Production Phases and Market for Timber Gridshell Structures: A State-of-the-Art Review

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Timber gridshell is a structure with a doubly curved shape that is made of grid timber laths. Gridshell structure can be a solution of interest in modern free-form structures that are environmentally sustainable. However, there is a lack of academic research focusing on the potential markets and the production stages based on this construction technology. The aim of this literature review is to investigate the gridshell structure to identify its global production process, as well as the partners involved in the architectural examples studied. A review of both peer-reviewed scientific articles and grey literature resources (*e.g.*, magazines, web pages, *etc*.) was conducted to gather information about timber gridshells. The design examples found were categorized as small, medium, and large gridshells. The categorization is based on the size and level of complexity of the design examples. Production phases and partners involved in the design and construction of these structures were identified for each category. Furthermore, the motivations and barriers to using gridshell designs in construction, and the potential market segments were determined.

Keywords: Gridshell; Timber construction; Production phases; Process; Sustainability; 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, posts 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 assembly forms (Mupona 2004). Space frames provide free-formed structures, which are promising solutions for contemporary and innovative needs in building construction.

An example of a space frame structure is a gridshell, which was developed by Professor Frei Otto in 1962. Gridshells are 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 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 examples around the world. When looking at current academic literature, there are examples concerning gridshell definitions, 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 building structure. There is a need for a holistic point-of-view, along with technical research, for companies that are interested in exploiting timber gridshell technology.

This paper analyses the use of timber gridshells in the construction industry and the motivations for choosing this specific system. This review also investigates construction methods to build current gridshell examples 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 these goals, a literature review was conducted and a list of 20 contemporary examples of gridshell structures was extracted. Grey literature resources were also investigated, including the websites of stakeholders involved in gridshell construction projects. The analyses showed that the main stakeholders for medium-sized gridshells are architects, engineers, carpenters, and contractors, side-by-side with academic partners and clients. For small gridshells, some roles may be omitted, while for complicated ones, many roles and stakeholders are involved. The review also provides production phases for these categories.

This literature review could provide guidance to companies interested in developing gridshells to make decisions in terms of their resources and facilities. Moreover, this review can be viewed as a first step towards standardizing the construction of timber gridshells. In this paper, a definition of gridshell and its form-finding and erection phases are provided. Then, the methodology of the review is described. The next parts present the results and discussion, which is followed by a summarization.

PRELIMINARY CONCEPTS AND DEFINITIONS

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 that is given by Douthe *et al.* (2006) defines gridshells as structures "with the shape and strength of a double curvature shell, but made of a grid instead of a solid surface."

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 to 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 that have been used for designing gridshells and other related structures. These methods are physical modeling and computational form-finding (D'Amico 2015).

Physical modeling uses principals of nature to model the physical behavior of a structure (Toussaint 2007). One of the most used methods of physical modeling is the funicular approach or inversion method. Paoli (2007) defines this method as the use of chain models to describe structures and surfaces. Paoli (2007) states that "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 this by applying a scale version of this load to a chain and then flipping 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. Harris *et al.* (2003) notes that 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."

The main techniques for the erection of a gridshell structure 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 structure. The push-up method uses jacks and scaffolding to push the lattice up from underneath the structure. The ease-down method is based on using scaffolding and assembling from the top (Paoli 2007; Quinn and Gengnagel 2014). Figure 1 shows three examples of gridshell structures.

Fig. 1. Left picture is the Toledo gridshell (Gridshell.it 2012), middle picture is the Helsinki Zoo's observatory tower (Paoli 2007), and right picture is the 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 peer-reviewed scientific articles and grey literature resources (*e.g.*, magazines, world wide web pages, *etc.*), were used to gather all the necessary information. In particular, the questions that need to be addressed are the following:

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

Three databases were used for the literature searches, namely Science Direct, Emerald, and Google Scholar. Thirty relevant articles were selected and analyzed and some other articles were extracted from the references of articles read. A certain number of M.S. theses and Ph.D. dissertations about the gridshell structures were also examined. The years of publication of the majority of these articles were 2000 or later, which shows the increasing inclination to this building structure in the twenty-first century. Definitions of the gridshell and free-formed structures, and basic elements for construction for form-finding and erection were extracted from these papers. Moreover, some examples of gridshell structures were initially presented in the scientific literature.

