Process analysis and improvments for production of engineered wood structures in an engineer-to-order system

Thèse

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Résumé

Augmenter la part de marché du bois dans la construction non résidentielle est un objectif important dans les pays où les produits forestiers et de bois d'ingénierie jouent un rôle fondamental. Afin de faciliter la production de structures en bois innovantes, il est nécessaire de mettre sur pied des procédures de réingénierie en termes d'analyse de marché et d'amélioration de la productivité. L'objectif principal de cette thèse est de faciliter la production de bois d'ingénierie (produits en lamellé-collé) destiné à être utilisé dans des structures en bois innovantes telles que les résilles en bois. Pour atteindre ce but, trois objectifs spécifiques sont définis.

Le premier objectif est de déterminer les phases de production et les opportunités de marché pour la production de résilles en bois. À cet égard, une revue de la littérature académique et de la littérature grise a été réalisée, et vingt échantillons ont été identifiés et analysés à l'aide de diagrammes de processus et de catégorisations. Les résultats ont montré qu'une structure en résille de bois est utilisée dans l'industrie de la construction en Europe et qu'elle est moins connue en Amérique du Nord, ce qui offre une opportunité de marché pour sa production et sa construction. La catégorisation des échantillons étudiés dans les petites, moyennes et grandes structures et l'identification des acteurs pour chaque catégorie fournissent une vue d'ensemble pour les entreprises qui envisagent la production de cette structure.

Le deuxième objectif de cette thèse est de fournir un modèle de simulation pour la production de bois lamellé-collé dans de petites usines et le processus d'application de techniques Lean pour apporter des améliorations. À cet égard, le système de production d'une entreprise québécoise a été analysé et un modèle de simulation créé. Afin d'éliminer chaque source de gaspillage, un outil Lean a été suggéré en fonction de la réalité du système à l'étude. Les résultats ont montré une amélioration notable du temps d'attente et de cycle suite à l'utilisation de techniques issues du Lean. Ils ont également contribué à souligner qu'une élimination du gaspillage limitée à 50% pouvait améliorer la considérablement la productivité pour les petites entreprises et s'avérer un premier pas important dans l'implantation du Lean.

Le troisième objectif est de fournir un outil de planification et d'ordonnancement de la production dans un contexte de production multi-projets d’ingénierie sur commande (*Engineer-to-Order*) de bois lamellé-collé. À cet égard, des modèles d'optimisation ont été créés. Le premier modèle (modèle 1) concerne la minimisation du coût de production total, tandis que le modèle 2 vise la minimisation de la durée totale des projets. Le modèle 3 cherche plutôt à réduire le temps de mise en route sur la presse, le poste goulot du système de production considéré. Le modèle 4 intègre les trois objectifs de réduction des coûts, de durée et de temps de mise en route. Deux scénarios d’ajout de projets de grande et de moyenne envergure ont été conçus et testés. Le test des scénarios démontre qu'il y a une capacité suffisante pour l’ajout d’un projet de grande envergure ou de neuf projets de taille moyenne sans recourir à la sous-traitance. L'ajout d'un projet de grande envergure est plus sensible à la période d'insertion, pouvant exiger du temps supplémentaire selon la date de début du projet.

Les travaux de cette thèse permettent donc de fournir des outils d'aide à la décision pour les entreprises œuvrant dans un milieu d'ingénierie sur commande afin d'améliorer leur productivité et la standardisation de leurs processus.

Mots-clés: Bois d'ingénierie, Petites et moyennes entreprises, Simulation, Optimisation multi-objectifs, Résille, ingénierie sur commande, Planification de la production, Planification de projet

Abstract

Increasing the share of wood in non-residential construction is an important goal in countries with major forest and engineered wood products. In order to facilitate the production of innovative timber structures, procedures should be re-engineered in terms of market analysis and productivity improvement. The main objective of this thesis is to facilitate the production of engineered wood to be used in innovative wood structures such as timber gridshell. To achieve this goal, three specific objectives are defined.

The first objective is to determine production phases and market opportunities for the production of timber gridshell. In this regard, a review of the academic and grey literature was conducted, and twenty samples were identified and analysed by making process charts and categorisations. The results showed that gridshell is used in the construction industry in Europe and is less recognised in North America, which provides a market opportunity for its production and construction. The categorisation of studied samples in small, medium and large structures provides an overview for the companies who consider the production of this structure.

The second objective of this thesis is to provide a simulation model for the production of glued laminated timber in small factories and the process of applying lean techniques to make improvements. In this regard, the production system of a Small and medium-sized enterprise (SME) was analysed, and a simulation model was created. In order to eliminate each source of waste, a lean tool was suggested according to the reality of the system under investigation. The lean methods were applied in the simulation model to analyse the potential improvements. Results showed a noticeable improvement in waiting and cycle time. It also showed that applying even 50% elimination of the wastes is also a considerable solution to improve productivity as a beginning step for SMEs.

The third objective is to provide a production planning and scheduling tool in the context of multi-project engineer-to-order production of glued laminated timber. In this regard, optimisation models were created. The first model (model 1) concerns the minimisation of total production cost while model 2 aims to minimise projects' makespan. Model 3 introduces the set-up time reduction and model 4 integrates the three objectives of minimising cost, makespan and set-up time. Two scenarios of adding complex and medium projects were designed and tested. Testing the scenarios showed that there is enough capacity for adding one complex project or nine medium projects without the need to outsource. Adding a complex project is more sensitive to the insertion period and beginning the project in different weeks leads to different results in terms of the overtime requirement.

As a result, the work of this thesis provides decision support tools for engineer-to-order environments which could help SMEs to improve their productivity and standardisation.

Keywords: Engineered wood, Small and medium enterprise, Simulation, Multi-objective optimisation, Gridshell, engineer-to-order, Production planning, Project scheduling.

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List of abbreviations

DES	Discrete-Event Simulation
DFMA	Design For Manufacturing and Assembly
DOE	Design Of Experiments
ETO	Engineer-To-Order
Glulam	Glued-Laminated-Timber
IMVP	International Motor Vehicle Program
MIP	Mixed-Integer Programming
MIT	Massachusetts Institute of Technology
MTO	Make-To-Order
NSERC	Natural Sciences and Engineering Research Council of Canada
NVA	Non-Value-Adding
RCPSP	Resource-Constrained Project Scheduling Problem
SMED	Single Minute Exchange of Dies
SMEs	Small and Medium-Sized Enterprises
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TPM	Total Productive Maintenance
VA	Value-Adding
VSM	Value Stream Mapping
WIP	Work In Process

You never change things by fighting the existing reality.
To change something,
build a new model that makes the existing model obsolete.

_ Richard Buckminster Fuller _

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Foreword

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Ghiyasinasab, M., Lehoux, N., Ménard, S. and Cloutier, C. (2018). "Using Lean Techniques and Simulation to Improve the Efficiency of Engineered Wood Production: a Case Study in a small factory", *International Journal of Industrial Engineering and Management.* 7(4) DOI: 10.4172/2169-0316.1000269

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Introduction

Environmental awareness increases the motivation to use wood as a renewable material which reduces CO_2 emissions (Kuzman and Sandberg, 2016). In order to increase the share of timber as a raw material especially in non-residential construction, it is necessary to pay attention to innovative structures that capture the eyes of the market. Wood construction systems typically encompass light frames, post and beams, massive wood structures, mixed and hybrid systems, and space frames (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 shell shape made of grid timber laths (Douthe *et al.*, 2006).

Different wood species have been used in gridshell systems such as larch, spruce, pine, oak, chestnut, and hemlock. In several important and recent constructions, glued laminated timber (glulam), which is a type of engineered wood, has been used for this structure. Engineered wood products are created using small pieces of wood adhered together with a bonding agent (Guss, 1995; Opacic *et al.*, 2018). They are used in residential and non-residential structures (Lam and Prion, 2003). Engineered wood products make better use of wood by combining small pieces of wood and putting aside the parts that have natural defects. They can be produced to have specific characteristics in terms of fire resistance and sound absorption (Opacic *et al.*, 2018). Glulam is one of the oldest engineered wood products and is a popular material in wood construction.

Building gridshell with glulam includes the production of glulam and then the construction of the structure that contains a combination of production and construction processes. The production of glulam, in this case, does not have the characteristic of mass production because the special design and dimensions should be produced for each construction project. These characteristics make a challenge for the optimisation and standardisation of the processes. Improvement approaches such as lean are well developed in mass-production and are even followed by the construction industry. However, production of customized prefabricated parts for construction projects, especially in Small and Medium-sized Enterprises (SMEs), have rarely been considered as the subject of systematic analysis and productivity improvement methods. Making improvements in the production of prefabricated parts such as glulam helps to increase efficiency while having greater control over the quality produced in the construction industry.

In the production planning context, the mentioned customized production for construction projects can be defined as engineer-to-order (ETO) system. ETO firms produce complex products which need specific design that does not exist before the customer order (Bertrand and Mutslag, 1993; Vaagen, 2017). Production planning in ETO systems is complex because of the higher level of production variability as it requires to manage due dates, capacity, order acceptance, and resource levelling efficiently (Ebadian *et al.*, 2009). ETO firms that produce designed products for construction projects are project-oriented as each construction project has its start time, design specifications and due date. Therefore, a project-oriented or project scheduling approach seems to be a suitable method for production planning (Márkus *et al.*, 2003; Alfieri *et al*., 2011; Carvalho *et al.*, 2015).

Canadian forest industry has encountered serious crises since 2005. In Quebec, Canada, the Government has therefore decided to update its management towards the policies that support improvements in the use of forest products. One of the specific goals in the updated strategic plan is to increase the use of wood products in the non-residential sector and in the construction of multifamily homes as well as to intensify the use of appearance wood products. In order to reach this goal, it is required to consider innovative buildings and find the best ways possible to combine wood with other materials in hybrid systems (Ministry of Natural Resources and Wildlife of Canada, 2008). Free-formed and modern structures such as timber gridshell which is suitable to be made of hybrid materials are therefore structures that worth to pay attention to. Although timber gridshell has the characteristics of an innovative and sustainable structure, most of its examples are built in Europe and is not well recognized in North America.

Furthermore, improvements in the construction industry and systems that work in the area of wood products manufacturing for construction should be considered to be able to increase the share of wood in construction. Productivity in the construction industry has improved more slowly than in the manufacturing sector which is related to the lack of standardisation since every project is different. According to the McKinsey Global Institute report (2017), a drastic increase in productivity would be possible if construction would tend towards a manufacturing-like system with a much higher degree of standardisation and modularisation. Conclusively, firms that produce structures or products specifically designed for construction projects have not got much attention in terms of productivity improvement methods as well as production planning and scheduling.

Industrial partner of this research is a SME that produces glulam for construction projects. This SME is interested to add gridshell into its production projects. It needs to understand the general processes of gridshell manufacturing and then make analysis if there is enough capacity in the factory to produce this new structure. The main questions that the SME encounters in the phase of considering gridshell production include: What are the motivations for construction of gridshell? What would be the potential market for this structure? In terms of productivity, there are serious issues that need improvement. The whole production system has not been analysed to reduce the non-value-adding activities and remove the other sources of waste as well. According to the observations and discussions with the production manager, the main problems in the production system are extracted. The production is not levelled and therefore there are periods where some stations are idle and other periods where overtime and outsourcing are required to meet the due date. Additionally, the production is not smooth, and the main bottleneck is the press machine. The process time is long, and a time-consuming set-up is needed.

This thesis aims to analyze how it is possible to improve the production of engineered wood in a SME as well as to facilitate its use in innovative structures such as gridshells. The first objective is to identify the production processes and involved parties as well as the motivations and barriers for the construction of gridshells. The second objective is to provide a system analysis tool for glulam production allowing to measure the impact of implementing lean manufacturing. The third objective is to provide a project scheduling tool which might help managers to analyse their capacity and decide on adding gridshell or other projects in their production system. Research questions linked to the contributions of the research are summarised in Figure 1.

Investigating the gridshell structure in the first phase of this study showed that there is a market opportunity for this structure in North America and it could be considered as a solution for increasing the share of wood in modern non-residential construction. It also showed that glulam has been used in a certain number of gridshell examples and is an appropriate material to be used in production of this structure. Therefore, production of glulam in the SME case was analysed. The analysis showed that it is required to increase productivity in the production system to make it ready for adding new products such as gridshell. The lean approach was applied to make the first steps of improvements. In the third phase, production and capacity planning was considered to complete the standardization steps and finally make it possible to consider adding production of the gridshell to the system.

Besides to provide methods to improve productivity in the SME under study, the contribution of this study relies on providing a comprehensive point of view for gridshell production phases and market opportunities; providing a simulation model for glulam production that could be used for testing various scenarios, suggesting step by step guide to apply lean approach in SME's; and providing a production planning model to be used for planning and capacity analysis in a SME that produces engineering wood. Moreover, the system under study is an ETO production system that produces engineered wood for construction projects. The characteristics of this system have not been considered in previous research and state an original contribution of this research.

General Research Question

How is it possible to facilitate production of engineered wood to be used in innovative wood structures such as timber gridshell?

Research Sub Questions

Contribution 1: Determine production phases and market opportunities

- Are timber gridshell structures used in construction industry?
- How were the examples built?
- What would the potential market for this structure be?

Contribution 2: Provide a simulation model and apply lean technics

- What is the production system needed to produce glulam in a SME?
- How can we improve the productivity, production and waiting time?
- How can we apply lean techniques in this system?

Contribution 3: Provide a production planning and scheduling tool

- How is it possible to schedule the production in each phase and each period for the combination of projects?
- How should production be planned to minimize the set-up time?
- Which types of projects should be accepted and in which periods?

Figure 1. Research questions

The first phase of the research followed a comprehensive investigation of the literature related to gridshell structures, including a general review of the technical production processes needed, the market expected, and the players involved. Studying most of the gridshell examples, with the purpose of understanding the production phases, led to categorising the examples as small, medium, and large-sized gridshells and defining 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. The contribution of the first phase is to provide an overview that covers existing examples of gridshell and their production phases. This study could provide guidance to companies interested in developing gridshells to make decisions in terms of their resources and facilities. Moreover, it could be viewed as a first step towards standardising the construction of timber gridshells.

The second phase of the research encompassed an analysis of the production in a SME for a prototype of gridshell using glulam as building material and the identification of a series of improvement steps based on the lean approach. The production system was analyzed, and the sources of waste identified. Then a simulation model was developed to measure the effects of the improvements proposed. The primary contribution of this research is to provide a simulation model for glulam production in SMEs which can be adapted to different cases. Developing a step by step approach that starts from feasible and less expensive improvements could motivate the managers to implement a lean approach. Another contribution is to use simulation and to apply the lean approach for glulam production designed for a specific gridshell system in order to analyze the processes, make suggestions for improvements and identify as well as prioritize the different sources of waste. Moreover, this research defines processes for the construction of gridshell with less waste which could motivate the construction of gridshell as a sustainable structure.

By taking steps in reducing waste and cycle time of the production, it becomes feasible to increase the number of gridshell systems produced in the factory. In this regard, managing and scheduling multi-projects become a key element to explore. The third stage of the research, therefore, led to the development of project-oriented optimisation models with the objective of cost minimisation (model 1), project makespan minimisation (model 2), press set-up time reduction (model 3) and a combination of all the three objectives (model 4). The models were tested for fifteen projects in a 40-week period. Also, scenarios of adding new projects were examined. The contribution of this study is to provide a planning and scheduling tool which reflect the characteristics of an ETO system for construction projects. As the SME considered in the study did not have any systematic planning, the research also provides a tool to facilitate strategic and tactical planning for the production of different engineered wood components.

Contribution of this study relies on prov In summary, the thesis provides a comprehensive analysis of the glulam production system and propose steps to increase its productivity while facilitating the adoption of innovative timber structures such as gridshell. The thesis is divided as follows: A review of the literature is provided in chapter 1. Chapter 2 describes the methodology and contributions. Chapter 3, 4, and 5 present the three original contributions of the thesis. The concluding section outlines the achievements and contributions of this work that are obtained through the linkage between all three contributions.

Chapter 1 Literature review

This chapter provides a literature review of the main methods and topics of the thesis which are the lean approach, simulation and optimisation. The lean approach is explained in section 1.1. Section 1.2 introduces the simulation method while in section 1.3, a comparison between simulation and optimisation models is provided. This review remains succinct as a comprehensive literature review covering the diverse research topics is included in each article inserted in the thesis.

1.1 Lean approach

Lean production techniques gained great attention when the International Motor Vehicle Program (IMVP) at the Massachusetts Institute of Technology (MIT) published its findings in 1988 (Womack and Jones, 1996). The findings showed that by following a lean approach, Japanese assemblers, especially Toyota, were the leaders in terms of productivity, quality, and inventory minimisation. Many books are published based on the Toyota Production System such as: the machine that changed the world: the story of lean production (Womack, Jones, Roos, 1991), lean thinking (Womack, Jones, 1996) and the Toyota way: 14 management principles from the world's greatest manufacturer (Liker 2004). Liker (2004) explained the 14 principles that could be used by managers in any manufacturing or service industry to improve their production system's efficiency.

- Principle 1. Base your management decisions on a long-term philosophy, even at the expense of short-term financial goals;
- Principle 2. Create continuous process flow to bring problems to the surface;
- Principle 3. Use pull systems to avoid overproduction;
- Principle 4. Level out the workload;
- Principle 5. Build a culture of stopping to fix problems, to get quality right the first time;
- Principle 6. Standardized tasks are the foundation for continuous improvement and employee empowerment;
- Principle 7. Use visual control so no problems are hidden;

- Principle 8. Use only reliable, thoroughly tested technology that serves your people and processes;
- Principle 9. Grow leaders who thoroughly understand the work, live the philosophy, and teach it to others;
- Principle 10. Develop exceptional people and teams who follow your company's philosophy;
- Principle 11. Respect your extended network of partners and suppliers by challenging them and helping them improve;
- Principle 12. Go and see for yourself to thoroughly understand the situation;
- Principle 13. Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly;
- Principle 14. Become a learning organization through relentless reflection and continuous improvement.

Implementation of lean techniques in the construction industry, which is named lean construction, did not grow as fast as lean production. The reason is related to the nature of construction, which is on-site while each project is constructed in a different location (Solomon 2004). According to Howell (1999), lean construction results from the application of a new form of production management to construction.

One of the top priorities in the lean approach is the elimination of waste (Nikakhtar *et al.,* 2015). Seven types of waste are defined by lean thinking: overproduction, defect, unnecessarily inventory, inappropriate processing, excessive transportation, waiting, and unnecessary motion (Liker 2004). These seven categories are the sources of waste in construction as well as in production (Shingo 1984). In a study concerning lean construction, Koskela (1992) enumerated defect, rework, design error, omission, change order, safety cost, and excess consumption of materials as waste groups that occurred in construction processes. An overview of waste classification from the literature can be seen in Figure 2.

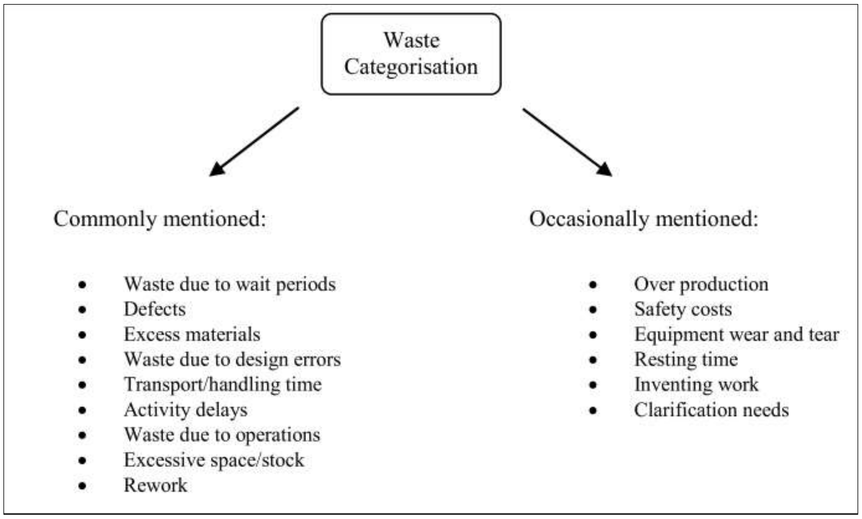


Figure 2. Waste categorisation, Nikhakhtar et al. (2015) based on Senaratne and Wijesiri, (2008)

The main argument of the lean construction concept is that processes need to be analyzed not only as transformations but also as flows and value generation. According to Tommelein (1997), there are two different types of activity, namely conversion and flow. Conversion refers to the activities that are required for the transformation of raw material or information into the final product. Flow refers to activities such as transportation, inspection, storage, and delay. The view of the process flow enables managers to improve their activities by recognising and reducing these kinds of waste. In fact, the process flow is not only composed of transformation processes but also of inspection and waiting activities as well as information, materials and equipment movement. Therefore, it provides an environment in which the possibilities of improvement are visible. Concentrating on the value transferred to the final product is another basic aspect of lean construction. From a lean perspective, activities can be classified as Value-Adding (VA) and Non-Value-Adding (NVA). In contrast to the NVA, VA activities are those that directly affect the production of the final product, increase the economic worth of a process, and are valued by the customer.

After determining the NVA and VA and the seven sources of waste, various tools and techniques of lean could be applied to improve the system. The key principles of lean production theory introduced by Koskela (1992) are samples of the general goals that might be achieved by applying lean approach.

- Reduce the share of non-value adding activities;
- Increase output value through systematic consideration of customer requirements;
- Reduce variability;
- Reduce the cycle time;
- Simplify by minimising the number of steps, parts or linkages;
- Increase output flexibility;
- Increase process transparency;
- Focus on controlling the complete process;
- Build continuous improvement into the process;
- Balance flow improvement;
- Benchmark.

The next sections introduce simulation as a tool which has been used for system analysis and scenario testing purposes and its application in studying the results of applying the lean approach.

1.2 Simulation

Law and Kelton (2000) classified the ways of analysing a system in two main categories: analysing the real system and analysing a model of the system. Analysing the real system and making the changes to see what happens, is most of the time costly or not possible. Models for their part can be physical or mathematical. Physical models are useful in some fields such as architectural models and form-finding for the structure. A vast majority of models for system analysis are mathematical models which represent a system by logical relationships and can be manipulated to predict the system's behaviour. Mathematical models can lead to analytical and simulation models. Figure 3 illustrates the ways to study a system as described by Law and Kelton (2000).

