief Propagation methods in order to exchange information between nodes and subgraphs for optimizing the overall design framework and its intrinsic constraints.

7. Conclusion and future work

This paper discussed the basis of Multi-Scalar Modelling methods and simulations, taking large-scale free-form timber structures as a particular design probe and using graph theory as the main modelling strategy. We also described the main dependencies that exist between the different objects within this particular Multi-Scalar Model as well as the structural and geometrical optimizations that can be operated across the different levels of resolution (or frameworks). Future research will investigate the implementation of a global design environment (or pipeline) enabling the linkage between the different mentioned design frameworks. This would allow the employment of Multi-Objective Optimizations that could negotiate the setting and calibration of all the parameters required across scales by the different trades involved within the design process.

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