Completion of the scientific literature review made it clear that timber gridshells are used in the construction industry. However, the review revealed that there is a lack of research about production phases, stakeholders involved in the construction projects, and market opportunities. Therefore, in order to gain an understanding of the trends in the production, as well as knowledge of the partners who are typically involved in the construction of this type of structure, other sources denoted as “grey” literature, such as magazines and websites, were consulted. In this step, 20 important timber gridshells were investigated. The investigated examples were categorized as small, medium, and large-sized gridshell. This categorization is based on both the size of the structure and the level of complexity of the project. By combining the analyses of scientific and grey literature, it became possible to define the groups involved and the production phases for the different categories of gridshell structures. The next step was to investigate the motivations of timber construction, along with the characteristics of gridshell designs, which then led to the analysis of the motivations and challenges of the structure and its potential market. This analysis was also an opportunity to better link the gridshell design solution to market opportunities. Figure 2 summarizes the steps of the research methodology.

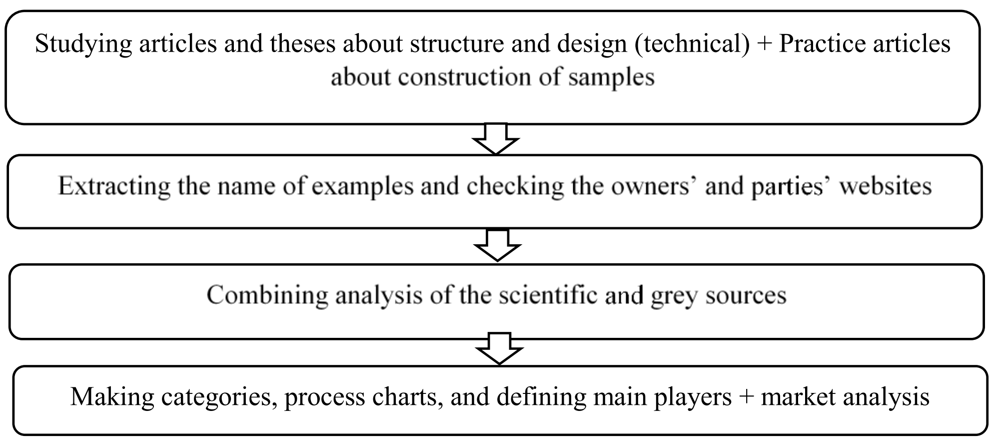

Fig. 2. Steps of literature review methodology

FINDINGS

According to Cooke (2013), it is important to understand the complexity of any construction project because of the nature of the construction industry, which is transient in terms of location and people involved. The complexity of a gridshell structure is not just a function of its size. There are different elements that make the structure more complicated to build. According to this review, the items affecting the complexity of gridshells include the size, shape, design, construction material(s), technology, number of involved parties, construction skills sets, and construction experiences. An emphasis on the use of special types 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 cost. The level of technology which is available for the design or construction, also affects the complexity of the structure. For example, using recent advanced software for form-finding makes it possible to design more complicated structures. Furthermore, when analyzing the parties involved in each example, it was observed that the more complex gridshells involved many different parties that had experience with building complex structures. Figure 3 illustrates the sources of complexity in a timber gridshell structure.

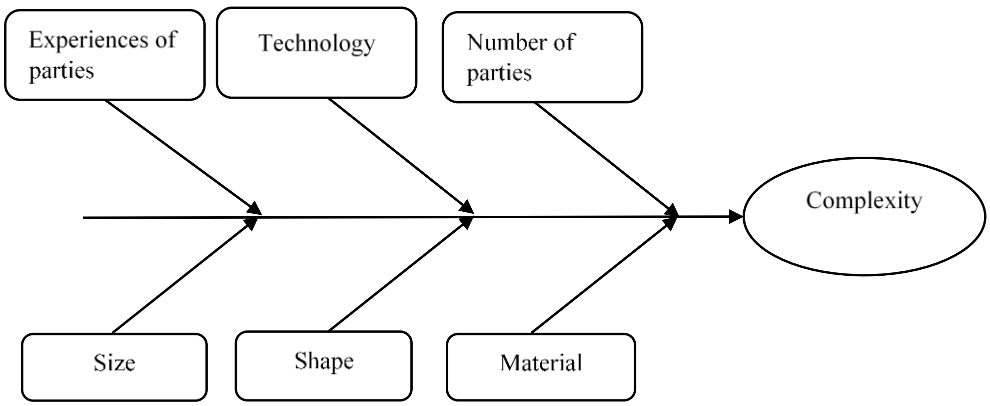

Fig. 3. Cause and effect diagram for level of complexity in production of a gridshell structure