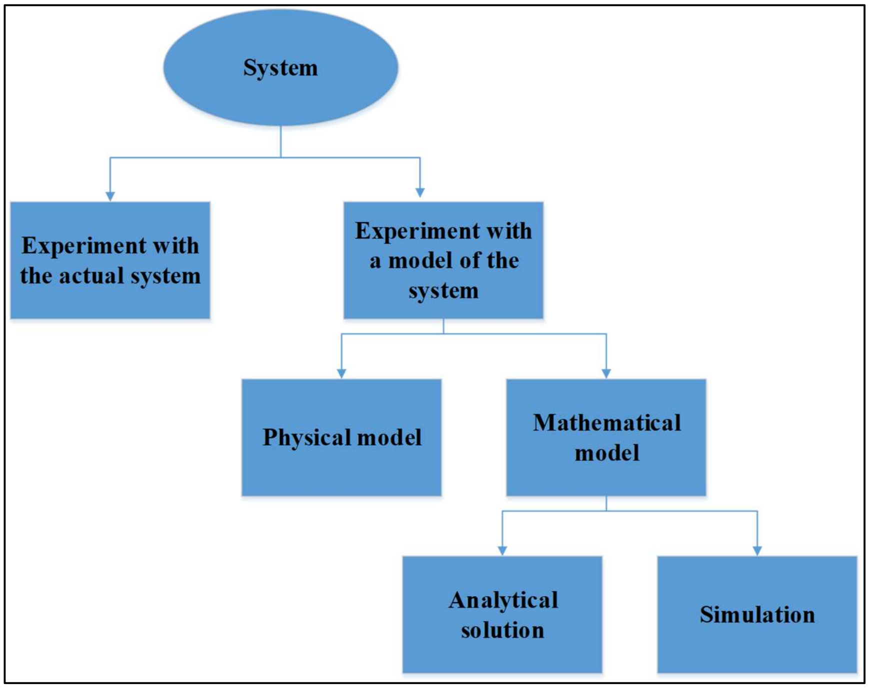


Figure 3. Ways to study a system from Law and Kelton (2000)

Simulation can be defined as an imitation of the performance of the real process or system over time (Abedi Saidabad and Taghizadeh 2015). The model, which is prepared based on the assumptions that reflect the real system, is expressed in the framework of mathematical, logical and symbolic relations among the components of the system. Simulation provides a model based on the history of the system which can be applied to understand how the system works and what will be its reaction in the future. One of the most useful applications of simulation is the possibility to analyse various what-if scenarios and predict the effects of possible changes on the key performance factors. Simulation is considered as one of the most common and widely accepted research tools in systems' operations and analysis (Banks *et al.* 2005; Abedi Saidabad and Taghizadeh 2015).

Law and Kelton (2000) categorized systems as discrete and continuous. In a discrete system, the state of a variable changes in distinct points of time while in a continuous system, the state of a variable changes continuously with respect to the time. As most of manufacturing and business systems are discrete, the most commonly used algorithm for simulation applications is a discrete-event simulation (DES). This type of algorithm concerns how the system evolves over the time and how the state of the variables changes based on that. The main goal of DES is to identify problem areas and quantify or optimise production system performance. DES is able to model and handle complex systems with highly dynamic decision rules and relationships between different entities and resources (Law 2008). DES has also been recognised as a powerful technique for the quantitative analysis of complex construction operations (Martinez 2010).

Computer simulation of production and logistics systems has been and is still widely in the literature. In particular, simulation helps to investigate potential failure causes of a production system or to choose between design alternatives (Gallo *et al.* 2007). Research that use simulation commonly follow the seven steps approach that is described by Law (2008) to build valid and credible simulation models. The first step concerns the problem formulation where the objectives of making the model and questions that need to be answered should be identified. This formulation contains the system configurations and general scopes of the model. The second step necessitates to collect information and data about the system under study and to determine the assumptions by providing a conceptual model. In the third step, the conceptual model should be examined carefully to recognise the errors in understanding the system components and flows. If the conceptual model is valid, then the next step (step 4) is to create the simulation model using a simulation programming software. The programmed model must be debugged and verified. Then, in step 5, the validation of the programmed model needs to be confirmed. The model could be validated by comparing the results of the model with the results of the real system (results validation). In addition, experts from the system simulated (factory) should confirm the model and its result (face validity). This step must be repeated until the validity is achieved. Then, step six concerns the design of different scenarios and their experimentation using the model as well as results analysis. The last step (step 7) involves to document and presents the results and assumptions of the model. These steps are illustrated in Figure 4.

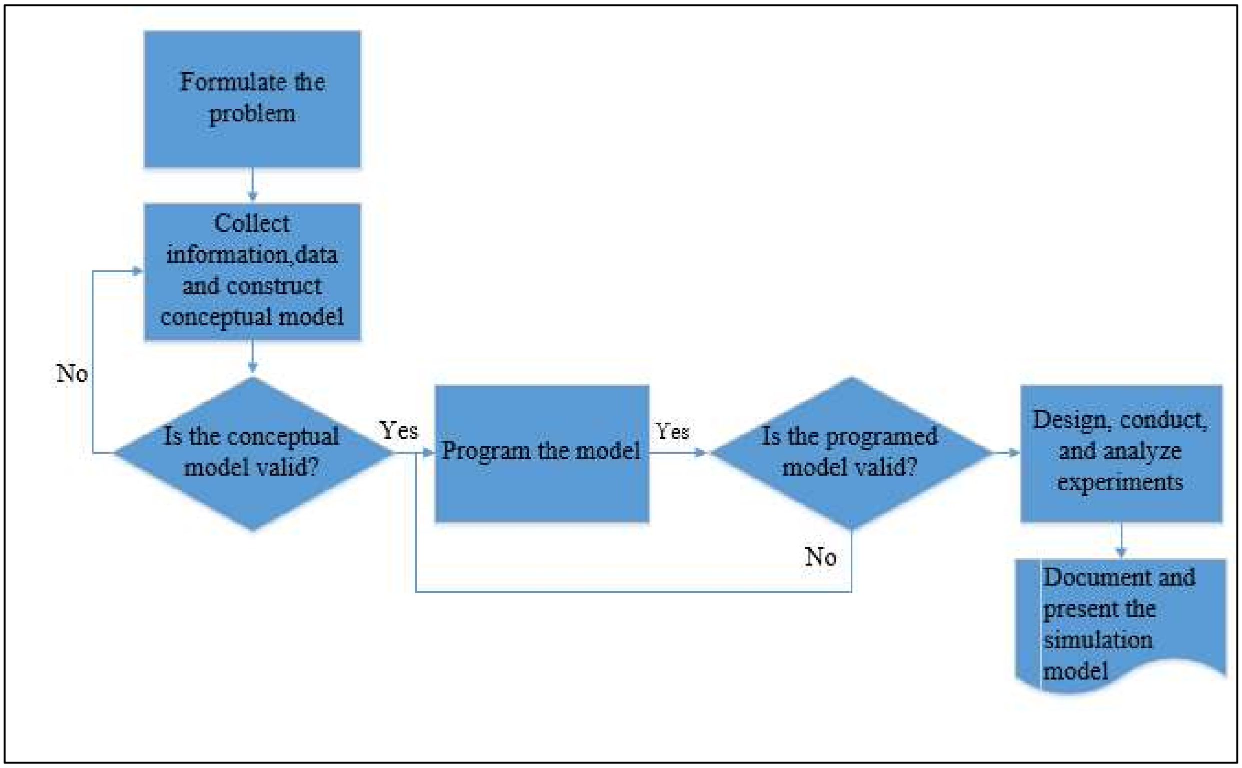


Figure 4. Seven steps to prepare a valid simulation model based on Law (2008)

In this section, an introduction to simulation was provided. Another category of mathematical modelling is optimisation modelling which is used in the third phase of this thesis. In the next section, an introduction about optimisation models and the advantages and disadvantages of simulation and optimisation models is provided.

1.3 Simulation versus optimisation

Optimisation is a method to find an optimal or the most efficient results for the objectives in a decision-making process which satisfies the existing constraints associated with the problem. The objectives aim to minimise or maximise an analytical mathematical expression. The most common objectives are to minimise the cost or maximise the profit. Constraints are mathematical expressions that demonstrate restrictions in resources and the conditions of the system. Optimisation methods can be applied in planning, network/transportation flow, inventory management, resource management, scheduling/workforce assignment, or financial investment – and thus provide the most proficient results available given the objective and constraints. Optimisation models may be implemented in various ways using, for example, linear programming, mixed integer linear programming and non-linear programming (Lund *et al.* 2017).

Both optimisation and simulation models have been applied vastly in terms of system analysis, problem-solving and decision making in various systems. However, there are advantages and disadvantages for each method that requires to be considered so as to apply the more appropriated model to each problem. Many researchers such as Abedi Saidabad and Taghizadeh (2015) and Lund *et al*. (2017) discussed the characteristics of these models. Some of the main differences between simulation and optimisation models are listed as follows:

- Optimisation provides one solution to be applied to solve tactical/operational issues and is a suitable method when optimised results are required for variables such as cost, while many constraints must be considered. On the other hand, simulation does not necessarily provide the optimal solution and absolute number, but it allows the decision makers to analyse what-if questions and make changes without changing the real system.
- Adding complexity and uncertainties in optimisation models is very complicated comparing to simulation models.
- False input becomes obvious during simulations whereas, in optimisation, it remains hidden in the optimisation algorithms.
- From the side of presenting data to the decision-makers like the managers of the companies, it is easier to understand simulation models and their visualisation helps the analyzer to explain the model logic and results.

1.4 Production systems

Ari Samadhi and Hoang (1995) categorized production systems based on the concept of customer order. Customer order decoupling point is the point where customer order arrives to the production system. In this regard, the production environment can be classified into make-to-stock (MTS), assembled-to-order (ATO), make-to-order (MTO), and engineered-to-order (ETO). Figure 5 illustrates the decoupling point for each production environment.

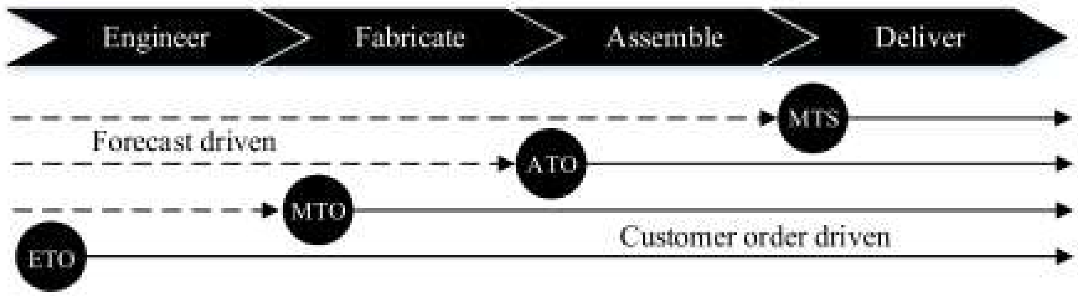


Figure 5. Decoupling point for each production environment (Olhager 2012)

In MTS, the products are standard and the production is not based on the customer's order. Products will be kept in inventory and then sold to the customer. In ATO production environment, product modules are produced to be used to assemble the final product when the order arrives. Different products could be produced by assembling the modules. In MTO, production starts after receiving the customer's order which defines the kind of product to be made. The difference between MTO and ETO is that in ETO, even engineering design of products is based on customer's order (Ari Samadhi and Hoang 1995).

1.5 Conclusion

This chapter presented a summarised review of the literature focusing on the methods and methodology of this research. A simulation model is developed in the second phase of this research to analyze how the glulam production system works and how the implantation of lean approach could make improvements. Optimisation models are also developed in the third phase of the research so as to minimise the cost and the setup time when planning the production of engineered structures for construction projects.

Chapter 2 Objectives, Case Study and Methodology

This research aims to analyse the production of engineered wood and to develop tools to facilitate its use in innovative wood structures. The project was conducted in collaboration with a SME located in the Quebec province. In this chapter, the SME under study is introduced and then the methodology and the thesis organisation are explained. Finally, a conclusion is presented.

2.1 Case study

This research was conducted in collaboration with a small company active in the architectural design of buildings and the production of glulam for the construction of projects. This SME has been involved in many commercial and residential projects such as houses, restaurants, sports halls, and libraries. Some of the projects were completely designed and constructed by the company, while there were some others for which the main contractor asked this company for the part of glulam production and construction. Three main shapes of glulam are manufactured in this factory, which are straight beams, round beams, arcs. If the design of project needs a customised form, special shapes might be produced (Figure 6).

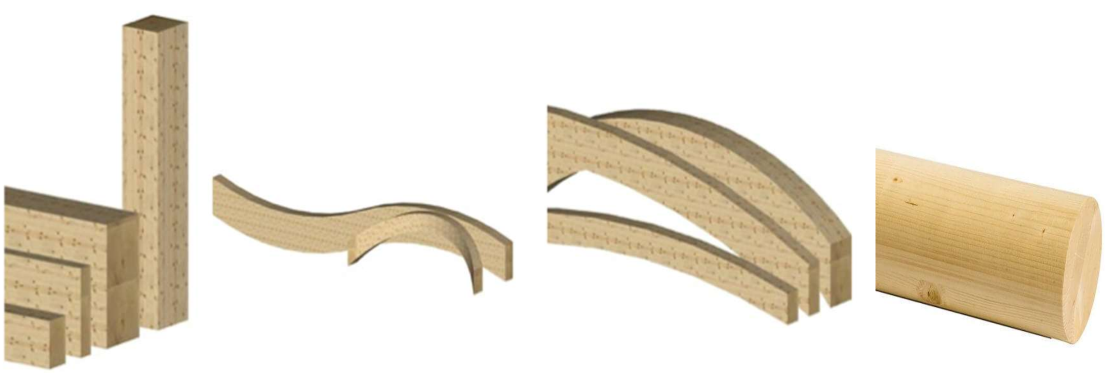


Figure 6. Straight beams, special shapes, round beams, and arcs.

The main raw material that the SME buys includes MSR (Machine Stress-Rated) 2100 and regular S-P-F (Spruce- Pine- Fir) lumber. The company categorises the wood from BF to D, where BF refers to the highest quality and D refers to the lowest quality. Wood with lower quality can be used in the middle layers of glulam while the wood used for the surfaces needs to be of high quality. Table 1. lists the wood grades and their position in glulam.

Table 1. Wood grades and their position in glulam

Zone	Visual Grade
Top face lamination	B-F
Within outer 1/8 section (top)	B
Remainder of outer ¼ (top)	C
Inner ½ or less	D
Remainder of outer ¼ (bottom)	C
Within outer 1/8 (bottom)	B
Bottom face lamination	B-F

Although the company has been involved in important construction projects, it remains a small factory with limited staff and equipment. The number of employees in each workgroup is listed in Table 2.

Table 2. Number of employees in each work group in the factory

Workgroup	**Number of employees**
Inspection	1
Production	8
Carpenter	4
Finishing	3
Engineering	2
Construction on-site	2
Maintenance	1
Drawings	2
Quality control	1
Administration and management	5

In order to analyse the production system, the first visit was conducted in February 2017 when a prototype gridshell project was under production. During the visits, time and work-study were conducted by observation and making movies and pictures. Moreover, interviews with the employees and production manager were executed to get knowledge about the production system, the problems and the challenges. The permission for taking pictures, recording movies and getting access to the documents was obtained by signing a document to keep the information confidential.

Following the visits and observations, related documents and detailed drawing for the project were asked from the production manager. During the modelling and problem-solving stage, meetings and discussions with the production manager were executed to assure the validity of ideas and hypothesis. Additionally, data for 15 projects for the year 2017 were demanded and received to be used for the optimization model.

2.2 Research methodology

The research project starts with a literature review to gather information about the global production process and market opportunities for gridshells. Grey literature resources are also investigated, including the websites of stakeholders involved in gridshell construction projects, and a list of 20 contemporary examples of gridshell structures was extracted. The investigated examples are categorised as small, medium, and large-sized gridshell. The groups involved and the production phases for the different categories of gridshell structures are identified. The next step is to investigate the motivations for timber construction, along with the characteristics of gridshell designs and analysis of the motivations and challenges of the structure and its potential market.

The next phase involved investigating the production of a small gridshell in the SME under study. It encompassed a combination of simulation and lean techniques to present improvement scenarios for the production system. In SMEs, it is challenging to convince the managers to apply improvement techniques as there have limited financial and human resources. Therefore, making a simulation model helps to test the scenarios which are expensive to be applied in the real system. The main steps included the data gathering, analysing and modelling the as-is situation with simulation, introducing improvements, applying improvements in the simulation model, and checking the results. The type of simulation used is discrete-event simulation and the simulation software exploited is Arena 15. The model is validated by statistical test as well as via face-to-face meetings with the president, the production manager, and the main engineer. The simulation model can, therefore, be viewed as a decision support tool to measure the impact strategic changes in the factory may have while considering a single project.

System analysis, simulation of production processes and improvement suggestions introduced a primary improvement level in the glulam production system. The next phase was to consider the production of multi-projects and to provide a production plan that makes appropriate changes in the system towards adding gridshell projects. Mixed integer linear optimisation models were therefore developed to provide a decision tool for weekly tactical scheduling as well as strategic decisions such as new project acceptance. These models aimed to minimise the cost (model 1), minimise projects' makespan (model 2), minimise set-up times (model 3) and minimise the four combined objectives (model 4). The weighted sum method was applied to solve the multi-objective models. Three scenarios were tested to analyse the impact of adding small (easy) and medium (difficult) projects. By using this tool, the SME will be able to analyse the capacity of adding one or more gridshell projects based on the complexity of the structure. The three phases of this research are summarised in Figure 7.

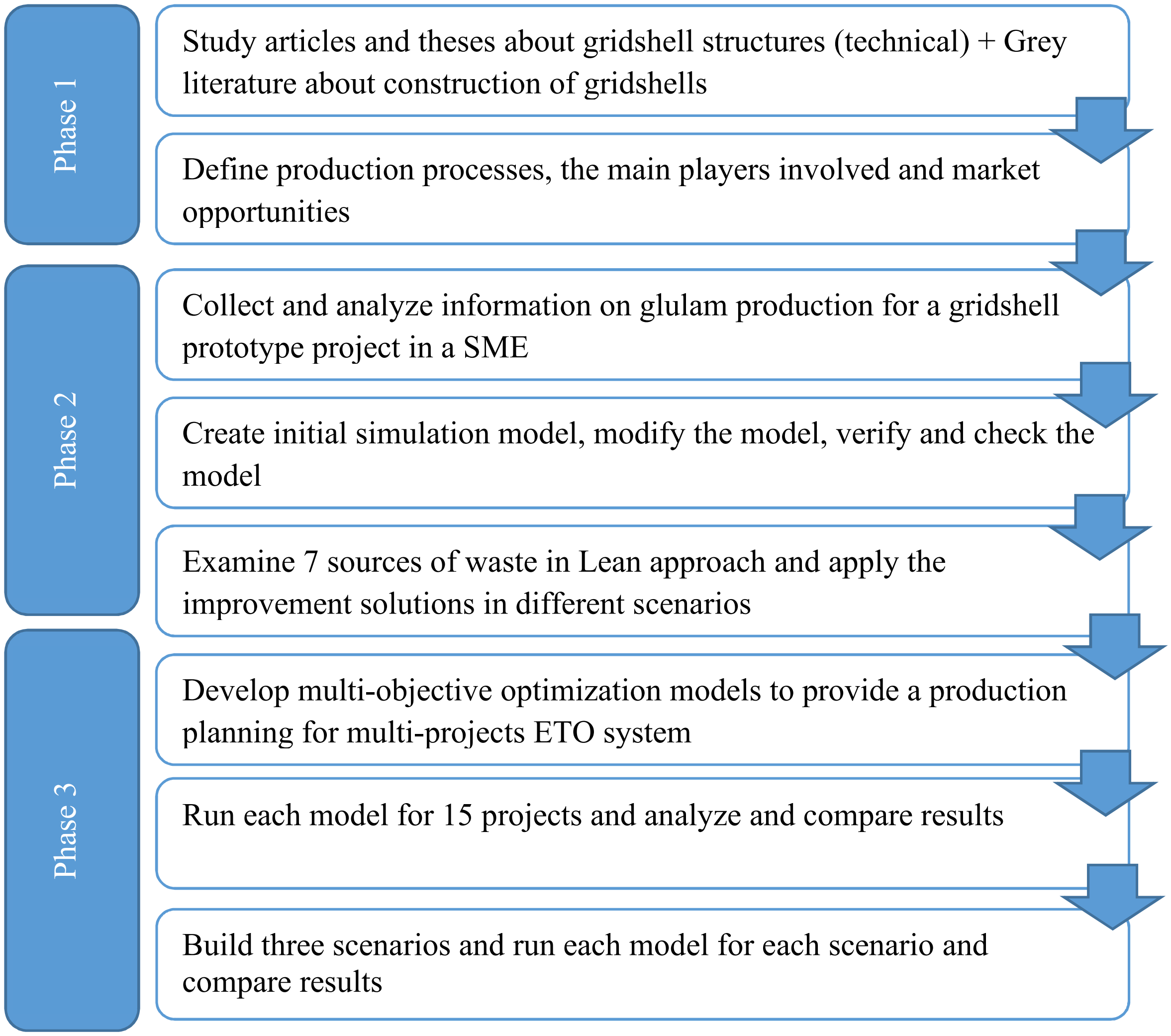


Figure 7. Methodology of the research

2.3 Thesis organisation

This thesis includes three original contributions (presented as three papers), which have been provided throughout chapters 3 to 5 as follows.

2.3.1 Organisation of chapter 3

Chapter 3 introduces the first article of the research entitled "*Production Phases and Market for Timber Gridshell Structures: A State-of-the-Art Review*". Figure 8 summarises the contents of chapter 3.

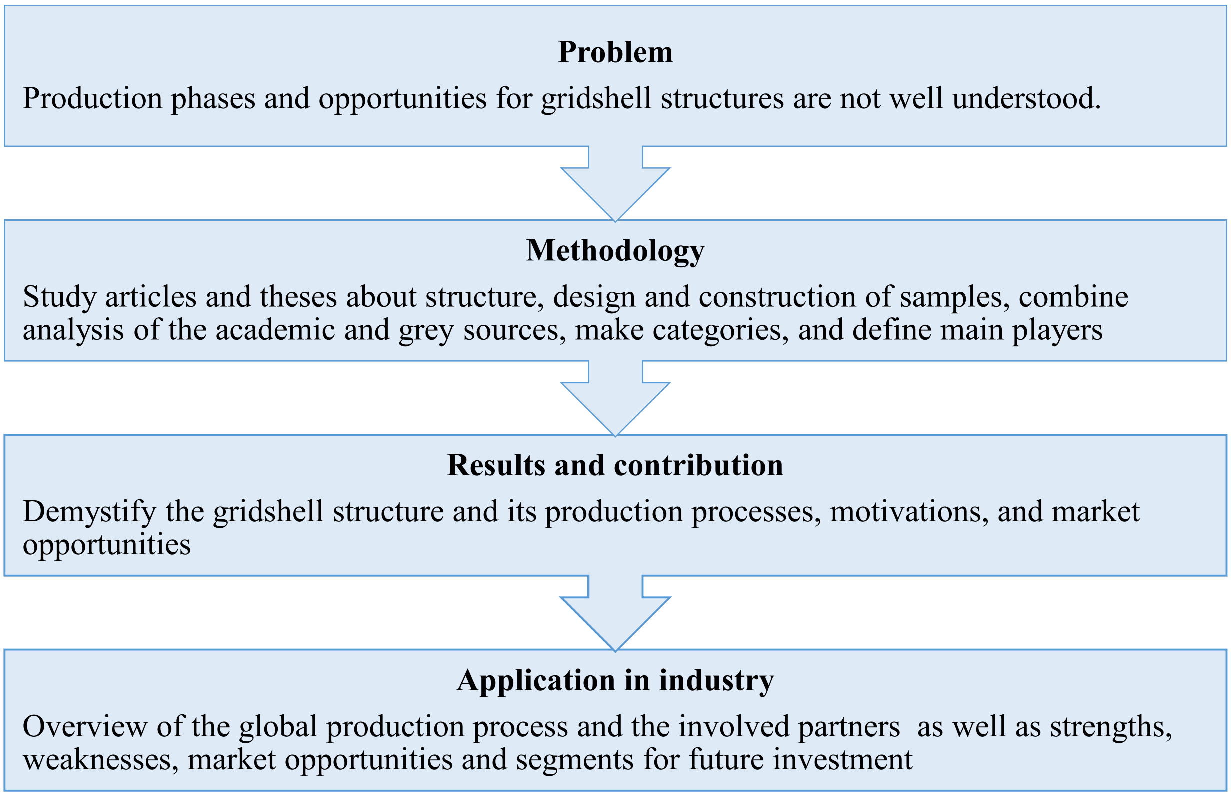


Figure 8. Research organisation in the first contribution

2.3.2 Organisation of chapter 4

The second paper, entitled "*Using Lean Techniques and Simulation to Improve the Efficiency of Engineered Wood Production: a Case Study in a small factory*" is presented in chapter 4. The contribution organisation of the paper is shown in Figure 9.

