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Production Phases and Market for Timber Gridshell Structures

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Abstract. Purpose – The aim of this research is to investigate the gridshell structure and its samples to identify its global production process as well as the stakeholders involved in the samples studied. Gridshell is not widely acknowledged as a timber solution and there is a lack of academic research focusing on the potential markets and the production stages behind it. This research attempts to develop these points of view.

Design/ methodology/ approach – A literature review based on both academic papers and grey literature was conducted to gather information about timber gridshells. The samples found were categorized as small, medium, and large gridshells. The categorization is based on size and level of complexity of samples. Production phases and players involved in the design and the construction of these structures were identified.

Findings – The result showed that the gridshell is used in the non-construction industry as twenty samples were identified. The gridshell samples were classified based on their levels of complexity. The global production process and the role of stakeholders were identified for each category. Furthermore, motivations and barriers to using gridshells in construction were determined.

Originality/value – Innovative structures that encourage the use of wood in construction are important in the development of sustainable solutions. This paper provides an overview that covers existing samples of gridshell and their production phases. It leads to making gridshells increasingly recognized for both the clients and those who are interested in exploiting this structure.

Keywords. Gridshell, timber construction, production phases, process, sustainability and green buildings, market, innovation.

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Introduction

Wood has been used extensively as a key construction material because of its availability in nature. Moreover, growing environmental awareness increases the motivation to use wood as a renewable material that reduces CO_2 emissions (Kuzman and Sandberg, 2016). Wood construction systems typically encompass light frames, post and beams, cross-laminated timber or massive wood structures, mixed and hybrid systems, and space frames . A space-frame is a three-dimensional structure and refers to a family of systems that includes grids, barrel vaults, domes, towers, cable nets, membrane systems, and foldable assemblies forms (Tobergte and Curtis, 2013). Space frames provide free-formed structures which are promising solutions for contemporary and innovative needs in construction.

An example of a space frame structure is Gridshell, which was developed by Professor Frei Otto in 1962. Gridshell is a structure with a doubly curved shape made of grid timber laths. The first large gridshell was built in 1975, in Mannheim, Germany (Naicu et al., 2014). Although timber gridshell has the characteristics of an innovative and sustainable structure, it is not yet recognized worldwide as a timber solution. The gridshell structure is typically associated with one single project and there are limited numbers of samples around the world. When looking at current academic literature, there are examples concerning gridshell's definition as well as its architectural and structural issues. Nevertheless, there is a lack of information available concerning the market, the production phases, and the standardization of this type of structure. For a company that is interested in exploiting timber gridshells, there is a need to get a holistic point of view along with the technical research.

This paper analyses the use of timber gridshells in the construction industry and the motivations for choosing this specific system. It also investigates construction methods to build current gridshell samples and the potential markets for this innovative structure. In this way, it becomes possible to describe the timber gridshell structure from a global production process point of view, while highlighting opportunities to increase the use of wood in non-residential constructions.

In order to achieve those goals, a literature review was conducted and a list of twenty contemporary samples of gridshell was extracted. Grey literature was also investigated, including the websites of stakeholders involved in gridshell construction projects. The analysis showed that the main players for medium-sized gridshells are architects, engineers, carpenters, and contractors side-by-side with academic partners and the client. For small gridshells, some roles may be omitted while for complicated ones, many roles and stakeholders seem to be added. The research also provides production phases for these categories.

The results could guide companies interested in developing gridshells to make decisions in terms of their resources and facilities. Moreover, the research can be viewed as a first step towards standardizing the construction of timber gridshells.

In the following pages, a definition of gridshell and its production are provided. Then the methodology of the research is described. The next parts present the results, a discussion, and the conclusion of the paper.

Preliminary concepts definition

According to (Dickson and Harris, 2008), “a shell is a three-dimensional structure that resists applied loads through its inherent shape. If regular holes are made in the shell, with the removed material concentrated into the remaining strips, the resulting structure is a gridshell”. Another definition defines gridshells as structures “with the shape and strength of a double curvature shell, but made of a grid instead of a solid surface” (Douthe et al., 2006).

The two main phases for constructing a gridshell include form-finding and erection. Form-finding refers to the process of determining the shape of the structure. It is important for the structures that feature a complex geometry (Naicu et al., 2014). In other words, this step consists of “finding the most efficient geometry that can both resist the external load and meet the architects’ requirements” (Paoli, 2007). There are two main methods which have been used for gridshell and other related structures. These methods are physical modeling and computational form-finding.

Physical modeling uses principals of nature to model the physical behavior of the structure (Toussaint, 2007). One of the most used methods of physical modeling is funicular approach or inversion method. (Paoli, 2007) defines this method as the use of chain models to describe structures and surfaces. “In order to determine the most effective shape for an arch, the load which the arch will have to resist should be known. It becomes possible to achieve it by applying a scale version of this load to a chain and flip the chain upside down. By adopting this shape, the arch will resist loads only through geometric stiffness.” Computational form-finding is a numerical optimization process. Numerical optimization uses an iterative calculation sequence and solves nonlinear problems to define the optimum shape (Toussaint, 2007). One of the techniques of computational form-finding, mainly used for gridshell structures, is Dynamic Relaxation. This method is based on "an interactive process of computer analysis that solves a set of non-linear equations. The technique modifies an initial approximation to the desired shape by minimizing the kinetic energy of the lattice as it is made to oscillate" (Harris et al., 2003).