Based on the size and complexity of the gridshell examples analyzed, the 20 examples found in the literature were divided into three groups: small gridshells, medium gridshells, and large gridshells. The aim of this categorization is to facilitate the description of gridshell examples and to consider the examples from academic projects to commercial gridshells. Based on the literature, it seems that the main purpose of building small gridshells is to investigate the structure and conduct academic research. The budget is typically provided by academic funding. These projects are not built based on a client's order, and professional companies are not hired for their construction. A group of professors, students, or people take the main roles of the architect, engineer, carpenter, and contractor. The size of these examples is between 80 to 300 m^2, and the gridshell structures built have not been used as commercial buildings. The medium-sized category includes four gridshells with the size between 60 to 550 m^2, which is close to the size of small gridshells. The reason for putting them in a different category is that the involved parties in the construction project are mostly professional companies that are hired by the client, and their functionality is more commercial. For instance, the size of the Chiddingstone gridshell in this category is smaller than the gridshells in the first category. However, this gridshell is a commercial building and was built by hired companies based on a client's order. It is furthermore the only gridshell with a frameless glazing system. In the category of large gridshells, the size is between 720 to 9,500 m^2, and it includes commercial buildings and several parties such as landscape architect, timber installation expert, and roof engineer. Table 1 lists the main characteristics of these three categories.

The parties involved and the production phases were analyzed for each category. A brief introduction of these examples is provided here followed by the parties involved and production phases.

Table 1. Characteristics of the Categories

Category	Size	Experience of parties	Functionality	Budget
Small	80 to 300 m^2	Academic professors and students	Not Commercial	Academic funding
Medium	60 to 550 m^2	Professional companies (Main parties)	Mostly Commercial	Academic funding and clients' investment
Large	720 to 9500 m^2	Professional companies (Many parties)	Commercial	Clients' investment

Small Gridshells

This category includes gridshells that are typically smaller and less complicated in shape and design in comparison to medium and large ones. The purpose of building these gridshells was not to gain financial benefits and few parties were involved in building them. The motivations for building these structures were to practice and improve the techniques to build larger gridshell structures. Gridshells in this category include the first gridshell erected by Frei Otto in 1962, at the German Building Exhibition in 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 timber members were finger jointed together to cross the span.

The second example is the roof for the "Life Science Trust" center in Pishwanton, East Lothian, UK. 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 volunteers (Bouhaya 2010).

This category also includes four gridshells made from 2007 to 2012 by researchers and students from the architectural faculty of the University of Naples. All of these gridshells were built in collaboration with architects, engineers, and students. The phases followed were: design, structure testing, obtaining building material, carpentry work, and erection. The groups worked together in all of the project phases. Erection of these gridshells was done manually. After finishing the carpentry work, the two-dimensional gridshell was assembled on site, and was erected using some timber laths to create distance from the ground (Gridshell.it 2012; Pone *et al.* 2013).

Another research project on this structure was conducted by Coastal Studio. Coastal Studio is an architectural research unit with the Faculty of Architecture and Planning at Dalhousie University (Nova Scotia, Canada). This research unit has been involved in gridshell construction projects in Canada and United States. Coastal Studio focuses on the development of innovative design and construction techniques that links 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 Coastal Studio's first project, which was built in 2010 at Ross Creek (Nova Scotia, Canada). This structure that resembles a gridshell, is a lamella which is made from 900 short pieces of thin boards that were less than a meter in length. Their first gridshell 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 (Dalcoastalstudio 2015). Another gridshell was built in 2015 in collaboration with the University of Louisiana (Lafayette, LA, USA). The pavilion is made of oak-wood planks and aluminum panels; the structure provides shade and a central meeting place for people. Table 2 lists the examples of small gridshell structures.

Table 2. Small Gridshells

Building name	Year	Size	Wood	Country
German Building Exhibition, Essen	1962	198 m^2	Pine	Germany
Pishwanton gridshell	2002	80 m^2	Larch	UK
Courtyard roofing of rural villa, Ostuni	2007	100 m^2	Larch	Italy
Masseria Ospitale’s terrace, Lecce	2010	100 m^2	Larch	Italy
Dining pavilion, Ross Creek Centre	2010	*	*	Canada
Toledo gridshell	2012	120 m^2	Spruce	Italy
Pavilion in Selinunte’s Archeological Park	2012	80 m^2	Yellow Pine	Italy
Farmers' market gridshell, Cheticamp	2015	300 m^2	Red Oak	Canada
Lafayette strong pavilion	2015	*	White Oak	USA

* Information not available in both the scientific and grey literature sources

Medium Gridshells

Medium gridshells are somewhat more complex but more commercialized than small examples. Small gridshells were built with the purpose of improving the abilities of research centers in design and construction of gridshell as a free-form structure, whereas the medium gridshells are ordered by a client and there is commercial motivation to build them. The first example 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 encourage the use of local chestnut wood in an aesthetically designed building (Woodnet 2003). The second example is the Chiddingstone Orangery gridshell, located in Kent, England. This gridshell is small according to the size but categorized in the medium category because of its structural complexity, as well as the close relationships between the groups involved in the project. The 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 example is an observatory tower at Helsinki Zoo in 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. Over 600 bolted joints hold the shell structure together (Bouhaya 2010). The last example in this category is located at Singapore University of Technology and Design (SUTD). A total of 3,012 panels were pre-fabricated and assembled together on site for its construction (Cityform 2013). These four medium gridshell examples, which are used as an exhibition hall, visitor center, museum, and monument, respectively, are summarized in Table 3.