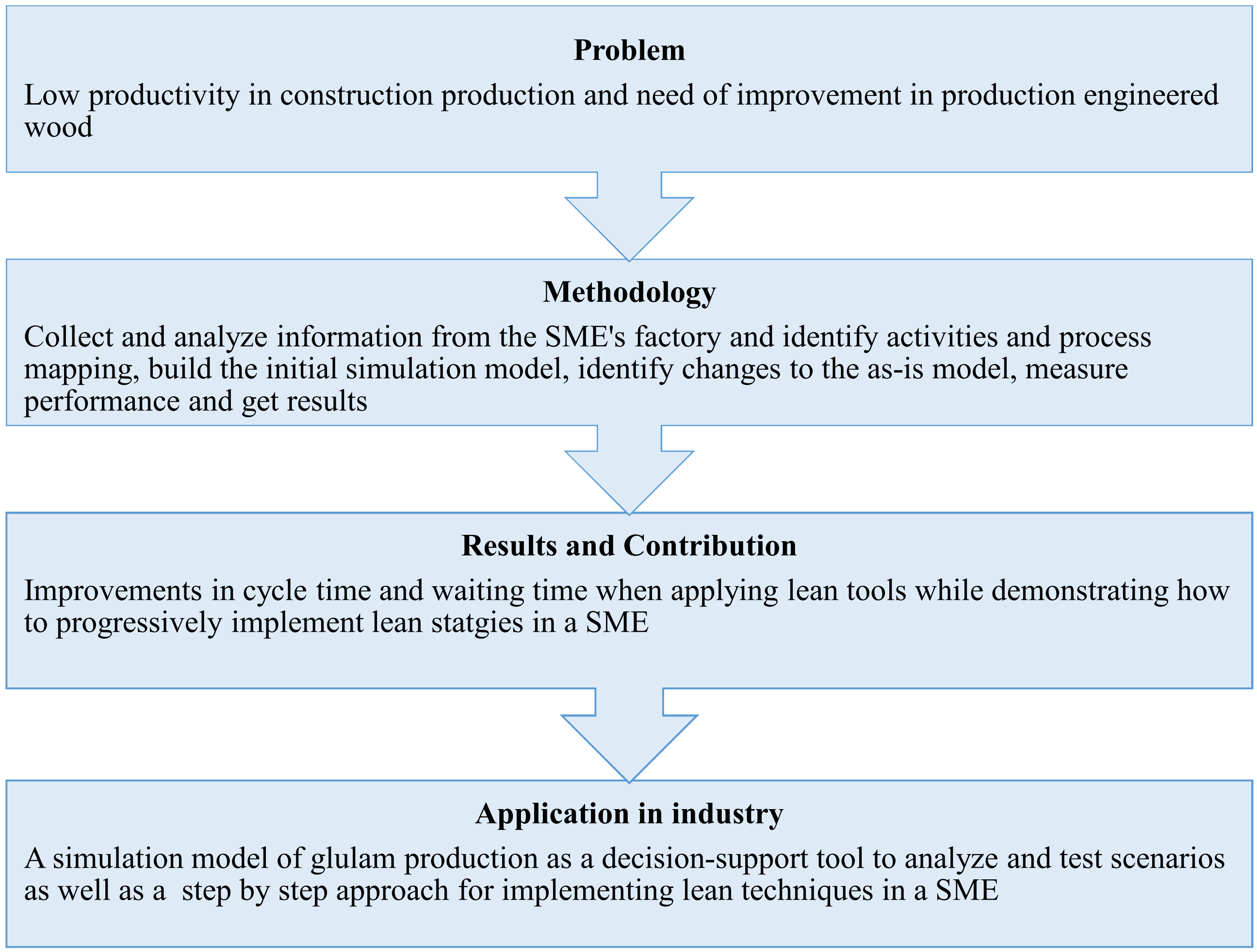


Figure 9. Research organisation in the second contribution

2.3.3 Organisation of chapter 5

The third paper, entitled "*Production planning and project scheduling for engineer-to-order systems*" is presented in chapter 5. The contribution organisation of the paper is shown in Figure 10.

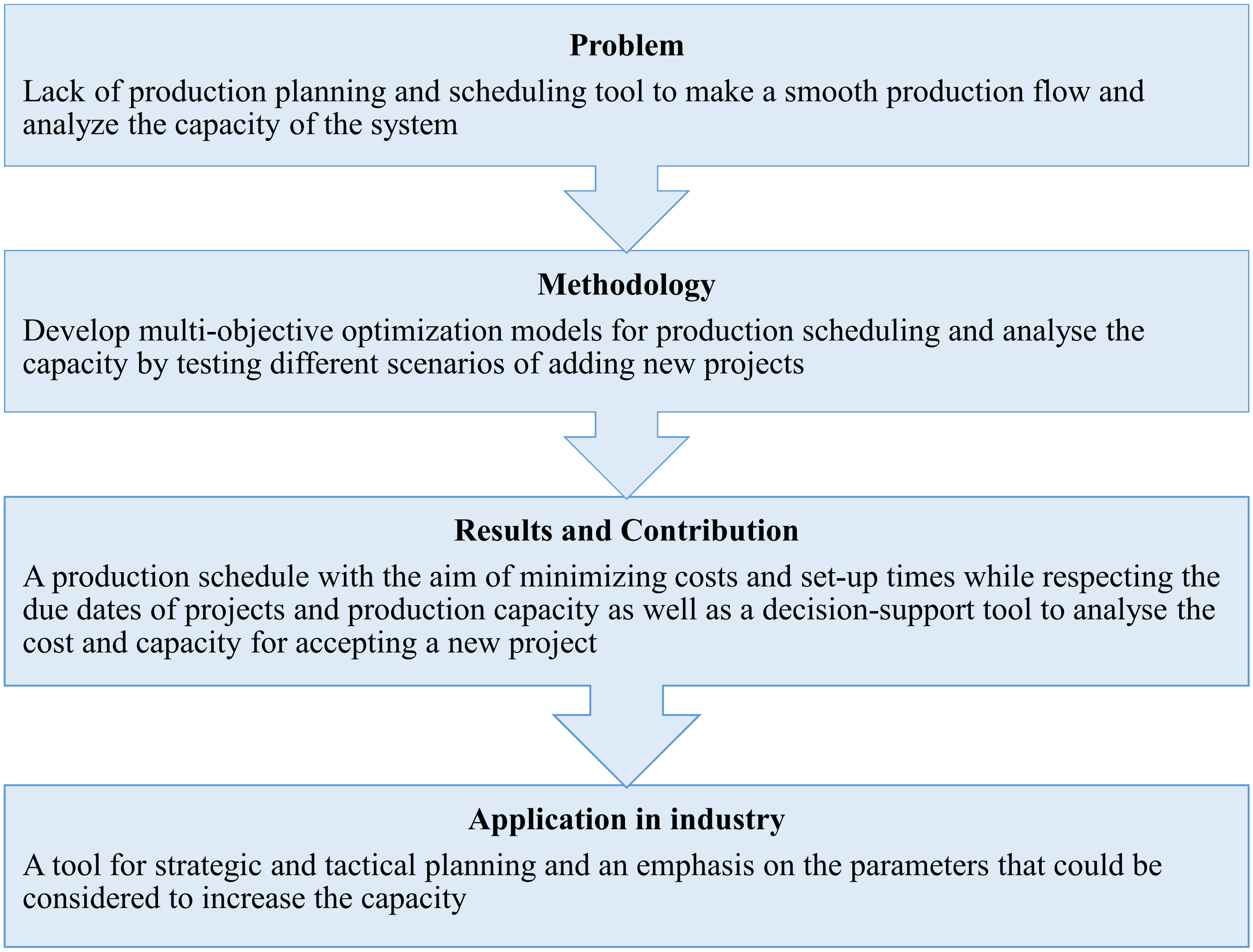


Figure 10. Research organisation in the third contribution

2.4 Conclusion

This thesis consists of three phases which encompass introducing a complex engineered wood structure, making the necessary changes to improve its production efficiency and developing the planning tool to allow its production on a larger scale. The research was conducted based on a thorough literature review, the creation of a simulation model and the development of optimisation models. Real data from a SME producing glulam for construction projects were exploited. Chapter 3, 4 and 5 present the papers 1, 2 and 3 explaining the contributions of the research in detail.

Chapter 3. Production Phases and Market for Timber Gridshell Structures: A State-of-the-Art Review

This chapter is earmarked to the article entitled " *Production Phases and Market for Timber Gridshell Structures: A State-of-the-Art Review* ". It was published in *BioResources Journal*, 2017.

Résumé

La résille en bois est une structure à la forme incurvée constituée de lattes de bois en grillage. La structure en treillis peut constituer une solution intéressante pour les structures modernes de forme libre qui sont durables sur le plan environnemental. Cependant, les recherches universitaires axées sur les marchés potentiels et les étapes de production basées sur cette technologie de construction sont limitées. L'objectif de cette revue de littérature est d'étudier la structure de la résille afin d'identifier son processus de production global, ainsi que les partenaires impliqués dans les exemples architecturaux étudiés. Un examen des articles scientifiques examinés par des pairs et des ressources en littérature grise (par exemple, des magazines, des pages Web, etc.) a été réalisé pour rassembler des informations sur les résilles en bois. Les exemples de conception trouvés ont été classés en petites, moyennes et grandes résilles. La catégorisation est basée sur la taille et le niveau de complexité des exemples de conception. Les phases de production et les partenaires impliqués dans la conception et la construction de ces structures ont été identifiés pour chaque catégorie. En outre, les motivations et les obstacles à l'utilisation des résilles dans la construction, ainsi que les segments de marché potentiels ont été déterminés.

Mots-clés: Résille, Construction en bois, Phases de production, Processus, Durabilité, Bâtiments verts, Marché, Innovation.

Abstract

Timber gridshell is a structure with a 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 categorised as small, medium, and large gridshells. The categorisation 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.

3.1 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 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 recognised 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 standardisation 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 standardising 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.

3.2 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 behaviour 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 optimisation process. Numerical optimisation 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) note 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 minimising 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 11 shows three examples of gridshell structures.

Figure 11. 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).

3.3 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 categorised as small, medium, and large-sized gridshell. This categorisation 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 12 summarises the steps of the research methodology.

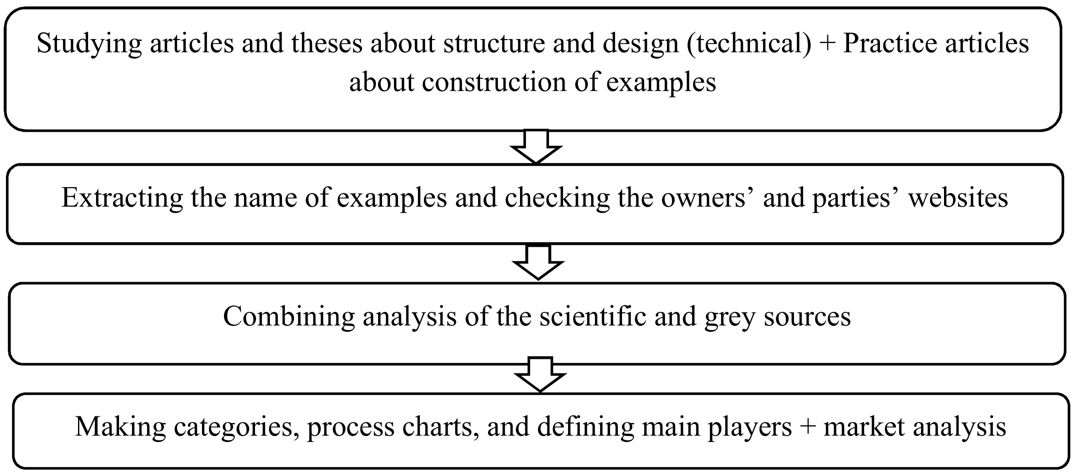


Figure 12. Steps of literature review methodology

3.4 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 13 illustrates the sources of complexity in a timber gridshell structure.

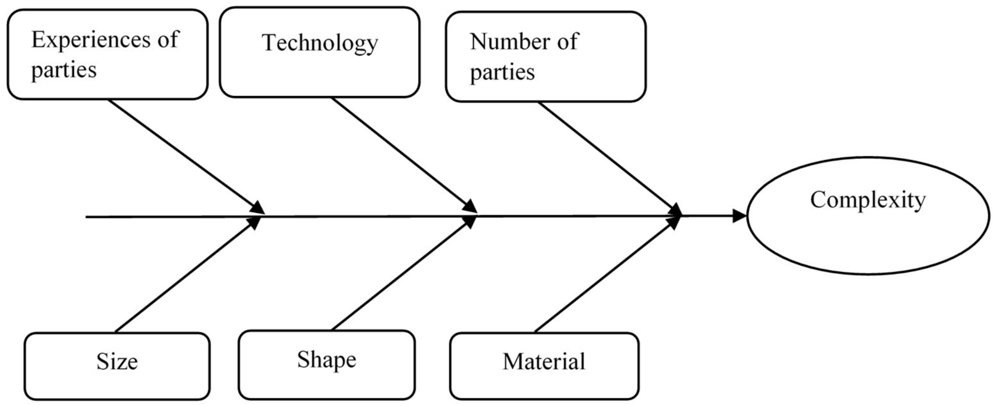


Figure 13. Cause and effect diagram for level of complexity in production of a gridshell structure

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 categorisation 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 3 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 3. Characteristics of the Categories

Category	Size	Experience of parties	Functionality	Budget
Small	80 to 300 m^2	Academic professors and students	Not Commercial (Research/ prototype)	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 the 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 emphasises 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 aluminium panels; the structure provides shade and a central meeting place for people. Table 4 lists examples of small gridshell structures.

Table 4. 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 commercialised 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 categorised 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 centre, museum, and monument, respectively, are summarised in Table 5.

Table 5. 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 fibre-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.

Table 6 presents the list of these gridshell examples.

Table 6. 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

3.5 Discussion

3.5.1 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 Figure 14, 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.

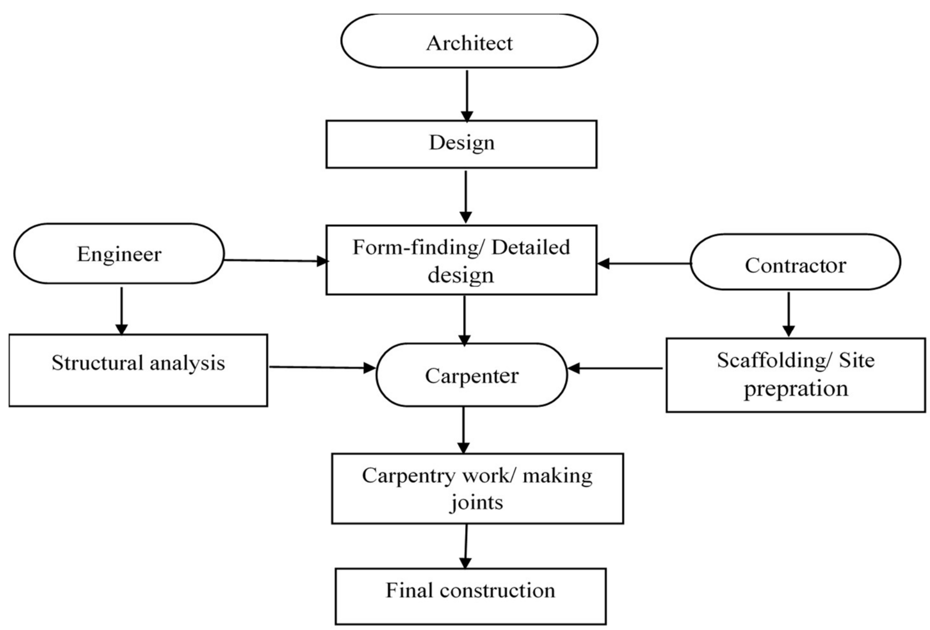


Figure 14. Diagram of the phases and partners involved for building a small and medium-sized gridshell

Rutten *et al.* (2009) emphasised 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 summarise 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 15 illustrates the phases and the partners involved for building a large and complex gridshell.

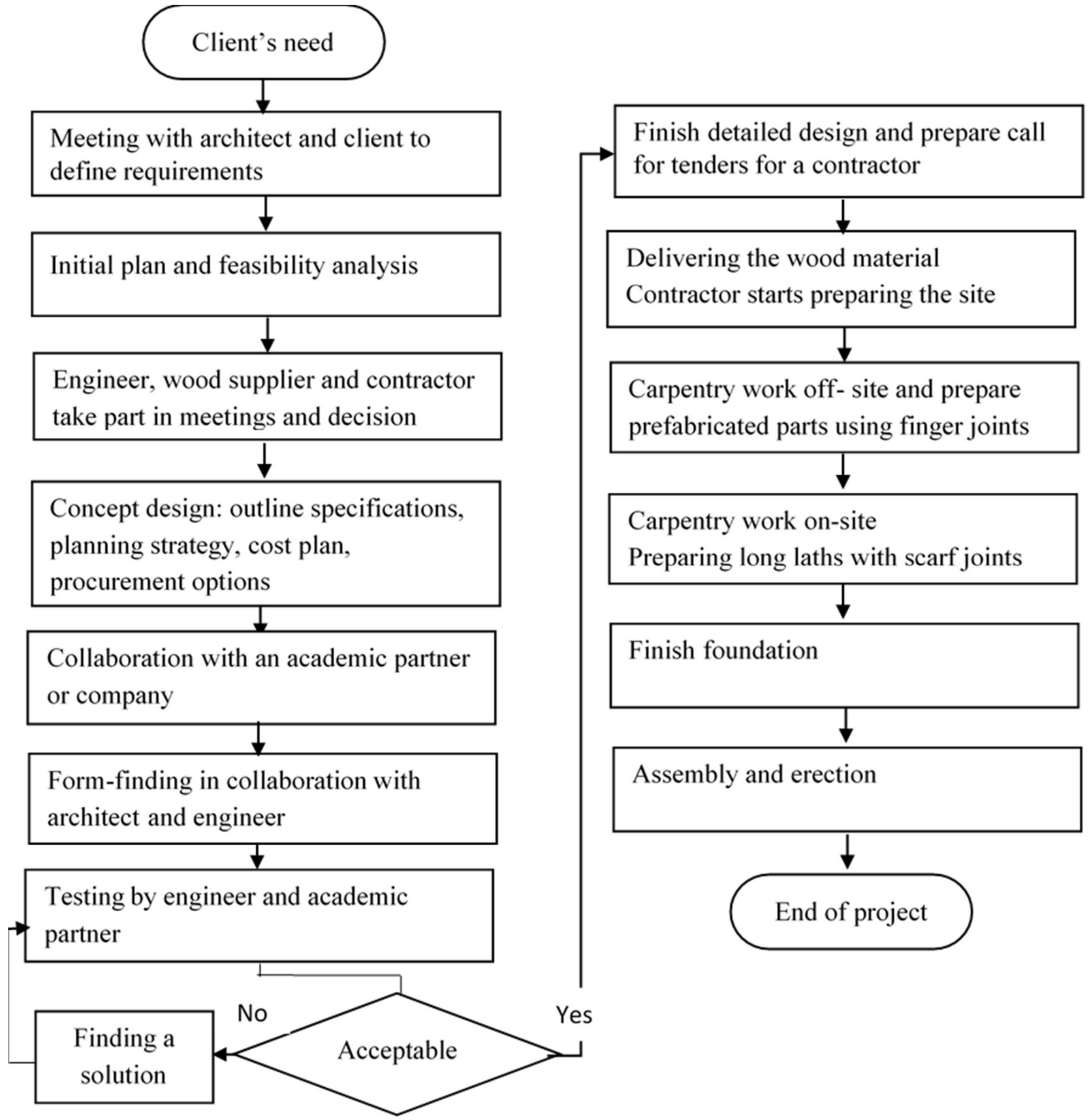


Figure 15. Production phases and partners involved for building a large and complex gridshell

3.5.2 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 centres, office buildings, and service firms), and institutional buildings (*e.g.*, schools, hospitals, homes for the elderly). 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.

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, organisation, 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.

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 emphasised. On the other hand, the fact that gridshell is not widely recognised 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 16 summarises the SWOT analysis for the gridshell building design.