The main techniques for the erection of gridshell are pull-up (crane and cables), push up, and ease down. The pull-up or crane and cables method uses cranes to pull the lattice from above. The push-up method uses jacks and scaffolding to push the lattice from underneath. The ease down method is based on using scaffolding and assembling from the top (Paoli, 2007). Figure 1 shows three samples of gridshell.

Figure 1 : Left : Toledo gridshell [I], Middle: Helsinki zoo, observatory tower (Paoli, 2007), Right: Centre Pompidou Metz (Lewis, 2011)

Methodology

In order to capture the interest of using timber gridshells in construction while better highlighting their global production process and market opportunities, both scientific and grey literature were used to gather all the necessary information. In particular, the research questions that had to be addressed encompassed:

1. Are timber gridshell structures used in construction industry?
    a. What were the motivations for their construction?
    b. How were the samples built?
2. What would the potential market for this structure be?

Three databases were retained for the research, namely science direct, emerald, and Google Scholar. Approximately thirty relevant articles were selected and analyzed and some other articles were extracted from the references of articles read. A certain number of Master's and PhD theses about the gridshell structure were also studied. The year of publication of the majority of the papers was after 2000, which shows the increasing inclination to this structure in the twenty-first century. Definitions of the gridshell and free-formed structures and the basic elements for construction like form-finding and erection were extracted from these papers. Moreover, some samples of gridshell structure were introduced in the academic papers.

Completion of an academic literature review makes it clear that timber gridshells are used in the construction industry. However, it revealed that there is a lack of research about production phases, stakeholders involved in the construction projects, and market opportunities. Therefore, to gain an understanding of trends in the production, as well as knowledge of the players who are typically involved in the construction of this type of structure, grey literature like magazines and websites were used. In this step, twenty important timber gridshells were investigated which can be close to all the existing samples. Studying most of the gridshell samples with the purpose of understanding the production phases led to categorizing the samples as small, medium, and large-sized gridshells. This categorization is based on both the size of the structure and the level of complexity of the project. By combining the analysis of academic and grey literature, it became possible to define players and production phases for the different categories of gridshell. The next step was to investigate the motivations of timber construction and combining it with the characteristics of gridshells, which then led to analysis of the strengths and weaknesses of the product besides the opportunities and threats in the market. This analysis was also an opportunity to better link the gridshell solution to market opportunities. Figure 2 summarizes the steps of the research methodology.

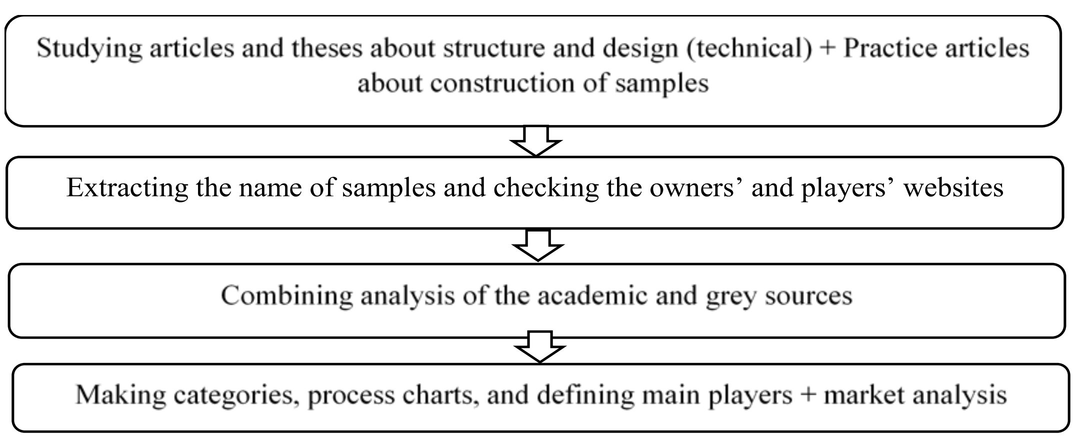

Figure 2: Steps of Research Methodology

The results

According to (Cooke, 2013), it is important to understand the complexity of any construction project because of the nature of this industry which is transient both in terms of location and people involved. The complexity of a gridshell structure is not just caused by the size. There are different elements which make the structure more complicated to build. According to our research, the items affecting the complexity of gridshells include the size, shape, design, material, technology, number of involved players, skills expected, and experiences. In particular, larger-sized gridshells are usually more difficult to build, while some smaller gridshells are complicated because of their special shape and design. An emphasis on the use of special type of timber may increase the complexity of the global production process since the characteristics of the wood species affect the form-finding, the carpentry, and the construction erection as well as the price and budget. The aid of advanced computer techniques seems to have made the architectural and structural design of recent projects a lot different. Furthermore, when analyzing the players involved in each sample, it was observed that most complex gridshells involved many players having experience with complex structures. Figure 3 illustrates the sources of complexity in a timber gridshell structure.