Table 3. Medium-Sized Gridshells

Building name	Year	Size	Wood	Country
Flimwell Woodland Enterprise Centre	1999	550 m^2	Chestnut	England
Chiddingstone Orangery gridshell	2007	60 m^2	Chestnut	England
Helsinki Zoo, observatory tower	2002	82 m^2	Pine	Finland
SUTD gridshell Singapore	2013	200 m^2	Plywood	Singapore

Large and Complex Gridshells

The third category consists of seven large and complex gridshells that are unique and special landmarks. The first example is the Mannheim Multihalle in Germany. It is the first large gridshell that was designed by Frei Otto in 1975. The final design of the pavilion required a free-form roof covering three separate spaces with a main hall (called the Multihalle), which spanned 60 m by 60 m (Happold and Liddell 1975; Addis 2014). 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 from paper-covered cardboard tubes. A secondary wooden structure had to be added to this gridshell to abide by the German laws that forbade the use of paper only for the structure of a building. 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 the Downland Museum in Sussex, UK. The triple-bulb hourglass roof is 48 m long and between 11 m and 16 m wide. It has an internal height of 7 m to 10 m. The roof is cladded with red cedar boards and polycarbonate glazing (Toussaint 2007). Another large gridshell was built in 2006 for the visitor center in Savill Garden in Windsor Great Park, UK. The roof has 90 m in length and a width of 25 m. It is formed in three sinusoidal curves which resemble the leaf of a tree. The shell is supported by steel beams (Liddell 2015; Harris *et al.* 2004).

Another complex gridshell is the Nine Bridges Golf Clubhouse designed by Shigeru Ban in South Korea. Twenty-one slender columns support 32 roof elements, which are assembled from more than 4500 detailed prefabricated timber segments (Worldarchitecture 2010). The building consists of a natural lighting and fresh-air system (Kuzman and Sandberg 2016). 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 with a hexagon shape of the floor map, made up of a series of modular elements, which are also hexagons measuring 2.9 m on each side. The structure is made from 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). Pods Sports Academy is another gridshell structure, which is used as a sports center. The building consists of five linked shells. The main structural components are glued-laminated timber, jointed by steel nodes. The structure encompasses (Harris *et al*. 2012):

- Six badminton-courts with an approximate 65 m span;
- Swimming pools with an approximate 35 m span;
- Training pool with an approximate 20 m span;
- Gym and dance studio with an approximate 25 m span; and
- Cafe and kindergarten with an approximate 15 m span.

These gridshell examples are listed in Table 4.

Table 4. Large and Complex Gridshells

Building name	Year	Size	Wood	Country
Mannheim Multihalle	1975	9500 m^2	Hemlock	Germany
Japan Pavilion, Expo 2000	2000	2500 m^2	Cardboard	Germany
Weald and Downland Gridshell	2002	720 m^2	Oak	England
Savill Garden gridshell	2005	2250 m^2	Larch	England
Haesley Nine Bridges Golf Clubhouse	2010	2592 m^2	Spruce (Glulam)	South Korea
Centre Pompidou Metz	2010	8500 m^2	Spruce (Glulam)	France
Pods Sports Academy	2011	5000 m^2	Spruce (Glulam)	England

DISCUSSION

Main Partners Involved and Production Phases

When looking at all the different gridshell projects, it was observed that the main tasks and number of parties involved in constructing these structures are related to the size and complexity of the structure. For example, small 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 partners to complete the structure. In this section, the different groups involved in each category of gridshells found in this review are highlighted, 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 building requirements. Architects were the providers of the initial design, in addition to developing the detailed design in collaboration with structural engineers. Engineers were responsible for the loads and performance of the structure. They also had the role of monitoring the construction in order to avoid problems. Engineers also collaborate closely with architects in the form-finding and material selection phases. Lumber providers and carpenters were involved in the decision-making and the design phases to provide consultation about wood selection. These groups also supplied the wood on-site and worked on joints and carpentry needs. The construction contractor was the entity responsible for the building of the gridshell. The contractor prepared the site, set the foundations and scaffolding, and assembled and erected the gridshell. In small gridshell projects, the other parties or a group of students performed the role of construction contractor.