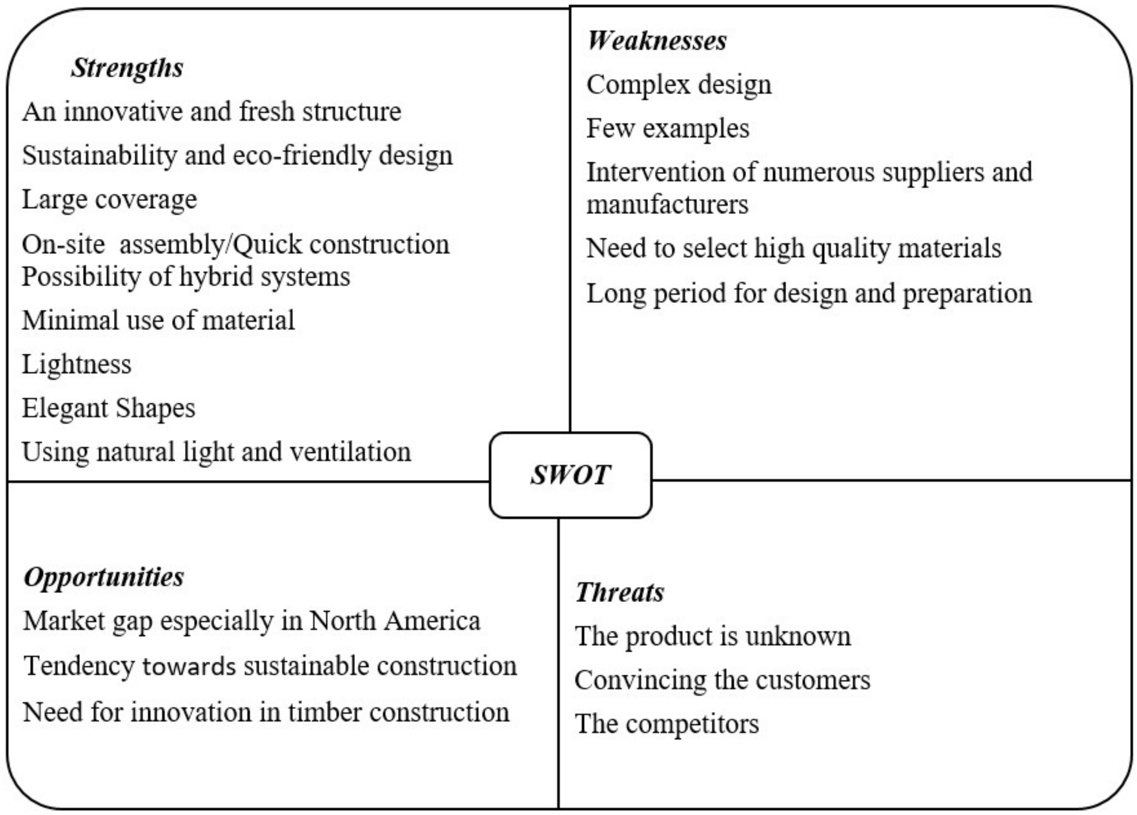


Figure 16. SWOT analysis of gridshell as an innovative structure

3.5.3. Market Segments

After the SWOT analysis and the introductions of motives for building gridshells, market opportunities are now discussed. Table 7 summarises 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 7. 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 Centres 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 centres Museums Landmarks Exhibitions Libraries Monuments	Savill Garden visitor centre 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 centres, swimming pools, and dance halls are places for which gridshell architecture is a suitable alternative. Additionally, Table 8 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 8. 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

3.6 Summary and Conclusion

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-span, lightweight construction, reasonable costs, and environmentally sustainable character, tend to favour 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 categorised 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 centres. 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 recognised. 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.

Chapter 4. Using Lean Techniques and Simulation to Improve the Efficiency of Engineered Wood Production: a Case Study in a small factory

This chapter is earmarked to the article entitled "*Using Lean Techniques and Simulation to Improve the Efficiency of Engineered Wood Production: a Case Study in a small factory*". It was published in the *International Journal of Industrial Engineering and Management*, 2018.

Résumé

Objectif: La fabrication de constructions modulaires a été reconnue comme une solution efficace pour améliorer la normalisation et accroître l'efficacité dans le secteur de la construction. La production de bois d'ingénierie pour des projets de construction peut être considérée comme un type de fabrication de construction modulaire. Le système de fabrication produits de bois d'ingénierie spécifique à la conception contient des processus de production reproductibles, tandis que chaque projet contient sa conception et ses spécifications uniques. Le bois lamellé-collé (lamellé-collé) est un type de produit de bois d'ingénierie qui s'applique à la construction en tant que produit respectueux de l'environnement. La production de lamellé-collé en forme courbe a généralement un temps de production significatif. Ce document examine les améliorations à apporter à la production de lamellé-collé en recherchant les sources de déchets dans les processus de production.

Conception / méthodologie / approche: Un modèle de simulation est d'abord créé pour reproduire la production de bois lamellé-collé telle qu'observée dans une petite et moyenne entreprise (PME) de la province de Québec. Les sources de déchets sont identifiées, des améliorations de type Lean sont suggérées et les solutions testées dans le modèle de simulation.

Résultats et originalité / valeur: Les résultats démontrent des améliorations du temps de cycle et du temps d'attente. Étant donné que l'élimination complète des gaspillages peut être coûteuse et difficile pour une PME lorsqu'elle commence à mettre en œuvre des techniques Lean, l'impact d'une diminution de à 50% des activités sans valeur ajoutée est comparé à une élimination à 100%.

Mots-clés: Lean, simulation, temps de cycle, industrie de la construction, production de bois d'ingénierie

Abstract

Purpose: Modular construction manufacturing (MCM) has been recognised as an efficient solution to improve standardisation and increase efficiency in the construction industry. Production of engineered wood for construction projects may be considered as a type of MCM. The production system of design-specific engineered wood contains some repeatable production processes while each project contains its unique design and specifications. Glued laminated timber (glulam) is a type of engineered wood product which is applicable to construction as an environment-friendly product. Production of curved glulam generally has longer production time than the straight glulam beam. This paper considers improvements in the production of glulam by investigating the sources of waste in the production processes.
Design/methodology/approach: A simulation model is built for glulam production and validated with a case-study for a gridshell project in a small and medium-sized enterprise (SME). Sources of waste are identified, lean methods are suggested for improvement and lean solutions are tested in the simulation model.
Findings and Originality/Value: The results demonstrate improvements in cycle time and wait time. Since complete elimination of waste may be costly and difficult for an SME when beginning to implement lean techniques, the impact of applying only a 50% decrease of non-value adding activities is compared with 100% elimination.

Keywords: Lean approach, simulation, cycle time, construction industry, engineered wood production

4.1 Introduction

Lean manufacturing techniques gained great attention when the International Motor Vehicle Program (IMVP) at the Massachusetts Institute of Technology (MIT) published its findings in 1988 (Womack and Jones 1996). Since then, lean theory has been adopted widely in manufacturing industries (Tokola *et al.* 2015). Following manufacturers, the construction industry also implemented and adopted lean concepts to reduce waste and increase efficiency (Farrar *et al.* 2004; Nikakhtar *et al*. 2015; Abbasian-Hosseini *et al.* 2014). However, productivity in the construction industry has improved more slowly than in the manufacturing sector. According to the McKinsey Global Institute report (McKinsey Global Institute 2017), global labour-productivity in construction has grown by only one percent per year over the past two decades, in contrast to a growth of 2.8 percent for the worldwide economy and 3.6 percent in manufacturing. The report suggests that a drastic increase in productivity would be possible if construction was to tend towards a manufacturing-like system with a much higher degree of standardisation and modularisation and a greater share of off-site production instead of on-site construction.

In this regard, making improvements in the production of prefabricated parts such as engineered wood could help increase efficiency in the construction industry. Prefabricated engineered wood products can be used in residential and non-residential construction projects. They can also be used for many types of structures because of their physical properties and aesthetic appearance (Opacic *et al.* 2018). Structural glulam is one of the oldest engineered wood products and is still very competitive in modern construction. Glulam is fabricated from wood boards which are glued together, and they form a beam cross-section of the desired shape (Malo and Angst 2008).

This paper focuses on the glulam manufacturing process and investigates how lean concepts could improve its production efficiency. For this purpose, a simulation model of the glulam manufacturing process was developed, in order to analyze the system, identify possible improvements based on lean concepts, and test different improvement scenarios. More precisely, a general simulation model for the prefabrication of glulam components was first built, based on the production process of a small and medium-sized enterprise

(SME) active in the architectural design of buildings, the production of glulam components, and on-site installations. The model was next adapted to simulate the production of curved glulam components required for a gridshell structure project. Then the seven sources of waste in the production process were analyzed and prioritised, according to lean principles. Elimination of three of the more significant sources were targeted (non-value adding activities, transportation, and defects). Lean tools such as single minute exchange of dies (SMED), U-shaped layout, total productive maintenance (TPM), and design for manufacturing and assembly (DFMA) were suggested as improvements and tested with the simulation. Lean solutions were considered both at the ideal level and at a more feasible level. The impact of completely eliminating non-value adding (NVA) activities (100%) versus partial reduction (50%) was analyzed and compared.

Previous studies which followed a simulation methodology were applied to a variety of production systems, however, to our knowledge, glulam production has not been considered in this type of study. The primary contribution of this research is providing a simulation model for glulam production in SMEs which can be adapted to different cases. Simulation results provide a decision-making tool for the managers who can preview the impacts of the proposed changes. Developing a step by step approach that starts from feasible and less expensive improvements could motivate the managers to implement a lean approach. Another contribution concerns the identification and prioritisation of sources of waste in the production of prefabricated parts for construction, considering the specific characteristics of this system.

In the following sections, a literature review encompassing lean concepts and the simulation approach is presented. The methodology is then described, and a simulation model of glulam production is introduced. Subsequently, the case study and the adopted model are described. The results and a discussion are finally presented, followed by managerial insights and conclusions.

4.2 Literature review

Lean manufacturing practices aim to reduce all forms of waste and inefficiency from production flow towards achieving efficient and flexible systems (Womack and Jones 1996). Implementation of lean techniques in the construction industry, which is called lean construction, did not grow as quickly as lean manufacturing. The reason being that construction is done on-site and that each project is constructed in a different location (Solomon 2004). Koskela (1992) states that lean construction shares the goals of lean production: elimination of waste, cycle time reduction, and variability reduction. One of the top priorities in the lean approach is the elimination of waste and the activities which consume the time of workers and other resources, without generating value for the final product. These kinds of activities are called non-value adding (NVA) activities in terms of the lean thinking theory (Nikakhtar *et al.* 2015). Taylor *et al.* (2013) provided a taxonomy of the different aspects of lean and the tools applied in the industry such as TPM, set up time reduction and kaizen.

Computer simulation provides an excellent environment to implement the principles of lean production (AbouRizk 2010; Abedi Saidabad and Taghizadeh 2015). Computer simulation is defined as the process of making a mathematically and logically explained model of a real-world system (Farrar *et al.* 2004). Simulation can be used for analyzing dynamic systems even where there is uncertainty, and the initial model can be used to test different scenarios for improvement.

The literature contains research on using simulation for implementing lean in a variety of sectors and industries. Although most of the cases are in mass production and large-sized companies, some research shows how the lean approach can be applied in SMEs (Mahfouz *et al.* 2011; Faisal 2016), job-shops (Li 2003) or in the process industry (Abdulmalek and Rajgopal 2007). Chen *et al*. (2010) studied implementation of a lean system in a small manufacturing company. They identified the production processes and created a current value stream map as well as a future map which served as a goal for future lean activities. They used the 5 whys method to identify the root cause for major bottlenecks and suggested kaizen events to improve the efficiency. Mahfouz *et al.* (2011) developed a simulation-based optimisation model to improve lean parameters in a packaging manufacturing SME. They measured three key performance factors: cycle time, WIP (work in process), and workforce utilisation, after applying lean tools such as facility layout and preventive maintenance.

Faisal (2016) examined the implementation of lean manufacturing using value stream mapping (VSM) for SMEs in the leather industry. Implementing the pull system showed improvements in the average throughput and decrease in WIP. Li (2003) carried out a simulation experiment to compare the effects of applying the just-in-time concept to the performances of push and pull systems. Abdulmalek and Rajgopal (2007) adapted lean principles for the process sector using VSM and built a simulation model to illustrate potential benefits of reducing lead-time and WIP. They followed lean methods such as the pull system, setup reduction, and total productive maintenance (TPM).

Parthanadee and Buddhakulsomsiri (2014) used VSM and simulation to improve the efficiency of the batch production system commonly found in SMEs. VSM was used to identify the problems and find solutions, and simulation was used to analyze the result of applying improvement suggestions. Schmidtke *et al.* (2014) proposed an enhanced VSM method combined with simulation for complex production systems and applied it to the case of exhaust gas purification catalysts production. Abedi Saidabad and Taghizadeh (2015) evaluated the function of production lines through computer simulation and made improvements using production line principles such as concurrency of the operations and the least distance. The results showed improvements in waiting time, cycle time, and efficiency for a case study in an iron foundry.

Tokola *et al.* (2015) studied lean manufacturing methods and how simulation is used to consider them. They analyzed 24 articles which addressed lean and manufacturing together. Of these, 46% used VSM to analyze the system and extract NVA activities. Kanban (38%), layout (29%), pull (25%), and WIP (25%) were the other main tools applied. The effects of takt time (21%) and SMED (17%) seemed easy to model as well. Reductions in WIP, lead time, labour, and floor space were frequent results in the simulations. Nagi *et al.* (2017) used a pull simulation model in a multiproduct assembly line. They applied line balancing and work-in-process controlling while developing a design of experiments (DOE) method to be tested by the simulation model. The result showed 14% improvement in throughput rate. Zarrin and Azadeh (2017) simulated a manufacturing organisation with maintenance strategy to evaluate the impact of resilience engineering principles on lean practices. The results showed that redundancy among the resilience engineering principles has the most impact on system performance.

As for lean construction, Farrar *et al.* (2004) presented a systematic approach for the application of lean theory in computer simulation models and implemented it for a case of road construction. The improvements in hourly production rate, resource utilisation, and project duration resulted through the elimination of NVA activities and from the implementation of a methodology of pulling material through the process. Nikakhtar *et al.* (2015) demonstrated improvements in cycle time and process efficiency by using multi-skilled teams and sensitivity analysis with simulation for the concrete pouring process. Abbasian-Hosseini *et al.* (2014) applied lean and simulation to determine the best combination of resources in a case study for the bricklaying process. Identifying NVA activities and following lean methods such as just-in-time (JIT) and the use of a pull system led to a 40% improvement in productivity.

Yu *et al.* (2013) and Moghadam *et al*. (2012b) worked on applying simulation for lean based improvements in manufacturing for modular construction. Ritter *et al.* (2017) mentioned that considerable effort is needed for production line flow balancing because of a large amount of variation and customisation in the home construction industry. They used simulation to evaluate the state of production in a case study and analyzed the result of improvements such as labour reallocation which showed an increase in production rate. In a recent research, Opacic *et al.* (2018) simulated an engineered wood production system using AnyLogic software. They analyzed the system and tested scenarios of different combinations of workers to improve the production processes based on system analysis. The studied mill produces engineered wood products as a final product and sells it to the customers.

Identifying the seven sources of waste and finding solutions to eliminate them are the main elements considered when implementing lean manufacturing. However, the priority and importance of the sources of waste, and how to eliminate them, are different based on the nature of each industry. Therefore, the seven sources of waste specifically related to the production of prefabricated parts for construction are described in this paper. It investigates, through simulation, the implementation of lean concepts for the production of prefabricated parts for construction which shares the characteristics of both manufacturing and construction industries.

4.3 Methodology and simulation model

With the aim of investigating the impact of implementing the lean approach in the production process for prefabricated glulam components by using the simulation of a case study, this research follows a methodology comparable to the other studies that use a combination of simulation and lean concept implementation. The first and second steps included data gathering and analyzing the glulam production process. A general simulation model was next built based on this production system. It was developed step by step to ensure its verification process. The general model was then adapted for a case study involving the production of glulam components for a gridshell construction project in an SME. Validation of the model was tested by looking at the results with the expert employees from the SME and via a statistical hypothesis test. After ensuring the validation, seven sources of waste in the production process were identified and solutions based on the lean approach were suggested. The suggestions (eliminating NVA activities, transportation and defects) were then tested as distinct scenarios to compare the results. Elimination of NVA activities (over-processing) was implemented in scenario 1, while partial elimination of NVA activities was tested with scenario 2. The results regarding the cycle time and the wait time were analyzed and compared in as-is, scenario 1, and scenario 2. Elimination of transportation and defects were tested respectively in scenario 3 and scenario 4. In the next step, all improvements were applied to analyze the result of implementing several lean tools simultaneously. Scenario 5 was created to combine complete elimination of NVA activities, elimination of transportation, and elimination of defects simultaneously. As well, scenario 6 was created, mixing partial elimination of NVA activities, elimination of transportation, and elimination of defects. The results of the as-is simulation model with scenario 5 and scenario 6 were analyzed and compared. Then, conclusions and managerial insights were extracted, and the results were presented to the company's manager. Figure 17 summarises the steps of the research methodology.

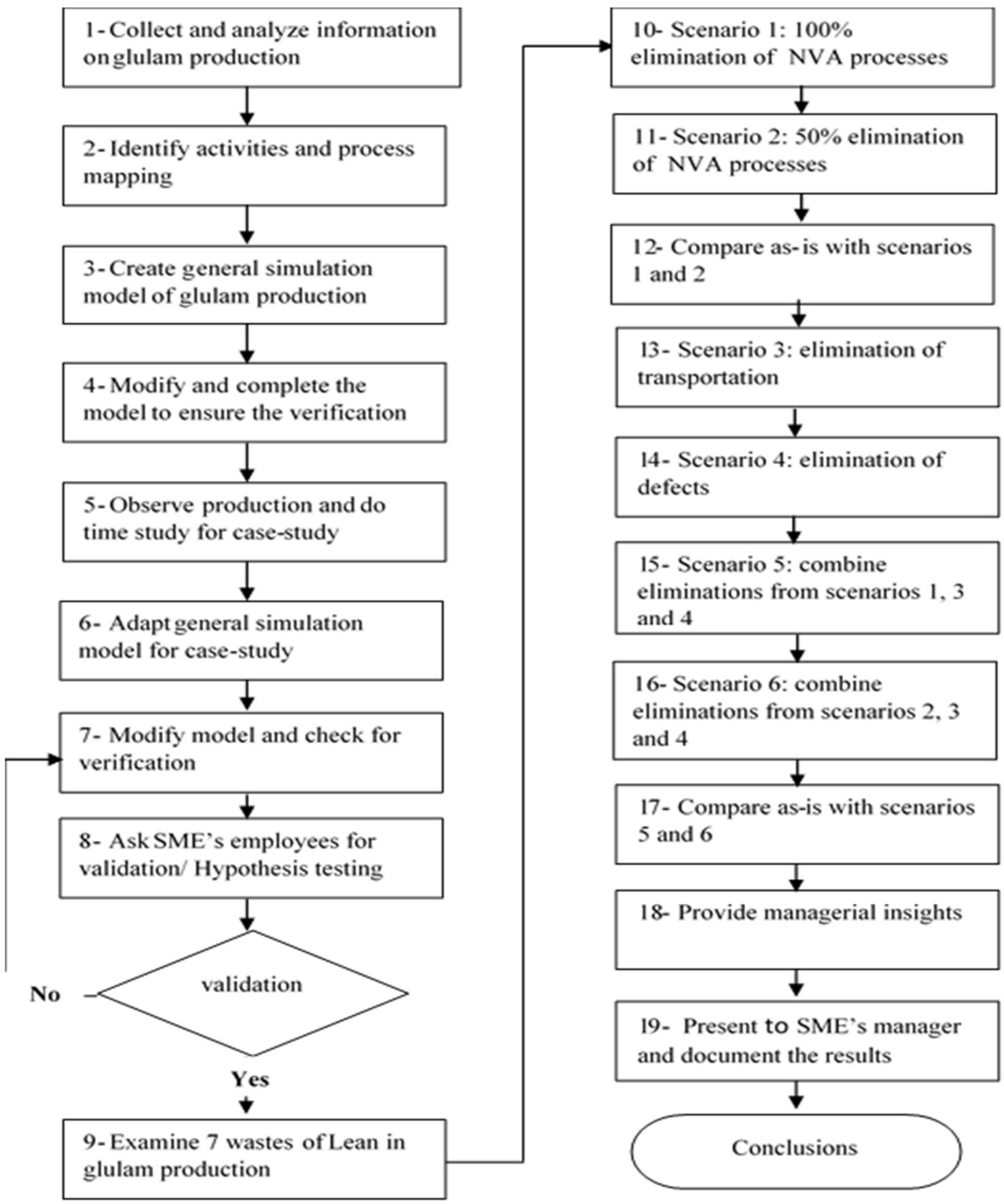


Figure 17. Research methodology

4.3.1 *Creation of the simulation model for glulam production*

To create the simulation model, the general production process of glulam was extracted from the literature and data was gathered from an SME in the Province of Quebec, Canada. A typical glulam manufacturing process consists of lumber drying (when purchasing green lumber), grading, trimming, finger jointing or end jointing, planing, face bonding, finishing, and fabrication (Puettmann and Wilson 2005). Since most suppliers provide dried wood, there is usually no need for drying in small factories. Purchased laths of wood are inspected to check for the humidity level, elasticity, visual defects, and knots. According to the quality level, wood layers are graded in different categories such as B, C, and D, where B is the best quality level. One of the advantages of glulam is the possibility of combining the lower qualities of lumber with the higher quality ones. The method consists of placing high-quality laminations on the outer parts of the cross-section where stresses are highest normally, and lower quality laminations in the inner zones to make combined glulam (Malo and Angst 2008). Figure 18 illustrates typical production processes for glulam.

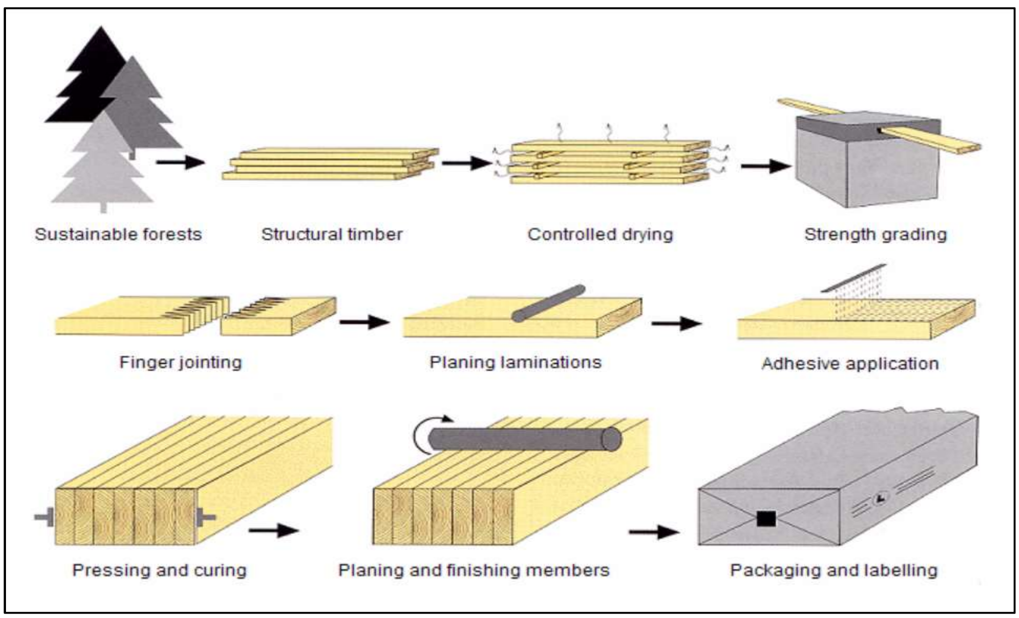


Figure 18. Sketch of the manufacturing process (Malo and Angst 2008, reproduced in www.glulambeams.co.uk)

The simulation model was developed in Arena 15. Basic and advanced process modules in ARENA such as process, decide, batch, separate, assign, and hold were implemented to model the glulam production processes. The process time of most of the process modules followed a triangular distribution. The triangular distribution is commonly used in situations in which the exact form of the distribution is not known, but estimates of the minimum, maximum, and most likely values are available (Kelton *et al.* 2009). Process time of pressing was assumed as a constant distribution based on the pressing and curing time needed. In the simulation model, the arrival of raw material was simulated based on the daily work schedule in the SME. Arriving wood is the main entity and the dimensions and degrees were assigned to it using an assign module. The batch module was used to make a glulam beam obtained by gluing layers together. Read and write modules were used to read the information concerning the size and number of layers for each beam. Advanced transfer modules in ARENA such as station and transport were applied to simulate the transportation of material and distances between the stations. In the production process, adhesives such as glue have to be added to the wood laths to make a finger joint. Laths are next planed to obtain a smooth surface and then glued and pressed together to make a beam. The beam must finally be planed as well. In the simulation model, planing of the laths after drying process is named planing 1 and planing of the beams after the press is named planing 2. Figure 19 illustrates the main processes and modules of the simulation model.