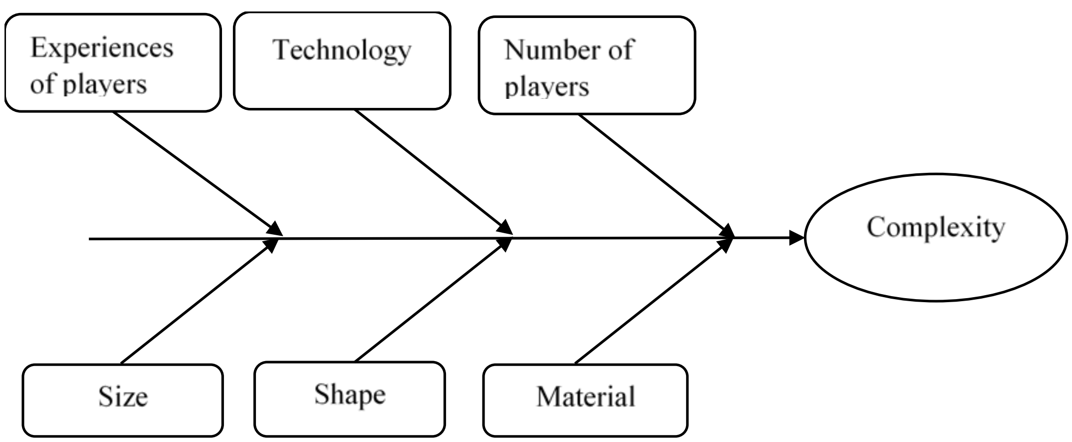

Figure 3: Cause and effect diagram for level of complexity in production of gridshell structure

Based on the size and complexity of the gridshell samples analyzed, the twenty samples found from the literature are divided into three groups and checked the players and production phases according to these three categories: small gridshells, medium gridshells, and large gridshells. A brief introduction of these samples is provided here followed by players and production phases.

Small and students' work gridshells

This category includes gridshells that are mostly smaller and less complicated in shape and design in comparison to medium and large ones. Aim of building these gridshells was not to gain financial benefits and there were not many players involved in building them. The motivations for building them were to practice and improve the abilities to work on gridshell as a new structure. Gridshells in this category include German building exhibition at Essen, which was the first gridshell built by professor Otto, and one experiment of a personal home in Pishwanton, England, using gridshell for the roof. It also includes four gridshells made from 2007 to 2012 by researchers and students in the architectural faculty of University of Naples. Another research project on this structure was conducted in Coastal Studio. Coastal Studio is an architectural research unit in the Faculty of Architecture and Planning at Dalhousie University, Nova Scotia, Canada [II]. They made three gridshells and there are three other ongoing projects in their program.

Essen gridshell was the first timber gridshell erected in 1962 at Essen, Germany. According to (Happold and Liddell, 1975) the dome had a super-elliptical base, 15 m by 15 m in size, with a central height of 5 m. The timber selected was pine and in order to achieve lengths of up to 19 m, several smaller members were finger jointed together. The second sample, Pishwanton gridshell, is a handmade gridshell that was built as the roof of a house. An architect designed it in collaboration with a structural engineer. They provided the wood, carpentry work and joints, and finally assembled it with the help of a group of people (Bouhaya, 2010). Four gridshells in Italy were built under the supervision of the architectural faculty of University of Naples. All of these gridshells were built in collaboration with architects, engineers, and a group of students. The phases followed were: design, test of structure, providing material, carpentry work, and erection. The group worked together in all of the project phases. Erection of these gridshells was done manually. After finishing carpentry work, the two-dimensional gridshell was assembled on the site, and went up using some timber laths to create distance from the ground [I]. The other research department, Coastal Studio, focuses on the development of innovative design and construction techniques that link new technologies with traditional methods and materials. Their research emphasizes lightweight, complex structures that have minimal environmental impact, and construction strategies that can be simply communicated to local craftspeople. A dining pavilion was their first project built in 2010 in Ross Creek, Nova Scotia, Canada. This gridshell is made from 900 short pieces of thin boards, less than a meter in length. Another gridshell was built in

2015 in collaboration with University of Louisiana in Lafayette, USA. The pavilion is made by oak-wood planks and aluminum panels that provide shade and a central meeting place for people. The last sample is a farmers' market in Cheticamp, Canada. This project was donated to Cheticamp to provide a permanent home for their weekly farmers' market. The completed pavilion consists of two concrete walls with a gridshell spanning between them [II]. Table 1 lists the samples considered as small gridshells.

Table 1 : Small and students' work gridshells

Building name	Year	Size	Wood	Country
German Building Exhibition at Essen	1962	198 m^2	Pine	Germany
Pishwanton gridshell	2002	80 m^2	Larch	England
Courtyard roofing of rural villa, Ostuni	2007	*	*	Italy
Masseria Ospitale's terrace, Lecce	2010	*	*	Italy
Dinning pavilion, Ross creek Centre	2010	*	*	Canada
Toledo gridshell	2012	70 m^2	Spruce	Italy
Pavilion in Selinunte's archeological	2012	80 m^2	*	Italy
Lafayette strong pavilion	2015	*	White Oak	USA
Farmers' market gridshell, Cheticamp	2015	300 m^2	Red Oak	Canada

* Information not available in both the academic literature and the grey literature

Medium gridshells

Medium gridshells seem to be somewhat complex but more commercialized than small samples. While the purpose of students' work was mostly to develop the research in the category of medium gridshells, there is a client who invests in the structure. The first sample is the Flimwell Woodland Enterprise Centre which is located in East Sussex, England. The principal philosophy behind the client's decision to build this structure was to motivate the use of local chestnut wood in an aesthetic designed building [III]. The second sample is the Orangery gridshell, located in the village of Chiddingstone in England. This gridshell is small according to the size but categorized as a medium one because of the complexity of the structure as well as the close relationships between players involved in the project. Chiddingstone Orangery gridshell is the world's first gridshell to support a frameless glass roof and is designed as a double-layered timber gridshell