As illustrated in Fig. 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 the 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 building contractor prepares the site for construction. Part of the carpentry work, such as finger jointing, can be done off-site. Part of the assembly can even be performed off-site. Finally, the assembly and erection are done, which are supervised by the engineers and architects.

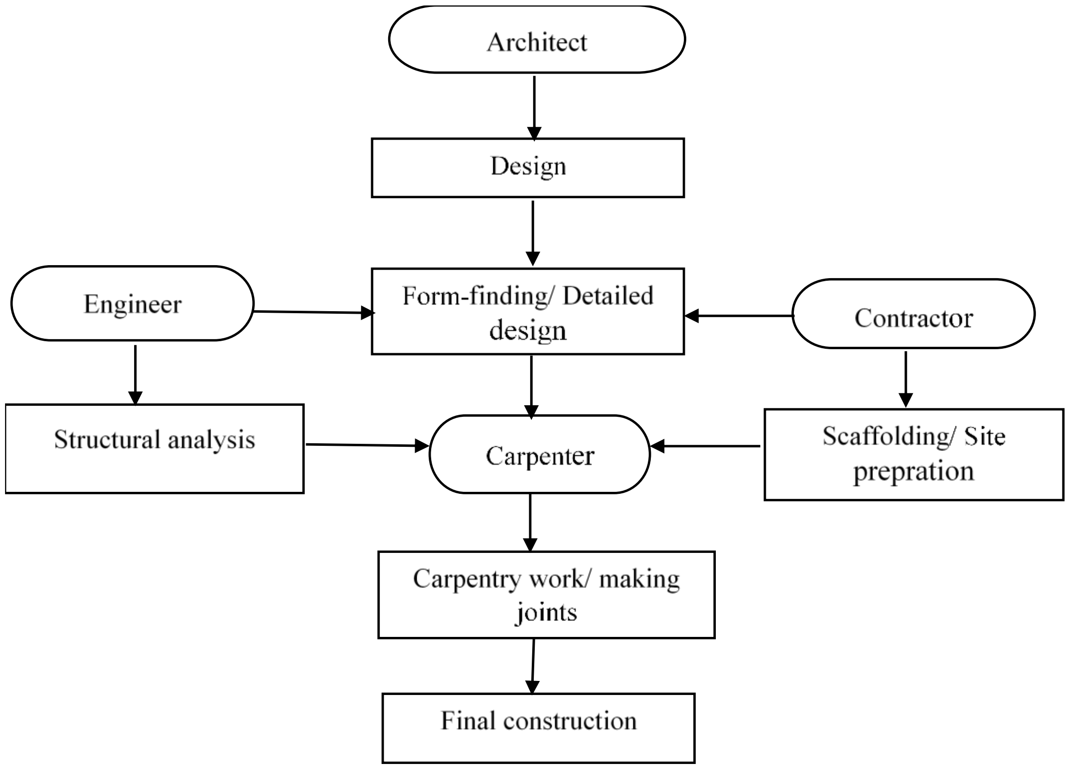

Fig. 4. Diagram of the phases and partners involved for building a medium-sized gridshell

Rutten *et al.* (2009) emphasized that close and stable relations between the different groups involved in the structure's construction contribute to innovation development. 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 design the shape of the building. In some of the gridshell projects, the carpenters jointly collaborated with the architects and engineers to design the details for the building.

For complicated and large-sized gridshells, there tends 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 a number of gridshells, mentioned that the process of creating the Downland gridshell was a case study for successful collaboration and innovation in architecture, engineering, and construction, which was led by a multidisciplinary team of practitioners (Harris *et al*. 2003). Harris described the first phase of the project as understanding the client's requirements to provide the right conceptual solution. He then lists modeling, prototype development, tests, timber selection, carpentry, and making long laths with finger joints and scarf joints as the subsequent production phases. The final part was to provide the nodes and connections, which are necessary for construction. Another example is the Pods Sports 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 detailed design, the contractor selection, and the procurement of a waterproof roof membrane.

By combining this information with that regarding the Mannheim Multihalle project (Happold and Liddell 1975), the Savill Garden gridshell (Harris *et al*. 2008), the Centre Pompidou Metz (Lewis 2011), and brochures and non-peer-reviewed literature sources for the other gridshells highlighted in the previous section, we can summarize the production phases as follows.

Planning: After the client's request for proposals and the acceptance of an architectural design, the client meets with the architect to define the building's requirements. An initial plan and feasibility analysis is then conducted by the architect. Involving engineers, wood suppliers, and the building contractor in these meetings and in the decision-making processes appeared to be essential in past projects to avoid inconsistencies in the following steps.