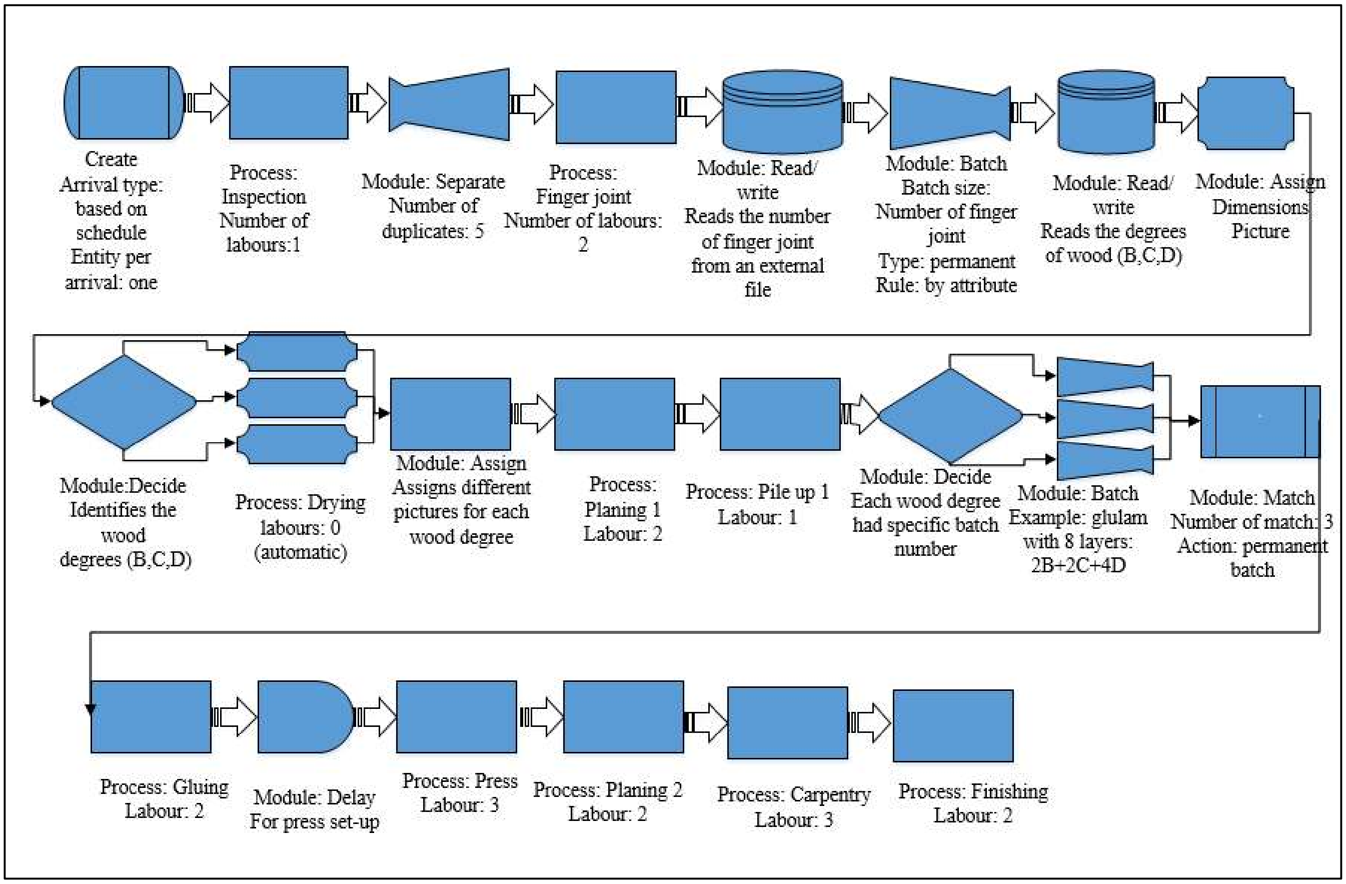


Figure 19. The main processes and modules in the simulation model for glulam production

4.3.2 Verification of the model

Model verification can be briefly described as building the model correctly. In order to avoid errors and problems, it is important to start with a simpler model and improve it gradually. This means breaking up the complete model into a simpler and smaller model and then adding more details to it, which is easier to debug. In programming, this method is called the divide-and-conquer approach. In each step, the model is run, and errors and syntaxes are checked, then more details are added in the next step (Chung 2004). After building the model, some tools and modules were used to visualise and check how the model works. These tools include using different entity pictures for different types of entities, following entities, changing entity pictures, changing resource pictures, displaying values and plots, and writing to an output file.

4.4. Case study

4.4.1 Adapting the simulation model to reflect the case study

The production of glulam for a particular construction project was observed and, based on the data gathered, the simulation model was modified to better reflect this reality. The construction project was a gridshell structure and all components were curved beams. Timber gridshells are free-formed structures which are defined as structures "with the shape and strength of a shell but made of a grid instead of a solid surface" (Douthe *et al*. 2006).

The SME responsible for producing this type of structure encompasses about thirty employees and one glulam production line. Three different shapes of glulam are manufactured in this factory: straight beams, round beams, and curved beams (arcs). Production processes for straight and curved glulam beams are the same. The difference comes from the set-up time for the press machine. For the straight beams, once the press machine is set, the same set-up can be used for all beams. While for the curved beams, the set-up must be changed for different radiuses. This difference makes the production of curved glulam more complicated and longer than straight beams.

The glulam production method in this factory is generally comparable to the standard glulam production process. However, there are differences based on the type of machinery, the level of optimisation, and the capacity of the factory. As a result, the production of a gridshell structure was investigated and process times extracted. Based on the available data, the simulated process times were defined as distributions, listed in Table 9.

Table 9. Process distribution parameters of glulam production

Process	Distribution	Distribution parameters (minutes)
Inspection	Triangular	a= 22, m= 25, b= 28 (a: min, m: mode, b : max)
Finger joint	Triangular	a= 1.1, m=1.5, b= 2
Drying	Triangular	a= 12, m=13, b= 14
Planing 1	Triangular	a= 5, m=6, b= 7
Pile up	Triangular	a= 12, m= 15, b= 18
Gluing	Triangular	a= 30, m=35, b= 40
Cold Press	Constant	Value : 150

Planing 2	Triangular	a= 21, m=24, b= 27
Carpentry 1	Triangular	a= 120, m=126, b= 132
Carpentry 2	Triangular	a= 120, m=126, b= 132
Carpentry 3	Triangular	a= 120, m=126, b= 132
Finishing1	Triangular	a= 36, m=41, b= 46
Finishing2	Triangular	a= 36, m=41, b= 46

Information from the factory such as machinery and human resources needed for each process, distances between stations, the failure rate of the equipment, and working time schedule, etc. were also added to the model. The same divide-and-conquer approach was applied to ensure the verification of the model. Figure 20 shows a screenshot picture of the simulation model for a gridshell project.

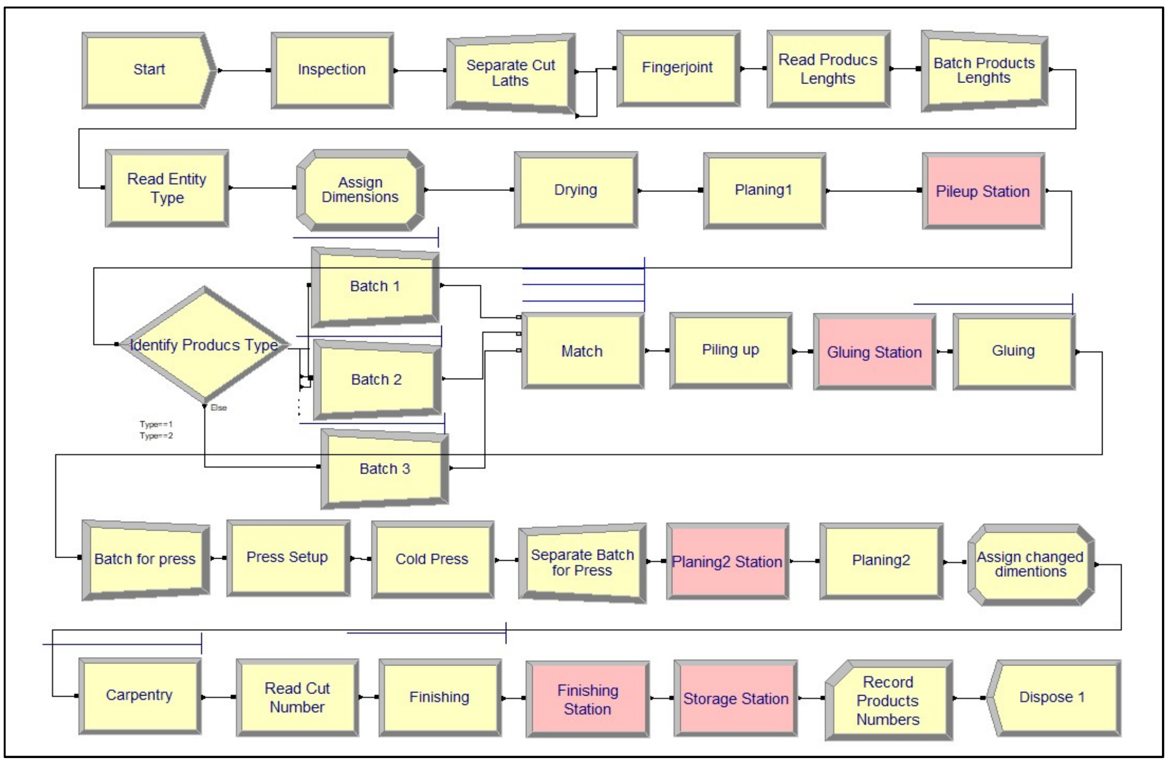


Figure 20. Simulation model of curved glulam production for a gridshell project in an SME

4.4.2 Validation of the model

Because of the random nature of a simulation model, a single run of the model is not sufficient (Kelton *et al.* 2009). Kelton *et al.* (2009) suggests running the model with an initial number of runs and to then verify if the confidence interval is acceptable. Based on Kelton *et al.*'s work, a formula was used by researchers such as Nikakhtar *et al.* (2015) and

Toledo *et al.* (2003) to identify the adequate number of runs. The formula is: $N(m) = \left[\frac{s(m)t_{m-1,1-\alpha/2}}{\bar{X}(m)\varepsilon}\right]^2$, where N(m) is the required number of simulation runs, m is the chosen number of replications, $\bar{X}$(m) is the sample mean from m replications and is the estimate of the real mean μ, S(m) is the standard deviation from m simulation runs, α is the level of significance (considered 95%), ε is an allowance for error. And $t_{m-1,1-\alpha/2}$ is the upper $1-\alpha/2$ critical point from the Student's t distribution with m-1 degrees of freedom. The initial 10 number of runs were tested and the mean and standard deviation for the production time was calculated. The results showed: $\bar{X}(10)$ = 178 and S(10) = 11.09. Based on the previous formula and considering 95% level of confidence, $t_{9,0.025}$= 2.262 and ε= 0.05, the number of runs should be more than 8 to obtain reliable results. Therefore, 10 runs is considered as sufficient for the simulation iterations.

One of the validation methods is comparing the simulation model output behaviour to the system output behaviour (Sargent 2013). The results were observed, and the average cycle time was compared with the cycle time for the real gridshell project. The comparison is shown in Table 10 (times are in hours).

Table 10. Comparing simulation time with real cycle time

Process	Real cycle time	Simulated cycle time	Difference
Production	168	178	5.95%
Carpentry	168.5	157.44	6.5%

To confirm the validity of the model, face validity was considered by asking knowledgeable individuals who know the system (Sargent 2013). The simulation model was presented to the employees from the factory and they confirmed that it represented the real operations faithfully. Moreover, a statistical test was used to ensure validity. A hypothesis test for the mean of the normal distribution with unknown variance was applied by using the student's t-test. The average project duration for 10 replications was 178 hours with a standard deviation of 14.28 hours. The hypotheses for this test were $H_0: \bar{X} = \mu = 168\ hours$ and $H_1: \bar{X} \neq \mu$. The significance level α=0.05 and the number of replications n=10. With the student distribution, $t_{\left(1-\frac{\alpha}{2};n-1\right)} = t_{(0.025;9)} = 2.262$. The statistical value

$t_0 = \frac{\bar{X}-\mu_0}{S/\sqrt{n}} = \frac{178-1}{14.28/\sqrt{10}} = 2.21.$ $|t_0| = 2.21 \ngtr |t| = 2.262$, then H_0 could not be rejected and the model was accepted as being valid.

4.5. Results

One of the top priorities in the lean approach is the elimination of waste. Seven types of waste are defined by lean thinking: overproduction, unnecessary inventory, unnecessary motion, waiting, inappropriate processing, excessive transportation, and defects (Nikakhtar *et al*. 2015). In the following subsections (5.1 to 5.7), the sources of these seven wastes were extracted from the case study. Lean methods were proposed to reduce three of these wastes, including NVA processes, transportation, and defects, while the impacts of these methods were analyzed using simulation.

4.5.1 Overproduction

Overproduction is not a major problem in this industry since production is always based on the customer's request.

4.5.2 Inventory

Storage of raw material, final or intermediate products in the production line, slows down the production. Generally, in glulam production, process time varies in different stations. Since a certain number of layers must be prepared and then glued together, some storage is inevitable. Production levelling should be considered which is not within the scope of this research. In this study, the focus was on reducing waiting time of materials in the workstations which lead to reducing storage. A detailed explanation is provided in the next sections.

4.5.3 Motion

Motion encompasses excessive movements of operators to use the tools and work with the machinery or to follow production processes. In this case-study, unorganised workplaces and lack of standard work charts were an important source of motion. 5S, visual control, optimisation of space, and standardised work charts at each workstation are lean methods that could reduce this motion.

4.5.4 Waiting

In this case, waiting does not add value to the product. Therefore, wait time is considered as a performance factor which should be reduced.

4.5.5 Over-processing (NVA activities)

Overprocessing refers to the activities which do not add value to the product. In this case, inspection and the set-up time for the press were sources of waiting. Pile-up of laths was another process that did not add value to the product. These three processes and the suggestion to eliminate them are discussed in the following.

Inspection

In this case study, one operator is assigned to the inspection process and does most of the work by visual inspection using a Mechanical Timber Grader (MTG). Reducing the inspection time to a minimum would reduce costs and delays as well as the risk of stopping the production line because the wood is waiting for inspection. There are three possibilities to reduce the inspection time:

- Purchasing an automatic wood scanner which costs between $400,000 and $800,000 (X-Ray model);
- Recruitment of another operator;
- Getting help from the current production staff.

The price of the inspection machine is not currently affordable for the company, therefore the feasible solution would be to increase the human resources. To investigate this change, the inspection module was first removed and the process eliminated in scenario 1. In scenario 2, the inspection time was reduced by 50% by adding another worker.

Press set-up

Another activity that needs to be reduced as much as possible is the press set-up time. The set-up process takes 4 hours each time the machine is used to produce curved beams. For the gridshell project, using only curved beams, set-up time is significant. According to lean production, the set-up time should be less than 10 minutes (Delago *et al.* 2016), using the Single Minute Exchange of Die (SMED) method. This objective is not possible for the factory, however, the following steps are suggested to reduce the set-up time from 4 hours to 2 hours:

1. Maximise the set-up activities that can be done while the press machine is working (external elements);
2. Simplify and streamline all elements;
3. Standardise procedures for the workers to follow and limit wasted time;
4. Create auxiliary tools and equipment to make the set-up quicker.

The suggested steps can be implemented by analyzing the use of the press machine in collaboration with the machine's manufacturer. In scenario 1, the delay module which simulates the set-up time was removed so as to analyze the result of eliminating set-up time. In scenario 2 the delay was reduced to 2 hours which represents a 50% reduction in set-up time.

Pile-up

In the production process, there is a station before gluing of the beam where the laths are piled up and an operator decides which combination of wood layers should be glued together. For example, to produce a 5 layer glulam beam, the two top layers must be of grade B, grade C is acceptable for the central layer, and the two bottom layers should be grade B. This process is required because the laths are produced by batches of quality degree instead of based on the glulam beam's needs. This process can be omitted and the operator will be freed if laths are produced using a daily plan based on glulam production needs. As with the two previous NVA activities, in scenario 1, the pile-up process was removed and the operator was freed. In scenario 2, the pile-up station was kept while the time was reduced by 50%.

The results of eliminating NVA activities

The lean approach aims to have a system with zero NVA activities and waste. Simulating the proposed methods to eliminate inspection, set-up, and pile up, showed that the cycle time could be reduced from 178 hours to 135 hours which is an improvement of 24 %. Wait time would be reduced from 202 hours to 162 hours, a 20 % improvement. The result shows noticeable improvements for this one project which suggests more improvements in the long term.

However, it is important to find feasible solutions that respect the real factory's situation. In most cases, inspection is assumed to be a NVA activity (Nikakhtar *et al*. 2015). In the production of engineered wood, inspection is an important process to ensure quality restrictions. Moreover, checking for knots and grading is part of the production process and cannot be eliminated.

Hence, instead of eliminating NVA activities completely, the factory in this case study thought it more realistic to aim for reducing inspection and set-up times by 50% instead of 100 %. In the second scenario, NVA activities were not completely eliminated and their times were rather reduced by 50% to examine the results. The simulated results show that cycle time was reduced from 178 hours to 146 hours (18% improvement instead of 24%) while wait time was reduced from 202 hours to 176 hours (13% improvement instead of 20%). Figure 21 illustrates the results and comparison between as-is, complete NVA elimination (scenario 1), and partial NVA elimination (scenario 2) for cycle time and waiting time.

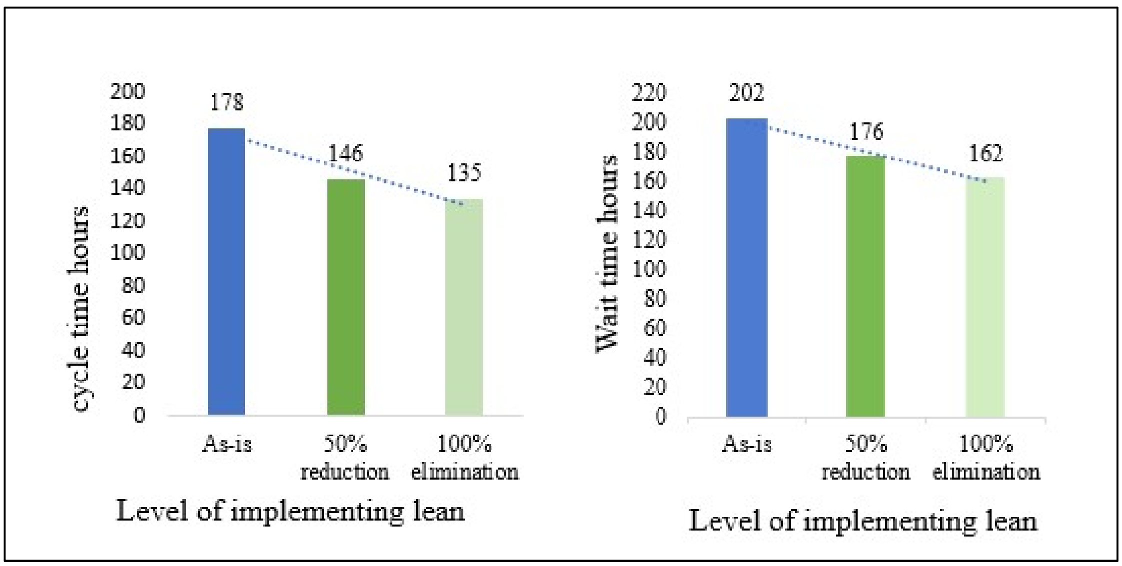


Figure 21. Comparing the effect of eliminating NVA processes on cycle time (left) and wait time (right)

4.5.6 Transportation

As shown in the factory layout in Figure 22, the production flow is not efficient. There is significant unnecessary transportation from the pile-up station to gluing, from the cold press to the planing 2 station, and from the finishing station to the exit door. Eliminating the pile-up process and changing the layout to make a U-shaped production line would improve the production flow. Figure 23 illustrates the suggested layout.

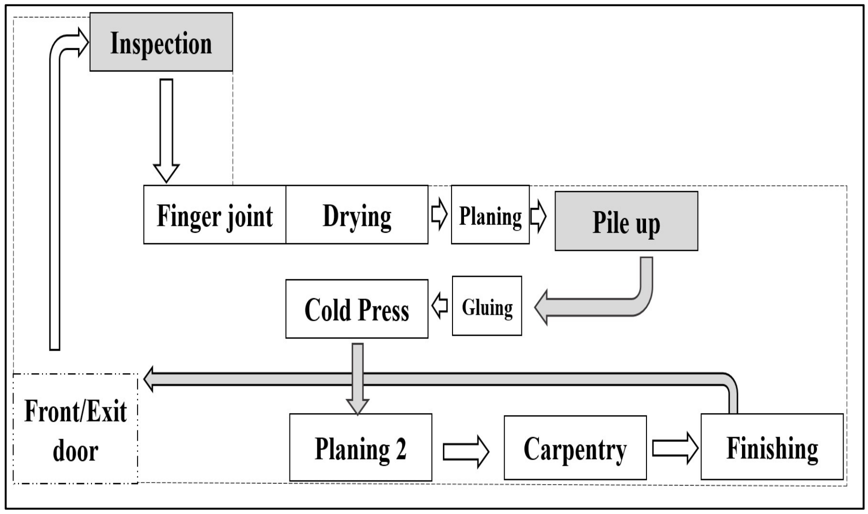


Figure 22. Current factory layout with unnecessary transportation

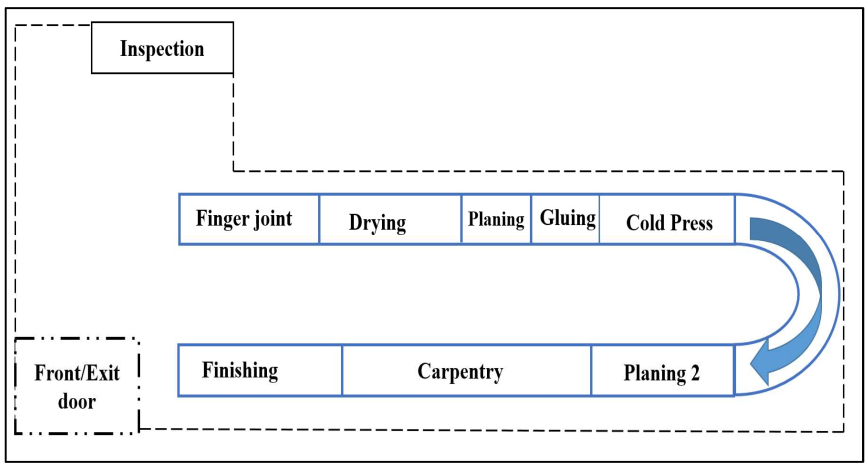


Figure 23. Suggested U-shaped layout

To ensure the feasibility of changing the layout, dimensions of the machinery and factory were measured and the accessibility to electricity was examined based on the layout plan. The proposed layout was furthermore validated with the experts in the factory. Then the U-shaped layout was applied in scenario 3 by changing the station modules and their distances and sequences. The results show that the cycle time was reduced from 178 hours to 176 hours which is not a noticeable improvement (1.12%). However, the wait time was reduced from 202 hours to 62 hours (69.53%) which is significant. Reduction in wait time results in a smoother flow of material in the production line. This change could lead to improvements in cycle time in the future.