(Naicu et al., 2014). The next sample is an observatory tower in Helsinki Zoo, Finland. It is a monument in the shape of a timber tower with a height of 10 m. The load-bearing structure consists of 72 long battens, with a section of 60 mm x 60 mm that are bent and twisted on the site from seven pre-bent types. Over 600 bolted joints hold the shell structure together (Bouhaya, 2010). The last sample in this category is located in Singapore University of Technology and Design. The structure comprised an orderly assembly of 3,000 unique plywood and 600 unique sheet-metal tiles. For construction, pre-fabricated parts were used and assembled together at on-site position [IV]. These samples (listed in table 2) indicate some functionalities for timber gridshell as exhibition hall, visitor center, museum, and monument.

Table 2 : Medium-sized gridshells

Building name	**Year**	**Size**	**Wood**	**Country**
Flimwell Woodland Enterprise Centre	2003	*	Chestnut	England
Chiddingstone Orangery gridshell	2003	60 m^2	Chestnut	England
Helsinki Zoo, observatory tower	2009	82 m^2	Pine	Finland
SUTD gridshell Singapore	2013	200 m^2	Plywood	Singapore

* Information not available in both the academic literature and the grey literature

Large and complex gridshells

The third category consists of seven large and complex gridshells that are mostly assumed as unique and special landmarks. The first sample is the Mannheim Multihalle in Germany. It is the first large gridshell that was designed by Frei Otto in 1975. The final pavilion design required a free-form roof covering three separate spaces, with the main hall (called the Multihalle) spanning 60 m by 60 m (Happold and Liddell, 1975). The second large gridshell was built about 22 years later by another architect named Shigeru Ban, in collaboration with Frei Otto. Shigeru Ban is well known for his innovative works on lightweight and sustainable structures. This gridshell was built as the Japan Pavilion for the "Exposition 2000 Trade Fair" in Hanover, Germany. The principle structure of the gridshell was made of paper-covered cardboard tubes. To abide by the German laws that forbade the use of paper only for the structure of a building, a secondary wooden structure had to be added. The gridshell was assembled flat and the erection process, taking great advantage of the bending properties of cardboard tubes, took only three weeks. Once the structure was in place, it was covered with a membrane fabricated from glass and fiber-reinforced fire-proof paper (Paoli, 2007). Another structure that has marked the history of gridshells is Downland Museum in Sussex, United Kingdom. The triple-bulb hourglass roof is 48 m long and between 11-16 m wide. It has an internal height of 7-10 m. The roof is clad with red cedar boards and polycarbonate glazing (Toussaint, 2007). Another large gridshell was built for the visitor center in Savill Garden in Windsor Great Park, United Kingdom, in 2006. It is 90 by 25 m, also a three-humped form, but with a lower profile, supported by tubular steel edge members braced to take the thrust loads from the shell (Liddell, 2015).

Another complex gridshell is the Nine Bridges golf clubhouse designed by Shigeru Ban in South Korea. Twenty-one slender columns support 32 roof elements, assembled from more than 4500 detailed prefabricated timber segments [V]. Another gridshell designed by Shigeru Ban is the Centre Pompidou Metz in France. The roof, inspired by a woven Chinese hat, is an astounding structural achievement: a hexagon echoing the shape of the floor map, made up of a series of modular elements, also hexagons measuring 2.9 m on each side. The structure is made from highly resistant glue-laminated wood (glulam), providing a mesh that can span lengths of about 40 m. A transparent membrane is applied to protect the wood in all weather conditions (Lewis, 2011). POD Sports Academy is another gridshell structure with the functionality of a sports center. The building consists of five linked shells. The main structural components are glued-laminated timber. Jointing at the steel nodes uses bonded rods with sockets and bolts. This building is an example of gridshell designed for functional use as a sports center. It encompasses:

- Six badminton court dry sports halls - approx. 65 m span
- Swimming pools with approx. 35 m span
- Training pool - approx. 20 m span
- Gym and dance studio - approx. 25 m span
- Cafe and kindergarten - approx. 15 m span (Harris et al., 2012).

These gridshells are listed in table 3.

Table 3: Large and complex gridshells

Building name	Year	Size	Wood	Country
Mannheim Multihalle	1975	3600 m^2	Hemlock	Germany
Japan Pavilion, Expo 2000	2000	1850 m^2	Cardboard	Germany
Weald and Downland Gridshell	2002	720 m^2	Oak	England
Savill Garden gridshell	2006	2250 m^2	Larch	England
Haesley Nine Bridges golf clubhouse	2009	2592 m^2	Spruce (Glulam)	South Korea
Centre Pompidou Metz	2010	8500 m^2	Spruce (Glulam)	Franc
Pods sport academy	2011	5000 m^2	Spruce (Glulam)	England

Main players and production phases

When looking at all the different gridshell projects, it was observed that the main tasks and people involved in constructing the structure seemed to depend on the characteristics of the structure such as the size, the level of complexity, and the cost. For example, student project gridshells were built by a small group of students and professors with the help of a few companies. However, complicated landmarks like Centre Pompidou Metz had several production stages conducted by different parties to complete the building. In this section, we therefore highlight the different players involved in each category of gridshells found from the literature review as well as the production process.