Concept design: The concept design is provided in the next step. It covers the outline specifications, the planning strategy, the cost plans, and the procurement options. In most of the projects, there is an academic partner involved to provide research and testing. For example, the University of Bath was the academic partner involved in some of the largest gridshells built in the United Kingdom.

Form-finding: The next step is form-finding, which is performed in collaboration with the architects and the engineers. Different types of tests need to be conducted to make sure that the structure will work properly. These tests may include checking the resistance for loads, wind, snow, *etc*. If the test results are acceptable, then the detailed design can be finished.

Contractor selection: A call for tenders is announced to find and choose the building contractor.

Construction: Preparation of the construction site can be started simultaneously with carpentry work. Part of the carpentry work can be done off-site, such as preparing the wood and finger jointing the pieces. Scarf joints are usually done on-site at a workshop. The connections should also be provided for joining the wood laths together during the assembly. When the building site is ready, and the building foundations and scaffolding are provided, the assembly and erection of the parts may be performed. The erection method for large gridshells is usually the ease-down approach with the use of scaffoldings. Figure 5 illustrates the phases and the partners involved 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 buildings. Characteristics of gridshell structures such as sustainability and lightness, on-site assembly and elegant shape are aligned with these factors. Non-residential buildings include three main categories: industrial buildings (*e.g.*, manufacturing plants, garages, workshops, and equipment warehouses), commercial buildings (*e.g.*, shopping centers, office buildings, and service firms), and institutional buildings (*e.g.*, schools, hospitals, homes for the elderly, *etc*.). Looking at the gridshell examples 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 gridshells. As a result, all these advantages can motivate companies to invest and use this structural design in different segments of market; however, some barriers may limit the construction of gridshells.