4.5.7 Defects (failure and rework)

The last category of waste which is considered in this study relates to defects. Two sources of defects are machinery failure and rework.

Failure

Based on the observations and operators' information, the simulation model represents the failure rate of machinery with a triangular distribution. In the factory, the sudden breakdown of machinery occurs, however, the rate of failure has not been documented. The first step of improvement would be to document failure occurrences and hold regular meetings to analyze the reasons. The second step would be to implement the Total Productive Maintenance (TPM) method. According to Abdulmalek and Rajgopal (2007), TPM involves:

- Constantly monitoring machinery breakdown and finding the failure rate;
- Discussions to find the source of the problems;
- Autonomous maintenance;
- Safety and environment management;
- Planned maintenance instead of condition-based maintenance.

According to the factory's work schedule, Tuesday to Friday the press machine is loaded with the layers of laths which were produced the day before. However, since the factory is closed on weekends and planed laths cannot be kept more than 24 hours, the press is idle on Monday morning while laths are being produced. Therefore, Monday morning is an appropriate time for preventive maintenance of the press. For the other equipment, lunchtime is suggested. The proposed times for preventive maintenance is presented in Table 11.

Table 11. Proposed preventive maintenance schedule

Machinery	Maintenance		Maintenance schedule	
	Uptime (days)	Downtime (minutes)		
Finger joint	7	60	Tuesday:	12h-13h
Drying	7	60	Wednesday:	12h-13h
Planing 1	7	60	Thursday:	12h-13h
Planing 2	7	60	Friday:	12h-13h
Press	7	120	Monday:	8h-10h

In the simulation model, equipment failure was defined with a triangular distribution and assigned to each machine. For example, for the press machine, failure rate was TRIA (80, 90, 100) with three hours of downtime. This rate means that, on average, after 90 uses, a three-hour failure occurs.

Rework

The main amount of rework for the specific project under study (gridshell structure) came from the inconsistencies in design detected at the carpentry station (second-last station). For this gridshell project, large curved glulam beams were built and then cut into smaller parts at the carpentry station. This design created waste in both material and process time. It was also the source of mistakes and rework. In all, the carpentry station realised that 20% of the products needed rework. When the company receives plans from the client's architect, the company must define the specifications for each glulam beam and provide detailed plans for production, carpentry and finishing stations. Using design for manufacturing and assembly (DFMA) methods for this process would be beneficial as they focus on improving the design phase in order to prevent errors in the final products. According to DFMA, the following steps must be considered:

- Use standard, off-the-shelf parts rather than custom components;
- Design for ease of fabrication;
- Aim for mistake-proof design;
- Design with predetermined assembly technique in mind.

The elimination of defects was applied in scenario 4 by removing the failure rate and the rework process from the model. Elimination of these wastes in the model showed that cycle time could be reduced from 178 hours to 175.7 hours which is not significant (1.23%), while the wait time was noticeably reduced from 202 hours to 89 hours (56% improvement). Lean concepts aim for the elimination of failure, however total elimination might not be feasible in this case. Nonetheless, with the simulation, this ultimate goal can be tested in order to investigate the possible gains in cycle time and wait time and encourage the company to implement TPM.

4.5.8 Summary

Table 12 summarises the sources of waste for the case study, their cause, and the lean tools proposed to reduce them. This list can be considered more generally for similar small companies that produce engineered wood for construction projects.

Table 12. Seven sources of waste and their cause

Waste	Cause	Lean tools
Overproduction	Not the main source in this case	-
Inventory	Not the main source in this case	-
Motion	Unorganised workplaces Lack of standard work charts	5S, Visual control, Standardised work charts
Waiting	Due to over-processing, transport, defects	Analysing the value stream
Over-processing (NVA processes)	Inspection	Eliminating NVA processes
	Set-up	SMED
	Pile-up	Eliminating NVA processes
Transportation	Inefficient layout	U-shaped layout
Defects	Failure	TPM
	Rework	DFMA

4.6. Discussion

4.6.1 Applying all changes simultaneously

Simulation results when reducing the three targetted sources of waste individually, all show improvements in cycle time and wait time. Scenario 5 was therefore created in order to simulate the implementation of all changes simultaneously. Scenario 5 tests complete elimination of NVA, transportation and failure. The results demonstrate 27% reduction in cycle time (from 178h to 129h) and 77% reduction in wait time (from 202h to 47h).

Additionally, the result of more realistic improvements which mean reducing the inspection and set-up times by 50% was investigated by creating scenario 6. The results show that with partial improvements of NVA, together with the elimination of transportation and defects, the cycle time still has 26% improvement (from 178h to 132h) and wait time indicates 75% improvement (from 202h to 50h). Charts in Figure 24 illustrate the comparison between partial (scenario 6) and complete (scenario 5) implementation of the lean approach. The result is interesting as there is a drastic reduction from the actual production system and partial implementation of a lean approach, while the difference between the partial and complete implementation is much smaller. This result confirms that using lean approaches to even partially reduce wastes can be profitable. For the SME, these first steps could lead to continuous improvement in order to reach higher levels of efficiency in the future. Table 13 summarises the changes and results for each scenario on cycle time and waiting time.

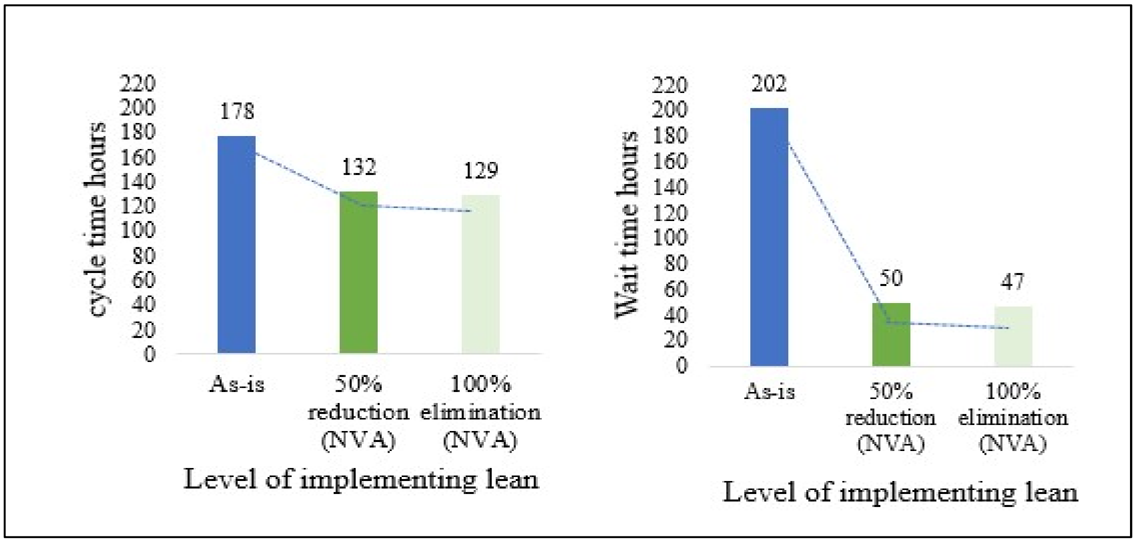


Figure 24. Comparing the effect of implementing all improvements on cycle time (left) and wait time (right)

Table 13. Summary of the scenarios and results

	Simulation Parameters						**Results**	
	Inspection time	**Set-up time**	**Pile-up time**	**Layout shape**	**Failure rate**	**Rework rate**	**Cycle time (hours)**	**Wait time (hours)**
As-is	Average 25 min	4 hours	Average 15 min	Original	3h per 90 uses	20%	178	202
Scenario 1	**0**	**0**	**0**	Original	3h per 90 uses	20%	135	162
Scenario 2	**Average 12.5 min**	**2 hours**	**Average 7.5 min**	Original	3h per 90 uses	20%	146	176
Scenario 3	Average 25 min	4 hours	Average 15 min	**U-Shape**	3h per 90 uses	20%	176	62
Scenario 4	Average 25 min	4 hours	Average 15 min	Original	**0**	**0**	175.5	89
Scenario 5	**0**	**0**	**0**	**U-Shape**	**0**	**0**	129	47
Scenario 6	**Average 12.5 min**	**2 hours**	**Average 7.5 min**	**U-Shape**	**0**	**0**	132	50

4.6.2 Managerial insights

Seven sources of waste are recognised in lean production and lean construction theory. The importance and role of these sources can vary in different industries. In the contexts of production for construction and mass customisation, production is based on the customer's order and inventory and overproduction are typically not the main issues. Therefore, the first step toward lean can focus on the reduction of NVA activities, transportation and defects. Even partial improvements could have a significant impact on efficiency. Improvements that do not require considerable investments seem more easily accepted by managers. However, complete elimination of these wastes should be taken into consideration as a long-term goal. Reduction of motion, inventory and overproduction should also be considered. After these basic steps of implementing lean concepts, and reaching a smooth production flow, other hidden problems may be revealed. Analyzing the production system and finding solutions for improvement should be repeated periodically to achieve continuous improvement as emphasised by the lean approach. The suggested steps are illustrated in Figure 25.

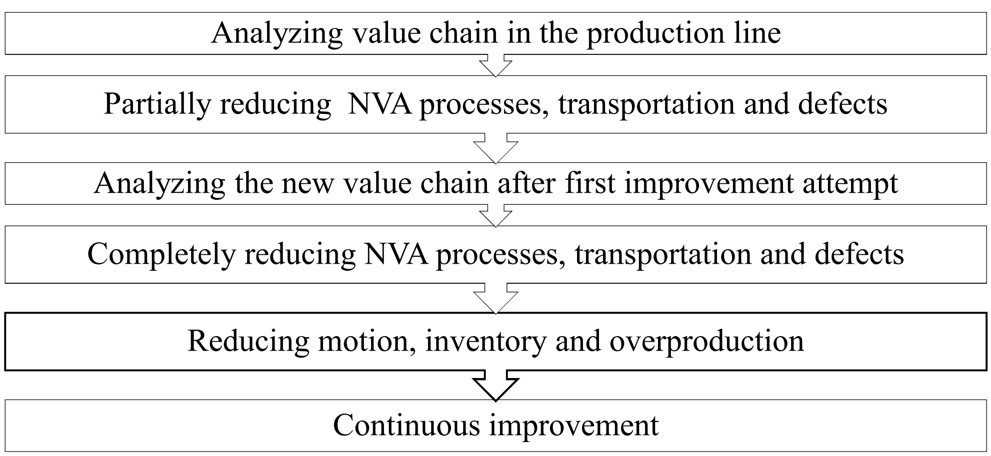


Figure 25. Steps to eliminate waste in small engineering wood production companies

4.7. Conclusion

This research considered applying the lean approach in an SME active in the architectural design of buildings and production of glulam components. Firstly, the production of glulam was simulated using Arena software. Then, the general simulation model was modified for the case-study under investigation.

The seven sources of waste were identified and improvements were suggested based on the lean approach. Three main sources of waste were highlighted as NVA activities, transportation, and defects. NVA activities include inspection, set-up and pile up. Simulating the elimination of these three activities led to a 24% improvement in cycle time and 20% improvement in wait time. However, a more feasible solution such as adding an operator to the inspection process and adapting SMED concepts resulted in a 50% decrease in inspection and set up times. This solution resulted in 18% improvement in cycle time and 13% improvement in wait time. The pile-up process could be eliminated by providing a standard action plan. Reducing transportation by changing the factory layout to a U-shaped layout gave 1.12 % improvement in cycle time and 69.53 % improvement in wait time. The machinery failure rate could be reduced by using a TPM system and rework could be eliminated with DFMA. These improvements led to a 1.23% reduction in cycle time and 56% reduction in wait time. Hence, improvement in NVA activities indicated a higher impact on cycle time, while improvement in transportation and defects showed a higher impact on wait time.

The impact of all improvements together was also considered. The result of eliminating these three sources of waste led to a 27% reduction in cycle time and 77% reduction in wait time. In the case of partial elimination of NVA activities, the results were 26% reduction in cycle time and 75% reduction in wait time, which is very close to the results for the complete elimination of NVA activities. From a managerial point of view, reducing NVA activities, transportation, and defects appeared as the improvement priorities for glulam production in the SME under study. Elimination of all sources of waste could be the next step which follows the concept of continuous improvement to achieve a lean production system.

This research attempts to apply the lean approach in an SME that manufactures glulam. Applying the method is limited to a case study of a gridshell project that represents production of curved glulam for a timber construction project. Studying more samples and considering the production of different projects would provide complementary results to improve the production of engineered wood for the construction industry.

Chapter 5. Production Planning and Project Scheduling for Engineer-to-Order Systems- Case Study for Engineered Wood Production

This chapter is earmarked to the article entitled "*Production Planning and Project Scheduling for Engineer-to-Order Systems- Case Study for Engineered Wood Production*" submitted in April 2019 to the *International Journal of production research*.

Résumé

Les petites entreprises qui fabriquent des pièces pour l'industrie de la construction rencontrent souvent des problèmes de production, faute d'optimisation systématique de leur planification. Dans cet article, une méthode de planification de la production pour un système multi-projets dans un environnement d'ingénierie sur commande est proposée. Plus particulièrement, quatre modèles d'optimisation sont développés puis testés à partir de données réelles issues d'un cas d'études. De tels modèles visent à minimiser les coûts d'opération, le temps de réalisation des projets et le temps de mise en route sur un poste goulot. Deux scénarios d'ajout de projets sont également testés afin de fournir un outil d'aide à la décision pour les décisions stratégiques au cours de la phase d'acceptation du projet. Cet article propose ainsi quatre modèles de planification de la production de pièces destinées à la construction pour un environnement d'ingénierie sur commande, en plus de mettre en lumière les complexités auxquelles font face les petites et moyennes entreprises.

Mots-clés: Bois d'ingénierie, ingénierie sur commande, planification de la production, planification de projet.

Abstract

Small companies that prefabricate parts for the construction industry in the context of engineer-to-order (ETO) systems, often encounter production issues as they usually do not systematically optimize their planning. In this paper, a production planning method for a multi-project ETO system is proposed. Four optimisation models testing combinations of three objectives are proposed. The main objective present in all models is cost reduction. The other objectives considered are minimising project finish time and minimising set-up time of a bottleneck station. The models are applied in a case study with an engineered wood production firm considering fifteen construction projects over a period of forty weeks. Two scenarios for adding long and complex projects and projects with medium length and complexity are also tested to provide a decision support tool in the project acceptance phase. This article contributes to the scientific literature by providing four production scheduling models for the prefabrication of ETO parts in construction and applying them to a real case. The research furthermore integrates a multi-objective production scheduling approach in a multi-project context, highlighting issues that have not been entirely explored in the real world production context.

Keywords: Engineer-to-order, project scheduling, engineered wood, production planning

5.1 Introduction

Make-to-order (MTO) and ETO production systems consider production based on customer orders. MTO firms produce standard or customised products while ETO firms produce complex products specifically designed for customer needs (Vaagen 2017). Production planning in these systems is complex because of the higher level of production variability (Ebadian et al. 2009). It must, therefore, manage due dates, capacity, order acceptance, and resource levelling efficiently. Since each order must meet its due date and a sequence of activities are required to complete the order, a project scheduling approach seems to be a suitable method for production planning (Márkus et al. 2003; Alfieri et al. 2011; Carvalho et al. 2015). The project scheduling approach is also suitable for firms that produce structures or products specifically designed for construction projects. These firms are project-oriented as each construction project has its start time, design specifications and due date. In some cases, firms must complete various construction projects simultaneously. Adapting an individual project planning approach to a multi-project context should then be considered in this environment (Fredriksson et al., 2017). In the context of production for construction projects, additional complexities are added such as the balance between the architectural design and production constraints, several kinds of stakeholder, several planning phases and lack of standardisation in planning.

This research considers the production planning of prefabricated engineered wood products for construction projects in an ETO context. Engineered wood products are manufactured by bonding small pieces of wood together using adhesives or other methods of fixation. They are used in various types of structures including residential and commercial ones (Opacic et al., 2018). The company for the case study is a small firm that works with main construction contractors as a subcontractor for the production of the engineered wood portion of the building projects. After the award of the project, the company receives the architectural design of the building prepared by the architect partner and specifies the design and the drawings for the production of the engineered wood portion. Technological production limitations may lead to changes in the design of the building which must be validated with the client. After the client's confirmation, the production phase starts (inspection and grading of the wood, finger jointing, drying, planing, gluing and press).

The next phases are carpentry (sawing and drilling to desired specifications) and finishing (sandblasting, colouring and adding resisting adhesives). As in many small and medium enterprises (SMEs), systematic production planning optimisation and scheduling do not exist, and the daily production plan is determined by experienced supervisors. Lack of tactical planning resulted in periods where some stations are idle and other periods where overtime and outsourcing are required to meet the due date. Additionally, the production phase is not smooth and the main bottleneck is the press machine. Its process time is long and a time-consuming set-up is needed.

Although many studies have addressed production planning, considering the particularities of the ETO system has received less attention especially at the tactical level (Fredriksson et al., 2017). Moreover, most of the researchers presented models and algorithms that have not been applied in real industrial cases (Zorzini et al. 2008; Carvalho et al. 2015). This paper aims to reduce this gap by providing project-oriented planning for an ETO production system and applying it to a small factory of engineered wood production. In particular, the research questions which guided the research were how is it possible to schedule the production in each phase and each period for the combination of projects? How should production be planned to minimise the set-up time? Which types of projects should be accepted and in which periods? The purpose is to provide a decision support tool that considers the simultaneous production of multiple projects in order to optimise the production costs and provide a better use of the production system's capacity while respecting due dates and resource constraints.

In order to address the research questions, a primary mathematical model (model 1) is presented for the production of multiple projects respecting the due dates and human resource capacity. At the project acceptance level, the model can integrate a potential project using the estimated time for each phase. At the tactical level, the model can be updated with the progress of current projects and the details of component quantities and dimensions. The objective function aims to minimise the global cost, including overtime and outsourcing costs. A second model (model 2) is next introduced, combining both cost minimisation and makespan reduction. As the press machine is the SME's bottleneck, a third model (model 3) encompassing cost minimisation and set-up time reduction is then described. Finally, a fourth model (model 4) combines all three objectives.

The SME under study has always used a rule-of-thumb planning method so implementing these models would be their first step towards increasing standardisation for the production of prefabricated parts in the factory. The planning models would allow for better use of the SME's capacity in terms of human resources and machinery and enable them to accomplish more projects. This tool could furthermore be used for tactical production planning by the production manager and chief executive for balancing resources with current and future demand while evaluating project bidding opportunities.

This research extends the previous studies by providing models that integrate a project scheduling approach for tactical planning in a multi-project environment, which is multi-objective and considers outsourcing, milestones of confirmation and set-up reduction. The prior research considered these issues separately and did not cover all of the aspects of ETO systems, especially for real cases, SMEs, and production for construction systems. Proposing a combination of objectives offers the possibility of analysing the aspects of each combination and generalizing the application of the models to situations in different systems.

The remainder of this paper is as follows. In section 5.2, a review of production planning models for forest products, project-oriented methods and multi-objective scheduling are provided. Section 5.3 describes the planning problem in the SME, the methodology followed and the models developed. Section 4 describes the experimentation of the models for the studied system. Section 5.5 discusses the main findings and scenarios. The conclusions are given in section 5.6.

5.2 Literature review

Production planning in the forest industry has been addressed in many studies, however, very few of them considered secondary wood products and engineered wood (D'Amours et al. 2008; Opacic and Sowlati 2017). Farrell and Maness (2005) developed a single period linear programming model for production planning in MTO secondary wood manufacturing plants. Although the model is generic, it relies on documented and detailed data about the production system which usually does not exist in SMEs. Ouhimmou et al. (2008) presented a mixed-integer programming (MIP) model to plan the wood supply for furniture assembly mills which concerns the procurement, sawing, drawing, transportation, inventory, outsourcing, and demand allocation. Dumetz et al. (2017) analysed the impacts of using different order acceptance policies using a case from the lumber industry that produces several co-products and by-products. Opacic et al. (2018) developed a simulation model for the production of a specific kind of engineered wood product and assessed the alternative scenarios for worker assignments. Providing tools for scheduling the production process and using them for due date negotiation is the future work that the authors proposed. Ghiyasinasab et al. (2019) developed a simulation model to study the production of glued laminated timber (glulam) for a construction project with the aim of making improvements based on lean thinking methods. However, these last two articles did not address the multi-project production context. The analysis of the production system in the latter work has been used in the current paper to consider multi-project production in the same company.

A project scheduling approach for production planning in MTO and ETO systems has been applied by many authors. Márkus et al. (2003) presented a resource-constrained project scheduling problem (RCPSP) to determine the timing and resource assignments of the activities for multiple projects with the objective of minimising the cost of production and outsourcing. Alfieri et al. (2012) proposed a project scheduling approach for a manufacturing-to-order environment. They cautioned that although activities may be aggregated to reduce the complexity, the precedence constraints between activities need to be considered because of their impact on the resource load. Instead of using traditional finish-to-start relations, they suggest using Generalised Precedence Relations and allow a certain amount of overlap among activities. Alfieri et al. (2011) developed the concept of Feeding Precedence Relation, to constrain an activity to start only after a certain percentage of its predecessor activity has been performed. Carvalho et al. (2015) presented an optimisation model to minimise the overall production costs and support tactical capacity planning in a medium-sized ETO organisation. What-if scenarios were generated to analyse the impact of specific decisions such as accepting a new demand. A literature review on the project scheduling approach for production planning provided by the authors shows that most of the published papers are methodological research studies based on hypothetical problem-solving (for example Márkus et al. 2003), and only two papers applied the model to a real industrial environment (Alfieri et al. 2011, 2012).

Mello et al. (2014) noted that outsourcing has been considered as a solution to adapt with the order fluctuations and technological complexities in ETO systems. They emphasised that more empirical research is necessary, to build knowledge upon the existent literature. This paper is an attempt to reduce the gap between theoretical and empirical applications of production planning models. While most research focuses on production, this paper presents a model that includes all of the phases starting from the design phase and client confirmation which are critical in ETO systems. The detailed complexities of the system are considered such as sharing a resource for both design and engineering phases. Moreover, multiple planning models encompassing the minimisation of cost, the project makespan and the set-up time are proposed and compared. The models are supported by a user-friendly interface so as to transform the model into a useful tool for the SME's manufacturing team.