For small and medium gridshells, the client always seemed to be the one defining the project, choosing the proposal, and providing the budget and requirements. Architects were the providers of the initial design while developing the detailed design in collaboration with structural engineers. Engineers were responsible for the loads and performance of the structure. They usually stayed in the project until the end and a part of their work was to observe and monitor the construction part in order to avoid problems. Engineers also seemed to collaborate closely with architects in the phase of form-finding and material selection. Wood provider and carpenter were involved in the decision-making phase and the design part to provide consultation about choosing wood. They also provided the wood on-site and worked on joints and carpentry jobs off-site and on-site. The contractor was the entity responsible for the construction of the gridshell. Their work consisted of preparing the site, foundation, scaffolding, and finally assembling and erecting the gridshell. In small gridshells, the other parties or a group of students performed the role of contractor.

As illustrated in Figure 4, the global production process for small and medium gridshells starts with the primary design conducted by the architect. The next production phase is the form-finding where an engineer must be involved and has to provide the structural analysis. Presence of contractor in this phase would be helpful in order to avoid problems in the construction phase. Material and joints are then prepared by the carpenter while the contractor prepares site for construction. Part of the carpentry work can be done off-site such as finger joints. Even part of assembly can be finished off-site. Scarf joints for providing larger laths are typically conducted on-site. Finally, the assembly and erection are done, supervised by engineers and architects.

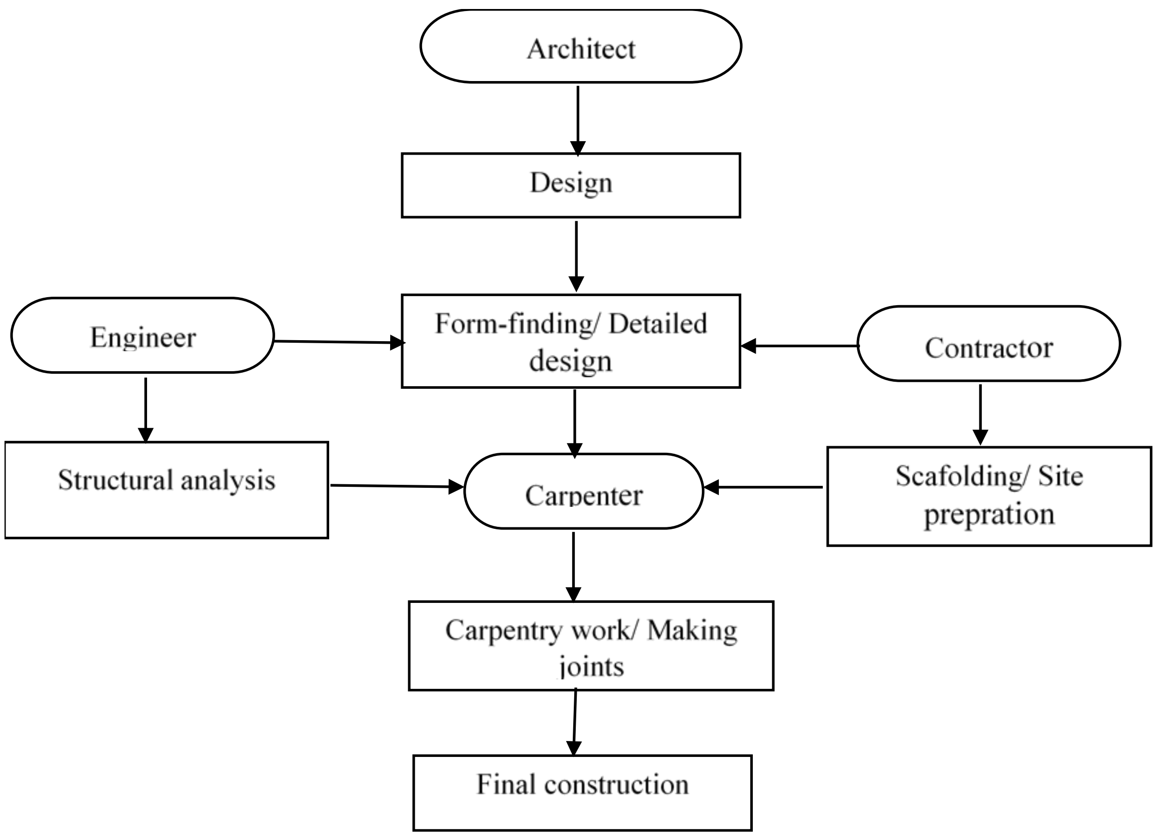

Figure 4: Diagram of phases and players for building a Medium-sized gridshell

Rutten et al. (2009) emphasized that close and stable relation between the different parties involved in a construction contribute to the development of innovation. In particular, an exchange of ideas and expertise early in the process helps to provide clarity of vision, develop the design, and devise ways in which a unique structure could be created. As shown in the global production process description, one of the essential and early stages of collaboration is between the architect and the structural engineer, especially in the form-finding process. Architects and structural engineers have to work closely together to make the shape of the building evolve in the two directions at the same time. In some of the gridshell projects, the carpenters also sat around the table with the architects and engineers to design the details of the building.