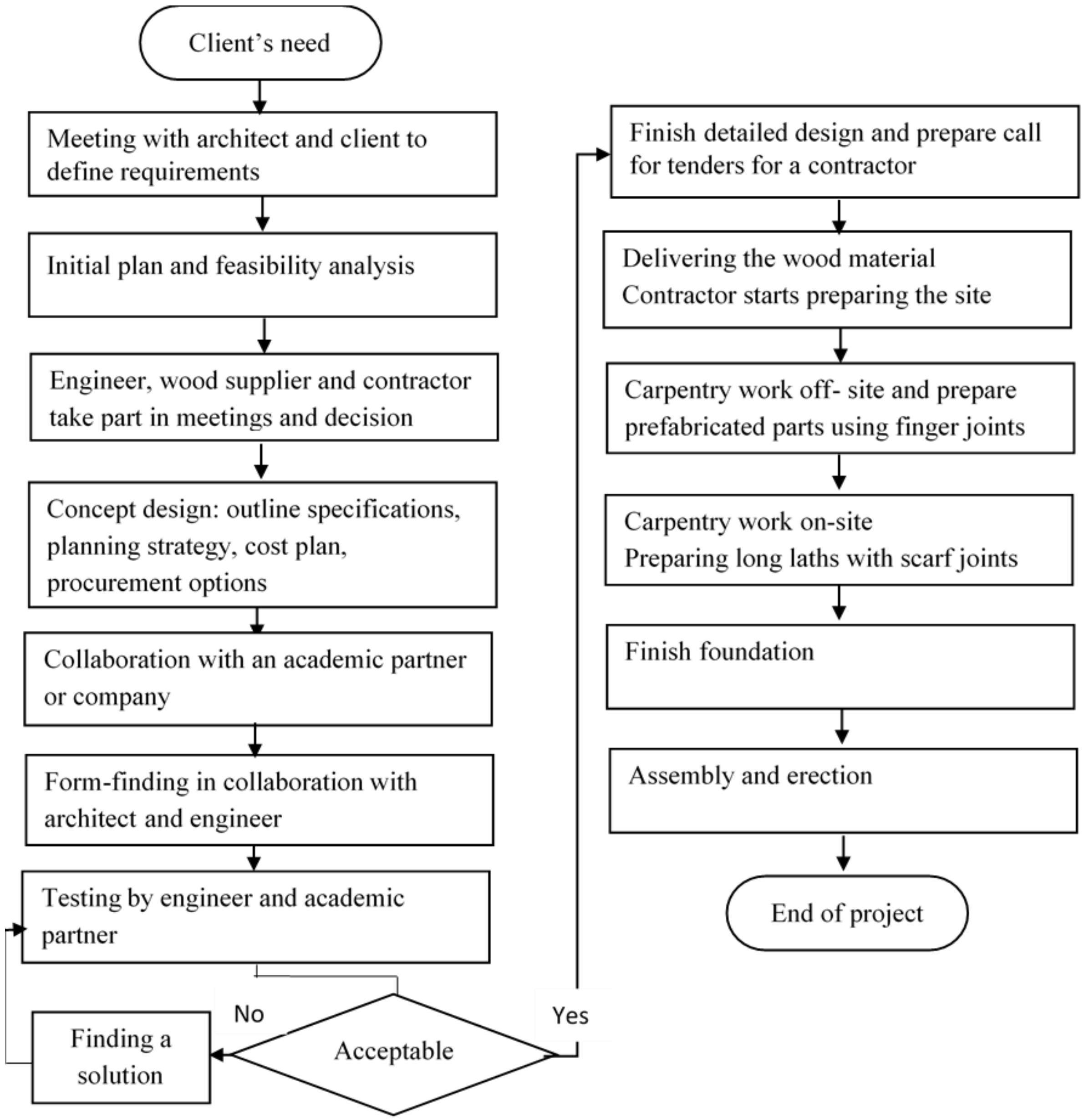

Fig. 5. Production phases and partners involved for building a large and complex gridshell

When considering a new product or a new market, a basic step is to analyze the motivations and barriers that are associated with it. A SWOT analysis is one of the several current strategic planning tools that can be used for this purpose. The SWOT acronym refers to the strengths and weaknesses of the service (or product) and the opportunities and threats that it faces. The purpose of a SWOT analysis is to gather, analyze, and evaluate information and to identify strategic options facing a community, organization, or individual at a given time (Ifediora *et al*. 2015).

According to the literature, the strengths of a gridshell structure rely on its elegant, innovative, and fresh shape. The structure captures the attention of visitors and the parties who are interested in enriching their experiences in modern architecture. Sustainability is another strong incentive for this structure. If timber is used for building the structure, flooring, cladding and other finishes, it makes a positive contribution to reducing global carbon emissions (Harris and Happold 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, this structure covers a large area without the necessity for columns, which represents 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 afterwards. For this reason, the construction time may be less. For example, the erection of the Japan Pavilion gridshell took only three weeks. The flexibility of the structure allows the use of a mix of different materials to make a hybrid structure which is another strong benefit of this design.

On the other hand, there are some weaknesses associated with the use of this type of structure. The design phase is time-consuming as the architectural design is complex and there are not many examples to use as benchmarks. There are plenty of stakeholders involved in large gridshell constructions and there is a need to manage the collaboration between them, especially in 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.