5.3 Methodology and modelling

5.3.1 Methodology

The goal of this research is to provide a decision support tool for tactical scheduling for a multi-project ETO system. A small engineered wood manufacturing company was visited and used as a case study. Three research questions were defined according to the literature review and analysis of the real case. 1. How is it possible to schedule the production in each phase and each period for the combination of projects? 2. How should production be planned to minimize the set-up time? 3.Which types of projects should be accepted and in which periods?

The methodology chosen was to develop a primary optimisation model that addresses the main objective of cost minimisation and then modify the initial model by adding other objectives and compare the results. Hence, four models were created so as to compare the proposed production plans. All of the models provide solutions for the first research question. The initial model was built with only the cost minimisation objective while the second model integrates both cost and makespan minimisation. The third model encompasses the minimisation of the press set-up time with cost minimisation to find a solution for the second research question. The fourth model was developed to combine all three objectives together. The weighted sum method was applied to solve the multi-objective models because of its simplicity and its approach based on prioritising the objectives.

To address the third research question, the model(s) may be used to generate what-if scenarios to verify the capacity before accepting new projects and to analyse the effects on the production scheduling plan. In the SME under study, a project's difficulty level is determined by dividing the time spent on design by the total board feet of glulam produced for the project. If K represents the ratio of design time per board feet, a project can be categorised as either easy ($0 \leq K \leq 1$), medium ($1 < K \leq 2$) or complex ($K > 2$). Two scenarios were tested to analyse the impact of adding projects from the categories of complex and medium projects. Given the sizes of the projects, in order to be comparable, scenario 1 added one long and complex project and scenario 2 added nine medium projects. The two scenarios were applied in each model and the results were analysed. Figure 26 summarises the methodology steps.

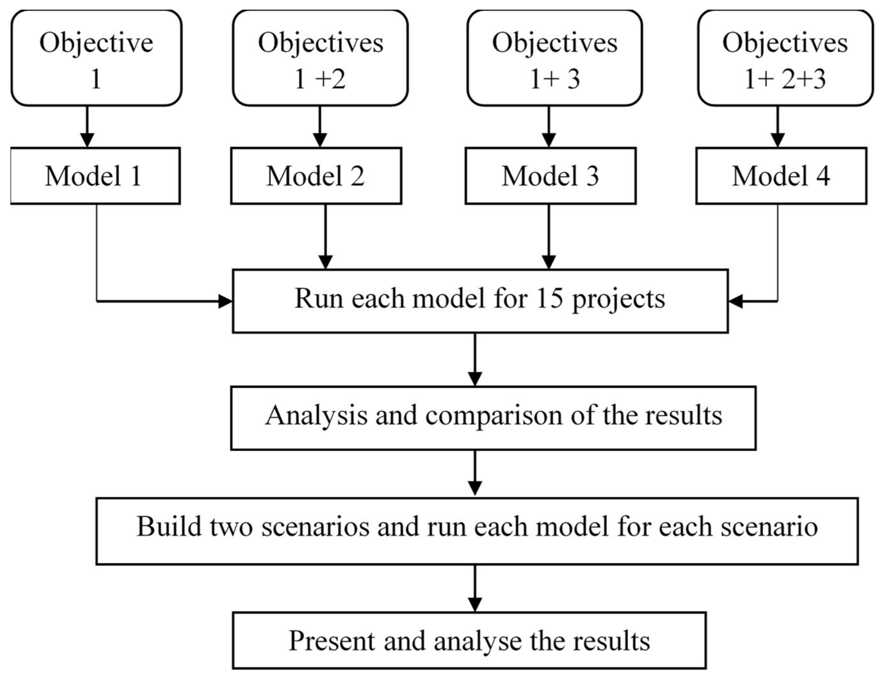


Figure 26. Methodology of the research

The models were implemented in GAMS software and solved for the case of 15 projects based on historical data from the studied SME. The results of each model contain the total and detailed costs and scheduling for resource allocation per phase, per project and per week. The following sub-sections describe the SME's processes and the production planning models proposed.

5.3.2 Presentation of the SME under study

The SME under study produces glulam which is a popular engineered wood product used in wood structures. Once the project is awarded, the company receives the architectural design of the building prepared by another subcontractor. Based on the architectural design, the company further details the design and drawings for the production of the glulam portion which determines the specifications of the structure such as the quantity of components and their dimensions. Technological production limitations may lead to changes in the design of the building which must be validated with the client. Client approval is a milestone that restrains the start of production. Once the design is finalised, the company's engineer and technician develop the specific plans (drawings) needed for production. Although these resources are mostly needed at the beginning of the project, they continue to monitor the project throughout the production phase and may need to adapt the design and/or the drawings as production progresses (engineering and drawing phases). The production phase involves the production of beams of preset widths with varying lengths and heights. The main sizes of widths are 80, 130, 175, 215 and 265 millimetres. Product volume is measured in board feet (0.00236 m^3). The capacity of production is on average 12,000 board feet per week. The carpentry station machines the components (cutting, drilling, etc.). The final step is finishing (sanding, staining, applying protective finish, etc.) and preparing the products for delivery. Carpentry and production as well as finishing and carpentry phases have a start-to-start relation with a time lag. Figure 27 illustrates the phases and their sequences.

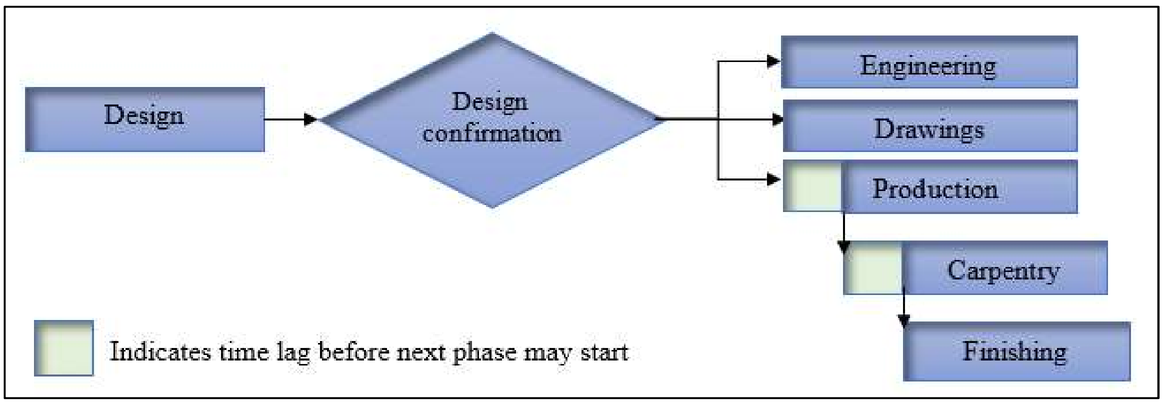


Figure 27. Phases for the completion of each project

The press machine involved in the production process has a fixed capacity in terms of length (19m), and height (1.1m) and several beams may be pressed at the same time. The SME's production manager typically attempts to combine products so as to maximise the load on the press with respect to its capacity. However, only products with the same width may be pressed together. According to the set-up and press time, the press machine is scheduled to be used twice per day, hence ten times a week. The SME was able to provide data for the fifteen projects they completed in a forty-week period including the man-hours per station, costs, sequences and project types. Other than the man-hour estimates per production phase established to bid on the project, no production planning or capacity analysis exists.

5.3.3 Modelling

In order to address production planning in an ETO context, the studied SME's production system was analysed and the main phases were extracted. According to the characteristics of the system, a project-oriented modelling approach was considered. The planning model aims to provide a weekly-based scheduling plan for the production of each project with the primary objective of minimising production, overtime and outsourcing costs. However, since two additional objectives were identified, a total of four production planning optimisation models were built. The first model was built with the objective of cost minimisation and constraints for capacity and sequence relations between activities (phases). The second objective considered was to minimise the finishing time of projects. A second model was built with the two objectives (i.e., minimising cost and finishing time). Models with different objective functions were proposed so as to present alternative solutions which could be compared in order to choose the more appropriate one. The first and second models do not consider the product characteristics and use the total estimated time per phase for each project. For the SME under study, set-up times for the press are substantial and several glulam beams may be pressed at the same time as long as they have the same width. Hence, a third objective aiming to reduce press set-up times by pressing products with the same width together was also considered. To add this third objective in the model, a set of products with different widths and parameters as well as variables regarding press set up were introduced. Model 3 was built considering objective 1 and objective 3 (i.e., minimising cost and press set-up) which was subject to all constraints of model 1 and newly defined constraints. Finally, model 4 was built considering objectives 1, 2 and 3 together. Hence, decision-makers may choose one model in particular or may choose to compare production plans proposed by the various models. For the precedence relationships among activities, the model permits finish-to-start activities as well as start-to-start activities with a lag. For the successor activities that start with a lag after the start of their predecessor, the percentage of completed work must not exceed the percentage of completed work of the predecessor. To our knowledge, this aspect is not present in other production planning models for the forest industry and this is why a project scheduling approach was used. However, in project planning models, the basic method for resource allocation is to allocate a resource full time to one activity of one project and to then start

the next project. For this SME, resources, such as the press, may work on several projects simultaneously. The four models proposed thus address these two particularities.
The models were furthermore developed under assumptions which reflect the SME's reality:

- The planning horizon is divided into distinct time periods (weeks);
- Start time of a project is when a project is awarded to the company;
- Backorders are not allowed as on-time deliveries remains a strategic asset for the SME under study. The company will always prefer to work extra shifts or to refuse projects instead of delivering projects behind schedule;
- The number of resources is fixed. Limited overtime and unlimited outsourcing is possible;
- Outsourcing is possible for production, carpentry and finishing separately and if one phase is outsourced, the others can still be done internally. A phase cannot be partially outsourced, it must be outsourced completely;
- The salary for workers is an average which includes the overhead cost.
- Times are in man-hours except for production where the available time is 40 hours per week;
- The binary parameter U_s defines if the work is done by the internal workforce or a partner of the project. In the construction industry, some activities are not outsourced but are performed by another stakeholder of the project. In this study, design confirmation is the client's task which affects the start time of production while no internal resources are assigned to it.

In order to resemble the SME's real system, the model needed to offer the potential of working on more than one project simultaneously. Hence the model allows finish-to-start activities as well as finish-to-start activities with a lag. A constraint was added so that at a given period the percentage of completed work does not exceed the percentage of completed work of the predecessor. The sets, parameters, variables, objective function and constraints common to the four models are presented in the following.

Sets and index

$p \in P$ Set of projects

$s \in S$	Set of project phases ={Design, Confirmation, Engineering, Drawing, Production, Carpentry, Finishing}
$t, t' \in T$	Set of time periods

Parameters

C_s^r	Cost of regular man-hours for phase s
C_s^o	Cost of overtime man-hours for phase s
Cap_s^r	Capacity of regular man-hours for phase s
Cap_s^o	Capacity of overtime man-hours for phase s
FS_s	1 when work in phase s+1 starts after finishing the work in phase s
ST_p	Earliest start time of project p
DT_p	Due date for finishing project p
$D_{p,s}$	Predicted time needed for finishing work in phase s for project p
L_s	Time lag before starting the next process after its prerequisite has started
$OC_{p,s}$	Cost of outsourcing phase s for project p
$OT_{p,s}$	Duration of outsourced work of phase s for project p (weeks)
$OA_{p,s}$	1 if outsource in phase s is possible
U_s	1 if the work in phase s is done with internal workforce
M	A large number

Decision variables

$XS_{p,s,t}$	1 if work in phase s for project p starts in period t
$XE_{p,s,t}$	1 if work in phase s for project p finishes in period t
$O_{p,s}$	1 if work in phase s for project p is outsourced
$TS_{p,s,t}$	Man-hours spent on work in phase s for project p in period t (regular + overtime)
$PTS_{p,s,t}$	Percentage of work completed for project p in phase s in period t
$TTS_{s,t}$	Total man-hours spent in phase s in period t (regular + overtime)
$TTS_{s,t}^o$	Total overtime (man-hours) spent in phase s in period t
$Start_{p,s}$	Period when project p starts phase s
$End_{p,s}$	Period when project p finishes phase s

Model 1

The objective function of the first model is to minimise the cost of work for regular time, overtime and outsourcing.

$$\text{Min } = \sum_{s\in S}\sum_{t\in T}[C_S^r\,(TTS_{s,t} - TTS_{s,t}^o) + C_S^o\, TTS_{s,t}^o] + \sum_{p\in P}\sum_{s\in S} OC_{p,s}O_{p,s} \quad (1)$$

Subject to

$$\sum_{t\in T} TS_{p,s,t} \geq D_{p,s} - M\big(1 - U_S + OA_{p,s}O_{p,s}\big) \qquad \forall\, p \in P,\ s \in S \quad (2)$$

$$\sum_{t\in T} TS_{p,s,t} \leq D_{p,s} + M\big(1 - U_S + OA_{p,s}O_{p,s}\big) \qquad \forall\, p \in P,\ s \in S \quad (3)$$

Constraints (2) and (3) ensure that if the work for phase s has not been outsourced, time spent in this phase should be exactly equal to the time needed to complete the work.

$$PTS_{p,s,t} \geq \sum_{t'\in T}^{t'\leq t} \frac{TS_{p,s,t'}}{D_{p,s}} - M\big(1 - U_s + OA_{p,s}O_{p,s}\big) \quad \forall\, p \in P,\ \ s \in S, t \in T \quad (4)$$

$$PTS_{p,s,t} \leq \sum_{t'\in T}^{t'\leq t} \frac{TS_{p,s,t'}}{D_{p,s}} + M\big(1 - U_s + OA_{p,s}O_{p,s}\big) \quad \forall\, p \in P,\ s \in S,\ t \in T \quad (5)$$

If the work of phase s has not been outsourced, constraints (4) and (5) calculate the share of work completed in phase s for project p in period t.

$$PTS_{p,s,t} \geq PTS_{p,s+1,t'} \qquad \forall\, p \in P,\ s \in S, \quad t \in T \ \ , t' \in T | t' \leq t + L_s \quad (6)$$

As the sequence of some phases is finish-to-start with a time lag, constraint (6) ensures that the percentage of work completed of the successor activity does not exceed the percentage of work completed of its predecessor.

$$\sum_{p\in P} TS_{p,s,t} \leq TTS_{s,t} \qquad \forall\, t \in T,\ s \in S - \{Engineering, Design\} \quad (7)$$

Constraint (7) makes sure that total man-hours spent on work in phase s (except engineering and design) for all projects is less than total time (regular and overtime) spent in phase s in period t.

$$\sum_{p\in P}\sum_{s'} TS_{p,s',t} \leq TTS_{s,t} \ \ \forall\, t \in T,\ s \in \{Design\}, s' \in \{Engineering, Design\} \quad (8)$$

Constraint (8) ensures that total man-hours spent on work in the design phase (cumulating design and engineering) for all projects is less than total time (regular and overtime) spent in period t.

$$TTS_{s,t}^o \geq TTS_{s,t} - \ Cap_s^r \qquad \forall\, t \in T,\ s \in S \quad (9)$$

For constraint (9), total overtime spent in phase s in period t is equal to or more than the total time spent in phase s in period t minus the capacity of man-hours in regular time.

$$TTS^o_{s,t} \leq \ Cap^o_s \qquad \forall\, t \in T,\ s \in S \tag{10}$$

Constraint (10) ensures that total overtime spent in phase s in period t does not surpass the capacity of overtime for this phase.

$$XS_{p,s,t} \leq \sum_{t' \in T}^{t' \leq t} TS_{p,s,t'} + M\big(1 - U_s + OA_{p,s}O_{p,s}\big) \ \forall\, p \in P,\ s \in S, t \in T \tag{11}$$

$$M \sum_{t' \in T}^{t' \leq t} XS_{p,s,t'} \geq \sum_{t' \in T}^{t' \leq t} TS_{p,s,t'} - M\big(1 - U_s + OA_{p,s}O_{p,s}\big) \ \forall\, p \in P,\ s \in S, t \in T \tag{12}$$

$$\sum_{t \in T} XS_{p,s,t} \leq 1 \qquad \forall\, p \in P,\ s \in S \tag{13}$$

The three previous constraints determine the value of $XS_{p,s,t}$, a binary variable indicating that work for phase s for project p started in period t. Constraint (11) indicates that the value of $XS_{p,s,t}$ will remain 0 as long as the sum of work done in phase s for project p is zero. Constraint (12) forces XS to equal one during the period when work on the project for this phase first starts. Constraint (13) ensures that XS cannot be equal to 1 more than once.

$$XE_{p,s,t} \leq \sum_{t' \in T}^{t' \geq t} TS_{p,s,t'} + M\big(1 - U_s + OA_{p,s}O_{p,s}\big) \quad \forall\, p \in P,\ s \in S, t \in T \tag{14}$$

$$M \sum_{t' \in T}^{t' \geq t} XE_{p,s,t'} \geq \sum_{t' \in T}^{t' \geq t} TS_{p,s,t'} - M\big(1 - U_s + OA_{p,s}O_{p,s}\big) \ \ \forall\, p \in P,\ s \in S, t \in T \tag{15}$$

$$\sum_{t \in T} XE_{p,s,t} \leq 1 \qquad \forall\, p \in P,\ s \in S \tag{16}$$

Constraints (14), (15) and (16) determine the value of XE, the period when the project finishes, based on the time spent in each phase. The logic for XE constraints is similar to the XS constraints.

$$Start_{p,s} = \sum_{t \in T} t(XS_{p,s,t}) \qquad \forall\, p \in P,\ s \in S \tag{17}$$

Constraint (17) determines the start time of project p, in phase s.

$$End_{p,s} = \sum_{t \in T} t(XE_{p,s,t}) \qquad \forall\, p \in P,\ s \in S \tag{18}$$

Constraint (18) determines the end time of project p, in phase s.

$$Start_{p,s} \geq ST_p \qquad \forall\, p \in P,\ s \in \{Design\} \tag{19}$$

Constraint (19) ensures that design phase starts after the earliest start time of the project.

$$Start_{p,s} + L_s \leq Start_{p,s+1} \qquad \forall\, p \in P,\ s \in S \tag{20}$$

Constraint (20) ensures that work in the succeeding phase starts after the start of its predecessor with a time lag.

$$End_{p,s} + L_s \leq End_{p,s+1} \qquad \forall\, p \in P,\ s \in S \tag{21}$$

Similarly, for constraint (21), work in the succeeding phase must finish after the finish time of its predecessor with a time lag.

$$Start_{p,s} + O_{p,s}OT_{p,s} + D_{p,s}(1 - U_s) \leq End_{p,s} \qquad \forall\, p \in P,\ s \in S \qquad (22)$$

For constraint (22), the end of outsourced work corresponds to the start time plus processing time.

$$End_{p,s} + L_s \leq Start_{p,s+1} + M(1 - FS_s) \qquad \forall\, p \in P,\ s \in S \qquad (23)$$

For the finish-to-start activities, constraint (23) makes sure that work in the next phase starts after the work in the previous phase is finished, plus a time lag (if exists).

$$End_{p,s} + L_s \leq Start_{p,s+1} + M\left(1 - OA_{p,s}O_{p,s}\right) \qquad \forall\, p \in P,\ s \in S \qquad (24)$$

For the outsourced work, constraint (24) ensures that work in the next phase starts after the work in the current phase is finished (for outsourcing, the relation between the two stations should be finish-to-start).

$$End_{p,s} + L_s \leq Start_{p,s+1} + M\left(1 - OA_{p,s+1}O_{p,s+1}\right) \qquad \forall\, p \in P,\ s \in S \qquad (25)$$

For the outsourced work in the next phase, constraint (25) ensures that work in the next phase starts after the work in the current phase is finished.

$$End_{p,s} \leq DT_p \qquad \forall\, p \in P,\ s \in \{Finishing\} \qquad (26)$$

Constraint (26) makes sure that the project is finished before its due date.

$$XS_{p,s,t}, XE_{p,s,t}, O_{p,s} \in \{0,1\}, TS_{p,s,t}, TTS_{s,t}, TTS^{o}_{s,t}, PTS_{p,s,t}, Start_{p,s}, End_{p,s} \geq 0 \qquad (27)$$

Model 2

Model 2 is subject to the same objective and constraints as model 1 (equations (1) to (27)) while adding the minimisation of project finish dates in the objective function.

$$\text{Min } = \sum_{s \in S} \sum_{t \in T} [C^{r}_{s}(TTS_{s,t} - TTS^{o}_{s,t}) + C^{o}_{s}\, TTS^{o}_{s,t}] + \sum_{p \in P} \sum_{s \in S} OC_{p,s}O_{p,s} \qquad (1)$$

$$\text{Min} = \sum_{p \in P} End_{p,'Finishing'} \qquad (28)$$

Subject to constraints (2) to (27).

Model 3

Model 3 is subject to the same objective and constraints as model 1, while aiming to press the products with the same width together and minimising the number of set-ups. The additional sets, parameters and variables needed are presented in the following.

Sets and index

$w \in W$ Different widths of products (80, 130, 175, 215, 265 mm)

Parameters

$TLP_{p,w}$	Percentage of time needed to produce products with width w in project p
$Bcap_w$	Time spent to produce products with width w which fill press for one load
$BNum$	Number of times that the press can be loaded per period

Decision variables

$TSL_{p,w,t}$	Time spent to produce products with width w in project p in period t
$BU_{t,w}$	Cumulative number of press loads for products with width w in previous periods + period t

The model's first objective remains (1) while integrating the following objective which aims to reduce the products which have not been pressed.

$$\text{Min } = \sum_{s\in S}\sum_{t\in T}[C_s^r(TTS_{s,t} - TTS_{s,t}^o) + C_s^o\, TTS_{s,t}^o] + \sum_{p\in P}\sum_{s\in S} OC_{p,s}O_{p,s} \qquad (1)$$

$$\text{Min } = \sum_{t\in T}\sum_{w\in W}[(\sum_{p\in P}\sum_{t'\in T}^{t'\le t} TSL_{p,w,t'}) - BU_{t,w}Bcap_w] \qquad (29)$$

Subject to

Constraints (2) to (27).

$$\sum_{w\in W} TSL_{p,w,t} \le TS_{p,s,t} \qquad \forall\, p\in P,\ t\in T,\quad s\in\{production\} \qquad (30)$$

Constraint (30) limits the time spent on all widths of each project in each period to the man-hours spent for work for the production of that project in period t.

$$\sum_{t\in T} TSL_{p,w,t} \ge TLP_{p,w}D_{p,s} \qquad \forall\, p\in P,\ w\in W,\quad s\in\{production\} \qquad (31)$$

Constraint (31) ensures that the total time spent on products with width w for project p covers the needed time for production of that width.

$$BU_{t,w} \ge {\sum_{p\in P}\sum_{t>1} TSL_{p,w,t}} \Big/ {BCap_w} \qquad \forall\, t\in T, w\in W \qquad (32)$$

Constraint (32) limits the cumulative number of times the press is used per period t for width w, to the capacity of the press for that width.

$$\sum_{w\in W} BU_{t,w} \le BNum \qquad \forall\, t\in\{T_1\} \qquad (33)$$

$$\sum_{w\in W} BU_{t,w} - \sum_{w\in W} BU_{t-1,w} \le BNum \qquad \forall\, t\in T-\{T_1\} \qquad (34)$$

Constraints (33) and (34) ensure that the number of times the press is used in each period does not exceed the feasible number.