For complicated and large size gridshells, there seem to be more sub-contractors involved such as acoustic specialists and roof engineers. Richard Harris, a structure engineer who was involved in the construction of numbers of gridshells, mentioned that the process of creating the Downland gridshell was a case study of successful collaboration and innovation in architecture, engineering, and construction, led by a multidisciplinary team of practitioners (Harris et al., 2003). He described the first phase of the project as understanding the client's requirements to provide the right conceptual solution. He then mentioned modeling, prototype development, tests, selection of timber, carpentry, development of the long laths with finger joints, and the scarf joint on-site as the subsequent production phases. The final part was to provide the nodes and connections necessary for the construction. Another example is for Pods Sport Academy. For this project, Harris et al. (2012), described the production phases as the design concept which includes architectural and structural design, the form-finding and the detailed design, the contractor selection, the construction of the waterproof membrane procurement for the roof.

By combining this information with that concerning the Mannheim Multihalle project (Happold and Liddell, 1975), the Savill Garden gridshell (Harris et al., 2008), the Centre Pompidou Metz (Lewis, 2011), and brochure and nonacademic reports for the other gridshells highlighted in the previous section, we can summarize the production phases as follows. After client's request for proposal and accepting an architect's design, there will be a meeting with the architect and the client to define the requirements. Initial plan and feasibility analysis will then be conducted by the architect. Involving engineers, wood suppliers, and the contractor in the meeting and in the decision-making process appeared to be essential in past projects to avoid inconsistency in the following steps. The concept design will be provided in the next step. It covers the outline specifications, the planning strategy, cost plans, and procurement options. In most of the projects, there is an academic partner involved to provide research and tests. For example, University of Bath was the academic partner involved in some of the largest gridshells built in United Kingdom.

The next steps will be the form-finding which is performed in collaboration with the architects and the engineers. Different types of test needed to be conducted to make sure that the structure would work properly. These tests may include checking the resistance for loads, wind, snow, etc. If the results are acceptable, the detailed design can be finished. Then the proposal (tender) will be announced to find and choose the contractor. Preparation off-site can be started simultaneously with carpentry work. Part of carpentry work can be done off-site, such as preparing the wood and finger joints. Scarf joints are usually done in the workshop on-site. The connections should also be provided for connecting the wood laths during assembly. When site is ready and foundations and scaffolding are provided, the assembly and erection will be performed. The erection method for large gridshells is usually ease down with the use of scaffoldings. Figure 5 illustrates phases and players for building a large and complex gridshell.

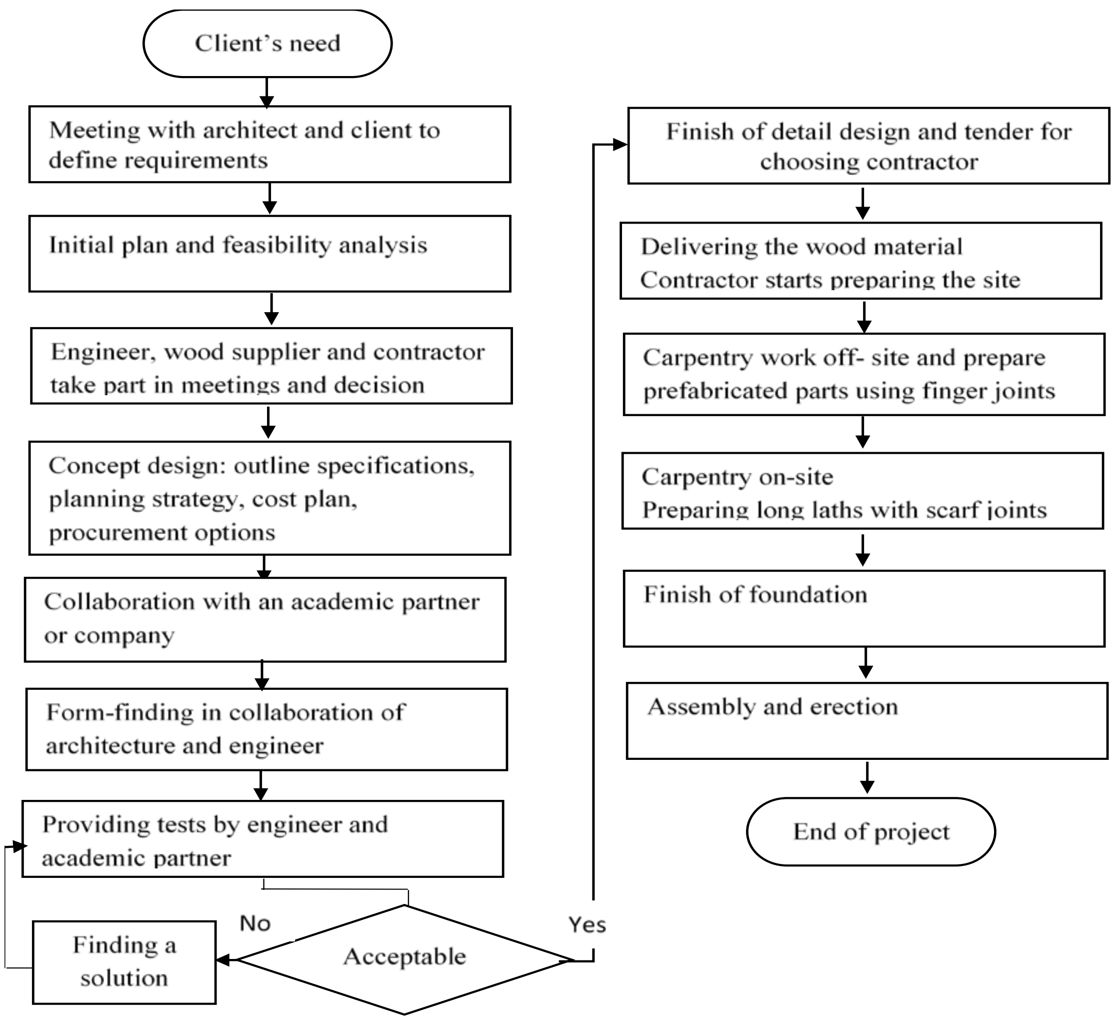

Figure 5: Production phases and players for building a large and complex gridshell