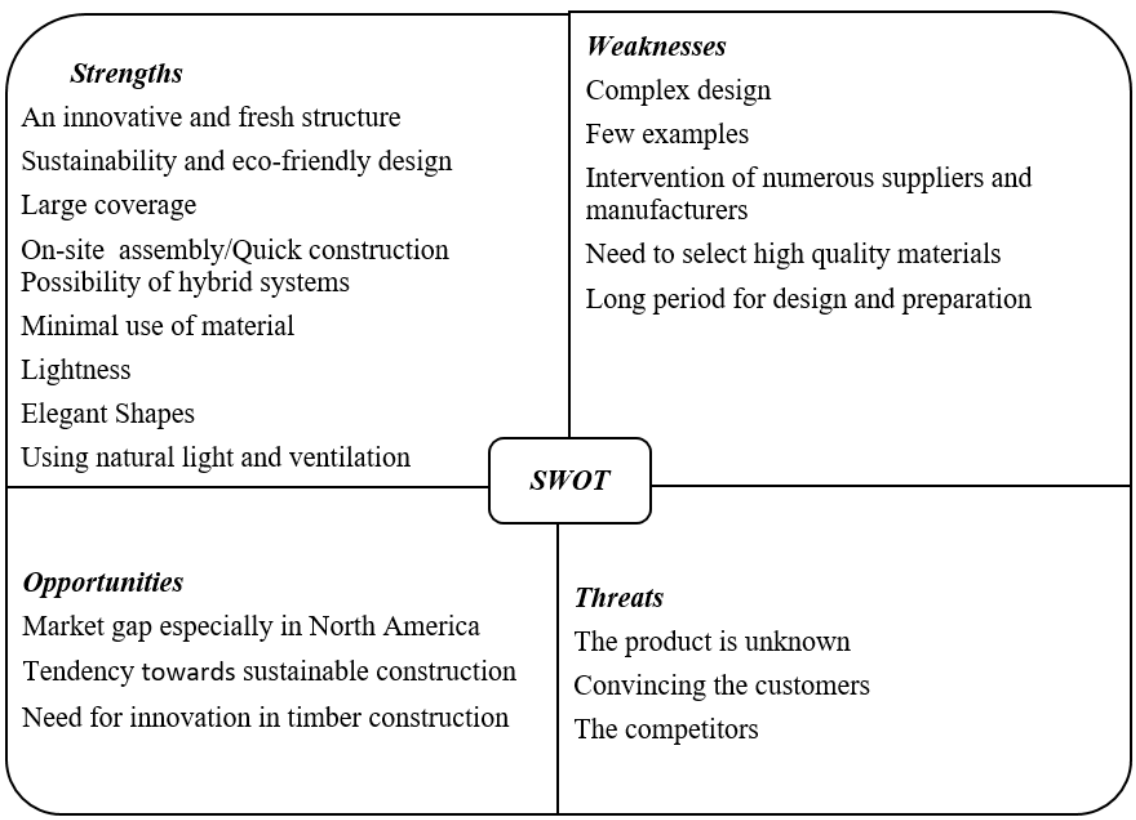

Fig. 6. SWOT analysis of gridshell as an innovative structure

In terms of market opportunities, as the number of gridshell structures are limited, there is an unfilled market for them, especially in North America. Putting this together with the tendency to increase market share for the use of wood in construction gives an overview of opportunities for gridshell constructions. In order to increase the use of timber in construction, the need for construction innovation should be emphasized. On the other hand, the fact that gridshell is not widely recognized is a barrier to market penetration. Since the architectural design is new and there are not many examples of it to compare to alternative designs, then additional efforts should be made to convince customers and make them confident about the success of this new design for a building project. Moreover, the reactions of competitors who use wood in construction should be taken as threats as long as the information about gridshell designs remains limited. Figure 6 summarizes the SWOT analysis for the gridshell building design.

Market Segments

After the SWOT analysis and the introductions of motives for building gridshells, market opportunities are now discussed. Table 5 summarizes the market segments of existing examples found in the literature review. These segments consist of the academic student projects, which are used as shelters, gathering places, and decoration.

Table 5. Market Segments Observed for Example Gridshells

Building type	Examples	Highlighted motivations
Student project and training Shelters Gathering places Restaurants (decoration)	German Building Exhibition in 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
Sports and leisure Sports centers Swimming pools Dance halls	Pods Sports Academy Haesley Nine Bridges Golf Club House	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

As mentioned previously, commercial and cultural places are another type of building for which the gridshell design was used. Furthermore, sports centers, swimming pools, and dance halls are places for which gridshell architecture is a suitable alternative. Additionally, Table 6 lists other market opportunities for gridshell structures which are currently not fully exploited. These types of buildings include public transportation stations (*e.g.*, train stations), industrial halls and warehouses, greenhouses, winter gardens, and zoos (in some areas).

Table 6. 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 buildings	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 gardens	Large coverage
Green houses	Lightness
Zoos	Elegant shapes
Plant research institutes	Using natural light and ventilation

SUMMARY

Timber gridshells are a promising solution to the growing interest in free-form architectural structures that are environmentally sustainable. The characteristics of timber gridshells, such as long-spans, lightweight construction, reasonable costs, and environmentally sustainable character, tend to favor this architectural building design in our time (Naicu *et al*. 2014).

In this review, the available literature about gridshell structures was analyzed, which led to identifying 20 examples that were categorized in small, medium, and large projects. These three categories consider the production of gridshell examples built from 1962 to 2015 as attempts to design lightweight structure systems with varieties in size, wood species, covering membrane and hybrid materials. The category of small gridshells introduces gridshells from the first prototype which was built by Frei Otto to the ones built by currently active academic research centers. The category of large gridshells indicates that the first large gridshell was built in 1975 and six other large gridshells were built from 2000 to 2011, while four of them were built by two famous architects. The wood species that were used in the construction, the site location of the projects and the main steps that must be considered for construction of the gridshell are mentioned.

Studying the examples shows that although gridshells have a complicated design, it is possible to manage construction of small prototypes in a research group. On the other hand, for construction of large gridshells, it is important to be aware that many parties are involved, and managing them is a challenging part of the work. Description of production steps highlights the importance of collaboration and involvement of the parties from the early steps of the work. Moreover, some of the advantages and disadvantages are noticeable in the description of the construction and the SWOT analysis highlights them. Finally, the market segments where these structures were used are listed and the opportunities for the future market based on the characteristics of the gridshell are suggested.

The reason for studying the examples is that there is a lack of examples for benchmarking, and the existing examples are not necessarily well recognized. Gathering the information about the design examples was a challenging part of this review, especially for small and medium gridshell categories; there was little information regarding these categories in the scientific and non-peer-reviewed literature. Further investigations on gridshell structural design could help the timber construction industry exploit this type of structure as a future market for their forest products instead of remaining a rare and special alternative.

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