Current and future markets

Gosselin et al. (2015) introduced sustainability, speed of erection, cost reductions, visibility, and lightness as motivations for using wood in non-residential building. Characteristics of gridshell structures are aligned with these factors that motivate construction stakeholders for using wood. In particular, a gridshell is a sustainable and light structure, the ability of on-site assembly and quick construction make it easy to build, and the elegant and unique shape provides the visibility. Non-residential buildings include three main categories: industrial buildings (plants, garages, workshops, and equipment warehouses), commercial buildings (principally, shopping centers, office buildings, and service firms), and institutional buildings (schools, hospitals, homes for the elderly, etc.). Looking at the gridshell samples found in the literature, most of them were in the segment of commercial buildings (i.e., Mannheim Multihalle, Japan Pavilion, Weald and Downland, Savill Garden gridshell and Centre Pompidou Metz). The elegant shape of the gridshell and the large span it covers makes it an appropriate alternative for commercial buildings. Moreover, sustainability and using wood as a renewable material is an advantage for timber gridshell. As a result, all these advantages can motivate some companies to invest and use this structure in different segments of market; however, some barriers may limit the construction of gridshell.

When considering a new product or a new market, a basic step is to analyze the motivations and barriers associated with it. SOWT analysis is one of the several existent strategic planning tools that can be used for this purpose. The acronym SWOT refers to the strengths and weaknesses of the service and the opportunities and threats which it faces. The purpose of SWOT analysis is to gather, analyze, and evaluate information and identify strategic options facing a community, organization, or individual at a given time (Osita Ifediora, Onyebuchi R, 2015). According to the literature, the strengths of gridshell structure rely on its elegant, innovative, and fresh shape. The structure captures the attention of visitors and the players who are interested in enriching their experiences in modern architecture. Sustainability is another strong motivation for this structure. If timber is used for building in structure, flooring, cladding and other finishes, it makes a positive contribution to reducing global carbon emissions (Harris, 2005). Besides the material, the structure itself makes it possible to use natural light and ventilation. The Nine bridges golf club gridshell is a good example of using natural light and ventilation. As mentioned earlier, covering a large area without the necessity for columns is another advantage of the structure. The lightness of the structure and minimal use of material make it an appropriate alternative for increasing the lightness of the building. In terms of construction, it is possible to make prefabricated parts and to assemble them on-site after. For this reason, the construction may be not time consuming. For example, the erection of the Japan pavilion gridshell took only three weeks. The flexibility of the structure creates another strong benefit as it makes it possible to find alternative solutions in terms of using another material beside timber to get a hybrid structure.

On the other hand, there are some barriers associated with the use of this structure. The design phase is time-consuming as the design is complex and there are not many examples that can be used as benchmarks. There are plenty of stakeholders involved in large gridshell constructions and there is a need to manage the collaboration between them especially at the early phases of the project. Finally, there is a need to provide high quality materials in order to make sure that the structure will be in good condition.

In terms of market opportunities, as the number of gridshell structures are limited, there is an unfilled market for it, especially in North America. Putting this together with the tendency to increase market share of using wood in construction gives an overview of opportunities for gridshell constructions. In order to increase the use of timber in construction, the need for innovation in construction is emphasized. On the other hand, the fact that gridshell is not widely recognized makes barriers for penetrating the market. As the product is new and there are not many samples to compare, efforts should be made to convince customers and make them confident about the success of the project. Moreover, the reactions of other competitors who use wood in construction should be taken as threats as long as it is unknown and no research has been conducted about it. Figure 6 summarizes the SWOT analysis for this research.

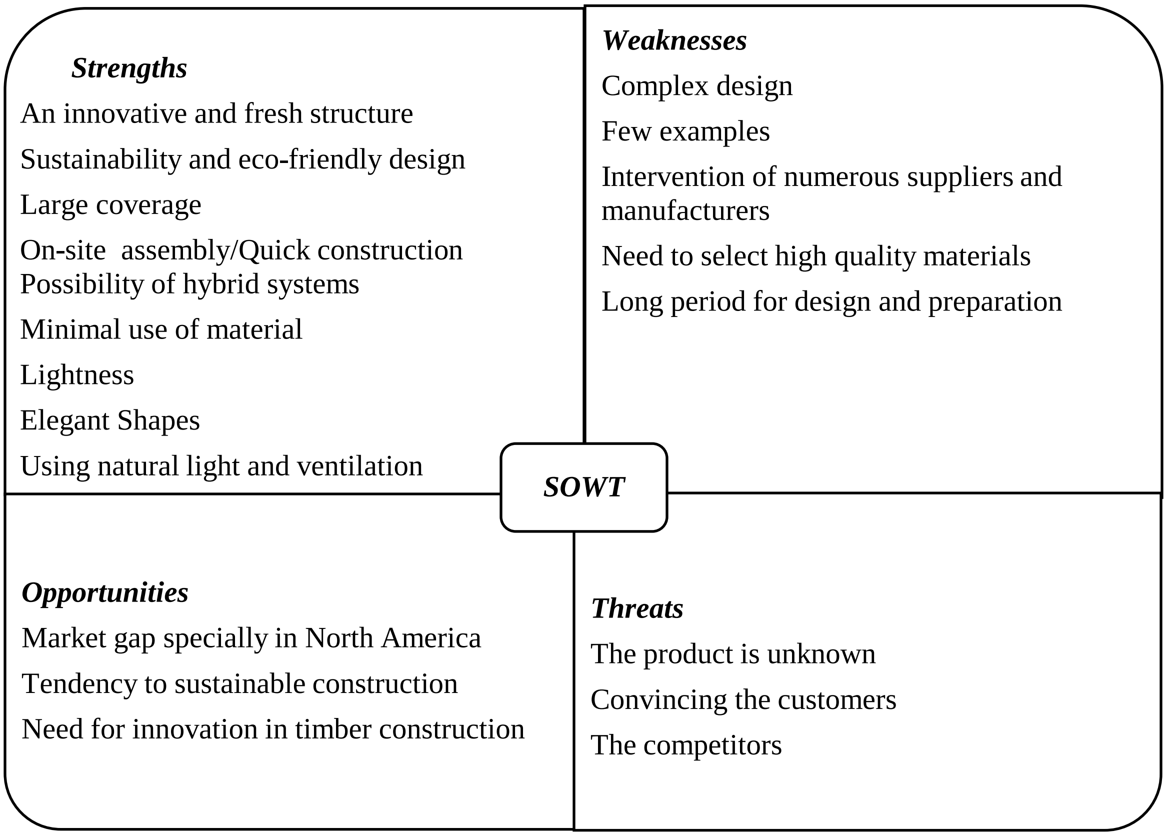

Figure 6: SOWT analysis for gridshell as an innovative structure

Market segments

After SOWT analysis and introducing motivations for building gridshell, market opportunities are discussed in this sub-section. Table 4 summarizes the market segments of existing samples found from the literature review. These segments consist of the academic student works, which are used as shelters, gathering places, and decoration. As mentioned previously, commercial and cultural places are another type of building for which gridshell was used. Furthermore, sport centers, swimming pools, and dance halls are places for which gridshell is a suitable alternative because of the ability of wood to absorb humidity and the gridshell acoustic characteristics. Additionally, table 5lists other market opportunities for gridshell structures that are currently not fully exploited. These types of buildings include public transportation stations such as train stations, industrial halls and warehouses, greenhouses, winter gardens, and some areas in zoos.

Table 4 : Market segments observed for sample gridshells

Building type	**Samples**	**Highlighted motivations**
Student works and training samples Shelters Gathering places Restaurants (decoration)	German Building Exhibition at Essen Naples School of Architecture SUTD gridshell Singapore Farmers' market gridshell, Cheticamp, Nova Scotia	An innovative and fresh structure Improving abilities in building complicated structures Sustainability and eco-friendly design
Sport and leisure Sport centers Swimming pools Dance halls	PODs sport academy Haesley Nine Bridges golf clubhouse	Covering large span Using natural light and ventilation Wood’s abilities to absorb humidity Wood’s characteristics about acoustic issues
Commercial Visiting centers Museums Landmarks Exhibitions Libraries Monuments	Savill Garden visitor center Weald and Downland museum Mannheim Multihalle Centre Pompidou Metz Orangery gridshell Flimwell Woodland Enterprise Centre Helsinki Zoo viewing platform Japan Pavilion, Expo 2000	Elegant Shapes and aesthetic Sustainability and energy saving

Table 5 : Market segments suggested for gridshells

Building type	Highlighted motivations
Public transportation stations	Large coverage / on-site assembly
Train station	Possibility of hybrid systems
Bus station	Minimal use of material/Lightness
Bicycle station	Quick construction process
	Sustainability and eco-friendly design
Industrial building	Large coverage/on-site assembly
Warehouse	Possibility of hybrid systems
Industrial halls	Minimal use of material/Lightness
	Sustainability and eco-friendly design Quick construction process
Green house and winter garden	Large coverage
Green houses	Lightness
Zoos	Elegant Shapes
Plant research institutes	Using natural light and ventilation

Conclusions

Timber gridshells seem to be a promising solution to the growing interest in free-form architecture in the context of an ever-increasing awareness of the natural limitations of our environment. The characteristics of timber gridshells such as long-span, lightweight, affordable and sustainable, argue that it should be a perfect fit in some of the architectural programs of our time (Naicu et al., 2014). In this paper, gridshell literaturewas investigated, leading to the identification of twenty samples that are categorized in small, medium, and large projects. The global production process and the main players for these categories were extracted, combining the academic and grey literature about the samples. Collaboration between the players, especially between architects and engineers from the primary steps, was pointed out as esential by some authors. Market opportunities and segments for future investment were also suggested. This paper hopefully would guide companies interested in developing timber gridshell structures. It introduces all important samples of gridshell and their characteristics together. Gathering the information about the samples was a challenging part for the research, specially for small and medium gridshells. There was not much description of them in academic papers or even grey literature. Further investigations with a holistic point of view on the gridshell structure helps to make it better known in construction industry. These researches can change the point of view of gridshell from a special and rare structure to a recognized type of structure that can be considered as a timber construction solution.

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