$TSL_{p,w,t}, BU_{t,w} \geq 0$, $BU_{t,w}$ = Integer (35)

Model 4

Model 4 integrates the three objectives ((1), (28) and (29)) and is subject to all of the constraints mentioned above.

$$\text{Min} = \sum_{s \in S} \sum_{t \in T} [C_s^r (TTS_{s,t} - TTS_{s,t}^o) + C_s^o \, TTS_{s,t}^o] + \sum_{p \in P} \sum_{s \in S} OC_{p,s} O_{p,s} \quad (1)$$

$$\text{Min} = \sum_{p \in P} End_{p,'Finishing'} \quad (28)$$

$$\text{Min} = \sum_{t \in T} \sum_{w \in W} [(\sum_{p \in P} \sum_{t' \in T}^{t' \leq t} TSL_{p,w,t'}) - BU_{t,w} Bcap_w] \quad (29)$$

Subject to

Constraints (1) to (35).

In the following section, the models are applied to the case study and computational results are presented.

5.4 Experimentation and results

This section explains the process of applying input data to the models and conducting experiments. The mathematical models were implemented in GAMS24.1.2 and the CPLEX solver. Models were first solved individually using the data for fifteen projects. The results were compared regarding total cost and the amount of required overtime for each phase (outsourcing was not required based on the results). In order to analyse the SME's capacity for adding new projects, two scenarios were then tested: adding a complex project (scenario one) and adding 9 medium projects (scenario two). This analysis aims to help managers adapt their marketing strategies and orient negotiations with clients in the future.

5.4.1 Input data

The general information about the employees available for each phase, salary per hour, overtime capacity and possibility of subcontracting used in the experimentation are listed in Table 14.

Table 14.Input data for each phase

Project Phase	Cost/ hour	Number of employees	Overtime capacity (Hour/week)	Subcontracting
Design + engineering	95	2	15	Not possible
Drawing	65	1	30	Not possible
Production	65	8	15	Possible
Carpentry	65	4	45	Possible
Finishing	65	3	35	Possible

Table 15 presents historical data for fifteen projects (P1 to P15). Confirmation time is based on the historical data and can be predicted by the knowledge about a client or be fixed in the contract.

Table 15.Input data for fifteen projects

Project	Start Week	Due-Date	Design (Man-hour)	Confirm (Week)	Engineering (Man-hour)	Drawings (Man-hour)	Production (Hour)	Carpentry (Man-hour)	Finishing (Man-hour)
P1	1	23	201	1	425	62	81	738	318
P2	8	29	24	6	68	88	44	340	268
P3	9	17	15	3	46	8	10	101	78
P4	12	40	269	4	432	98	150	891	458
P5	18	25	17	1	61	26	17	141	94
P6	18	28	7	2	31	9	27	57	12
P7	20	35	2	1	120	20	27	202	209
P8	25	38	92	4	92	23	44	324	182
P9	27	40	12	8	1	22	2	72	19
P10	27	40	84	6	8	4	13	101	35
P11	31	40	17	5	13	34	42	163	110
P12	33	40	13	2	0	30	13	252	120
P13	33	40	3	0	29	3	17	95	53
P14	33	40	19	1	5	4	8	114	116
P15	36	40	0	0	15	2	12	81	17

Table 16 shows the time required for a full load of the press per width and the percentage of products per width in each project based on the products' volumes.

Table 16. Production time for a full load of the press per width and percentage of each width per project

	$Bcap_w$	Project														
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
	Hours	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Width 1 80 mm	3	0.5	33.1	3.2	9.8	1.5	63.5	2.1	-	8.7	2	-	-	26.6	-	-

Width 2 130 mm	4	70.8	51.8	66.6	47	65	33.2	10.8	7	86.6	21	-	-	3.6	20	2.4
Width 3 175 mm	5	23.4	13.4	22.7	43.2	28.0	-	69.8	-	4.7	1	93.4	-	15.6	80	97.6
Width 4 215 mm	7	0.7	1.7	7.5	-	-	-	17.3	93		76	6.6	100	54.2	-	-
Width 5 265 mm	8	4.6	-	-	-	5.5	3.3	-	-	-	-	-	-	-	-	-

5.4.2 Defining weights for the multi-objective functions

Models 2, 3 and 4 are multi-objective and the objectives have different magnitudes. In order to use the weighted sum method, the objectives were normalised using the formula: $\frac{f_i(x)-z_i^*}{z_i^N-z_i^*}$. Values for z_i^* and z_i^N, which are the best and the worse solutions of each objective function, are presented in Table 17. The total objective function formula is: $F(total) = Min \sum_1^n \frac{w_i(f_i(x)-z_i^*)}{z_i^N-z_i^*}$. An optimal solution in the multi-objective optimisation context is a solution where there exists no other feasible solution that is strictly better for at least one criterion and not worse in the remaining criteria. This is the notion of Pareto optimality (Ballestın and Blanco, 2011).

Table 17.The best and worse solutions of each objective function

		Model 2	Model 3	Model 4
$f_1(x)$= Min	z_1^*	\$867,935	\$867,935	\$867,935
cost	z_1^N	\$2,105,850	\$2,260,405	\$2,526,595
$f_2(x)$= Min	z_2^*	416 (days)	-	416 (days)
makespan	z_2^N	497 (days)	-	514 (days)
$f_3(x)$= Min	z_3^*	-	126 (hours)	126 (hours)
set-up	z_3^N	-	6,959 (hours)	9,100 (hours)

In order to solve model 2, it becomes necessary to define the weights for $f_1(x)$ and $f_2(x)$. For the case under investigation, the priority is to minimise the cost as the due date is considered in the constraints and minimising makespan is considered as a secondary objective. The weights of w_1= 0.9 and w_2= 0.1 and w_1= 0.8 and w_2= 0.2 lead to the nondominated solutions as shown in Table 18. The result of $f_2(x^*)$ for w_2= 0.2 is equal to the minimum of $f_2(x^*)$ = 416, which means increasing the weight of w_2 would not offer a better solution for the second objective. Since cost minimisation is the first priority, different weights were tried and the result of w_1= 0.999 and w_2= 0.001 was selected as it gives the best result for $f_1(x)$.

Table 18. Pareto frontier for model 2

w_1 w_2	0.9 0.1	0.8 0.2	0.7 0.3	0.999 0.001
$f_1(x^*)$	$875,482	$878,002	$878,002	$867,935
$f_2(x^*)$	417 (days)	**416** (days)	**416** (days)	426 (days)
$F(total)$	0.007	0.007	0.006	0.0001

To solve model 3 with the two objectives of cost and press set-up minimisation, the weights from w_1= 0.1, w_2= 0.9 to w_1= 0.9, w_2= 0.1 were applied (Figure 28). According to the SME's decision makers, these two objectives should have equal weights. Moreover, solving the model with w_1= 0.5, w_2= 0.5 provides a smoother production without a considerable increase in cost.

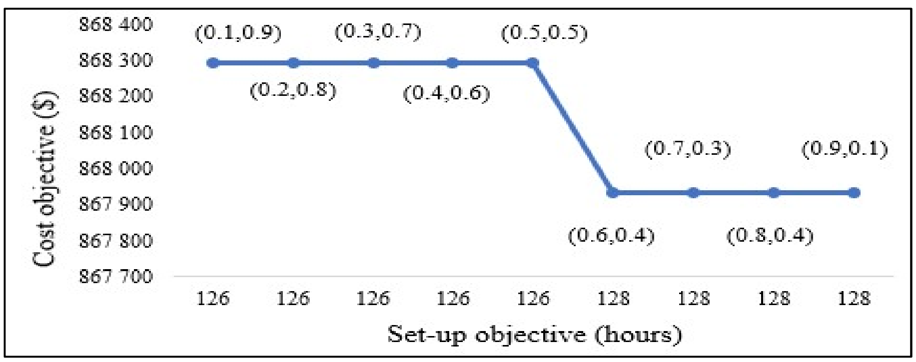


Figure 28. Pareto frontier for model 3

For model 4 encompassing the three objectives, based on the previous results, w_1= 0.45, w_2= 0.1, w_3= 0.45, was applied (Table 19). As this combination leads to the best result for the second objective, increasing w_2 was not considered. Instead, decreasing w_2 was analysed to find better results for the other two objectives and the weights and results which are shown in the third column of Table 19 were selected.

Table 19. Pareto frontier for model 4

w_1 w_2 w_3	0.45 0.1 0.45	0.495 0.01 0.495	0.4995 0.001 0.4995
$f_1(x^*)$	$878,034	$868,538	$868,471
$f_2(x^*)$	**416** (days)	447 (days)	465 (days)

$f_3(x^*)$	338 (hours)	165 (hours)	126 (hours)
$F(total)$	0.013	0.005	0.001

5.4.3 Tactical Planning Results

The cost results for the four models are shown in Table 20 . For each model, the total cost for the 40-week horizon is given as well as the regular and overtime costs per phase.

Table 20. Main results of the four models for fifteen projects

Model	Cost (Dollars)							
	Total	Design	Drawings	Production	Carpentry	Finishing	Design overtime	Carpentry overtime
Model 1	867,935	201,685	28,145	263,640	238,680	135,785		
Model 2	867,935	201,685	28,145	263,640	238,680	135,785		
Model 3	868,295	200,545	28,145	263,640	238,680	135,785	1,500	
Model 4	868,472	200,165	28,145	263,640	238,558	135,785	2,000	179

The detailed information for all projects per phase and week is available in an Excel file but cannot be illustrated in one figure. However, a cumulative time schedule for the four models is given in Figure 29.**Error! Reference source not found.** If we look at model 1, we can see that weeks 6 and 11 are idle for all phases, while when looking at model 2, only week 11 is idle and part of the capacity of week 6 is used. Given the objectives in model 2 to minimise costs and project finish time, all of the projects are finished before their due date. With the current combination of projects tested, model 2 does not incur extra cost but it could add inventory costs if early delivery of projects is not permitted. On the other hand, if providing the products sooner than the due date is acceptable for the client and contractor, the production plan proposed by model 2 would free up capacity at later dates.

Models 3 and 4 integrate the objective of reducing press set-up time. As listed in Table 20, model 3 adds $ 1,500 in design overtime costs while the costs of other phases remain the same. In model 4, overtime costs of $2,000 in the design phase and of $179 in the carpentry phase are added. The end of the finishing phase for the last project is in week 40 for models 1, 2 and 3 while in model 4, it is in week 39. Nevertheless, model 4 has the highest cost.

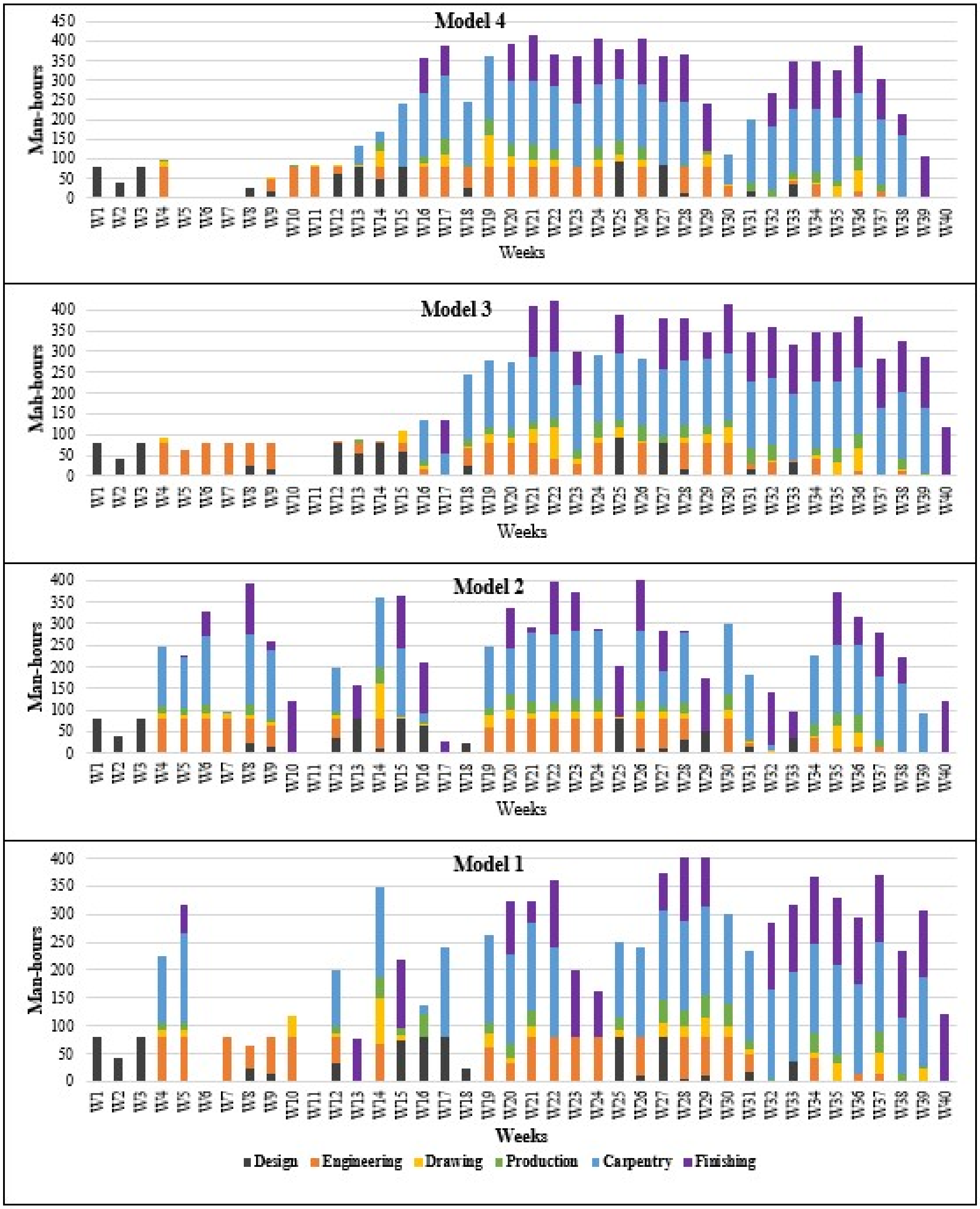


Figure 29. Cumulative view of the production plans proposed by model 3 and model 4

In order to analyse the SME's bottleneck more closely, Figure 30 illustrates the used and available capacity of the production phase per week for the four models. Compared to the schedule proposed for the production phase with model 1, the one with model 2 shows less fluctuation in resource use and less idle weeks in the beginning periods, while two periods at the end are available for future projects. Production based on model 3 started in week 13 while for models 1 and 2, production started in week 4. The reason is that model 3 aims to wait for the products with the same width to be pressed together so as to fill the press machine. This decreases resource use in the early weeks while increasing it after week 13. In model 4, the objective of minimising the makespan makes the model try to plan for some hours of production in week 4 and week 10. Because of the second objective applied in models 2 and 4, their last week for the production phase is in week 37 while with models 1 and 3, the last week for the production phase is week 39. The trade-off between model 3 and model 4 in the production phase is that model 4 increases fluctuations in the early weeks while it leads to two free weeks at the end of the time horizon. Its advantage is that in case of unexpected delays in the production time, there would be buffer time periods to compensate.

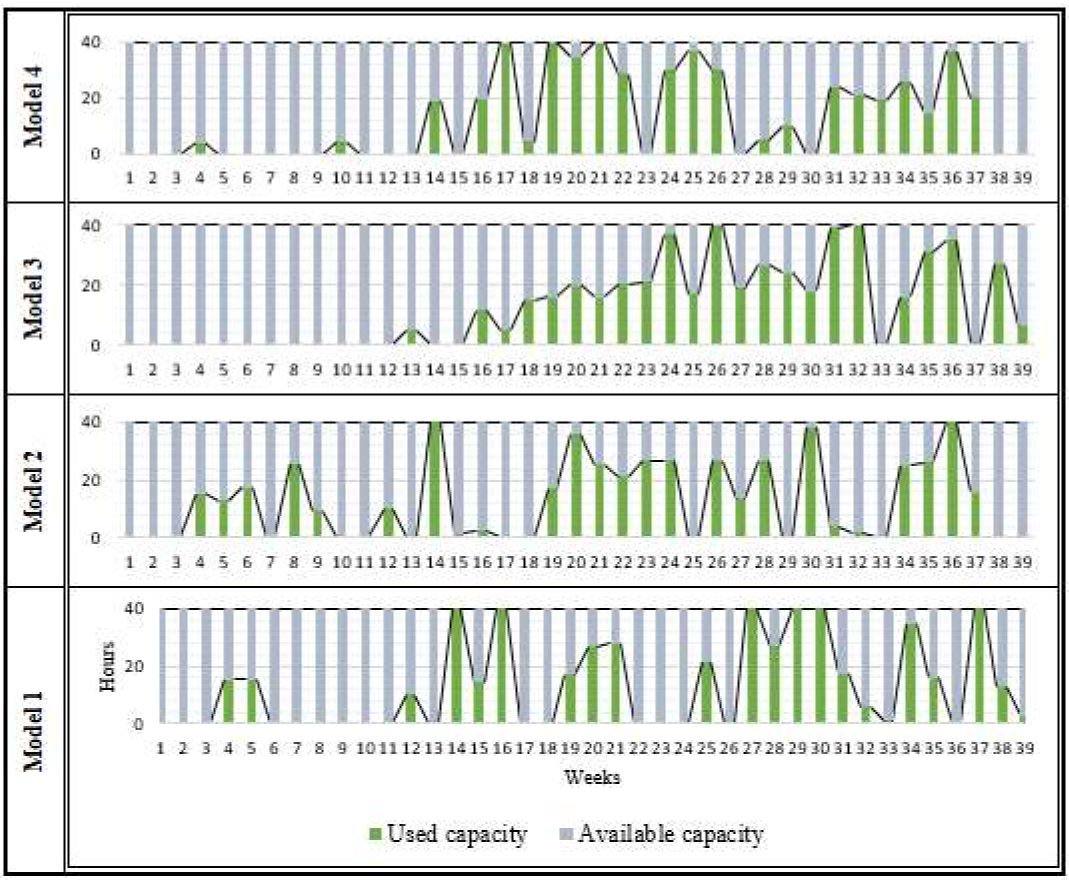


Figure 30. Used and available capacity for the production phase obtained with the four models

5.4.4 Scenarios for adding new projects

Besides providing scheduling for production, the models developed may be viewed as a decision support tool at the strategic level to help in determining if the SME should bid on a new project and, if so, which types of new projects could be accepted or planned at which periods. Two scenarios were therefore designed to analyse the alternatives to adding new projects in the planning. For scenario 1, adding a long and complex project was considered. In scenario 2, adding 9 projects with medium length and complexity was investigated. The following subsections describe the results for these scenarios.

5.4.4.1 Scenario 1- Adding a long and complex project

For the first scenario, one of the existing projects that had been classified as long and complex was added to the current fifteen projects. The addition of the new project was applied to each model for start dates ranging from weeks 1 to 19. Due to its length, the project could not be added after week 19 without exceeding the time horizon of 40 weeks. Table 21 details the costs for regular hours and overtime to complete all 16 projects, for each model and each start week considered. In model 1 and model 3, the first three weeks are suitable for adding the new project without adding overtime costs. While in model 2 and model 4, it would not be possible to add the new project without adding extra cost. This effect shows that the second objective of minimising the makespan is less effective (in terms of cost) when the number of projects increases.

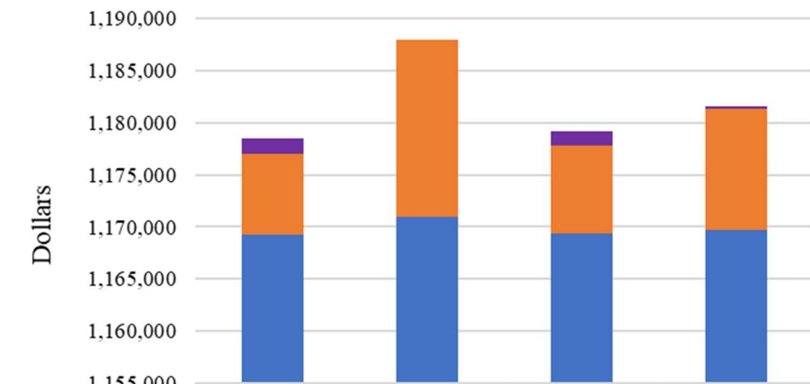
Table 21. Comparison of total costs according to project start week for scenario 1

Insertion week	Model 1			Model 2				Model 3			Model 4				
	Total cost ($)	Design overtime cost ($)	Carpentry overtime cost ($)	Total cost ($)	Design overtime cost ($)	Carpentry overtime cost ($)	Production overtime cost ($)	Total cost ($)	Design overtime cost ($)	Carpentry overtime cost ($)	Total cost ($)	Design overtime cost ($)	Carpentry overtime cost ($)	Production overtime cost ($)	Finishing overtime cost ($)
W1	1,042,195			1,042,644	1,871			1,042,195			1,043,591	3,898	1,457		
W2	1,042,195			1,042,555	1,500			1,042,195			1,043,284	3,755	596		
W3	1,042,195			1,042,975	1,625	1,235		1,042,195			1,043,604	4,205	1,266		
W4	1,042,278	345		1,042,623	1,785			1,043,454	4,936	234	1,045,655	6,938	5,685		
W5	1,042,278	345		1,042,697	2,091			1,043,151	3,984		1,044,065	7,388	305		
W6	1,042,278	345		1,042,682	2,030			1,043,063	3,276	260	1,044,361	8,290	560		
W7	1,042,278	345		1,042,885	2,375	380		1,043,124	3,872		1,044,044	6,050	1,257		
W8	1,042,278	345		1,042,562	1,530			1,042,812	2,569		1,046,824	15,203	3,106		
W9	1,042,278	345		1,043,020	3,436			1,042,705	2,127		1,042,705	2,127			
W10	1,042,555	1,500		1,043,020	3,436			1,043,092	3,739		1,045,527	1,009	9,784		
W11	1,044,835	10,998		1,047,599	22,516			1,045,188	12,470		1,046,440	16,425		959	
W12	1,047,558	22,345		1,047,599	22,516			1,047,498	22,094		1,048,967	28,218			
W13	1,047,259	21,102		1,047,335	21,418			1,047,736	22,886	152	1,047,783	23,249	27		
W14	1,047,235	20,998		1,047,616	22,588			1,047,392	21,656		1,050,949	21,498	8,700	2,683	
W15	1,047,235	20,998		1,047,599	22,516			1,047,380	21,220	293	1,047,839	23,516			
W16	1,047,313	21,325		1,047,259	21,102			1,047,319	21,350		1,047,953	23,191	610		
W17	1,047,879	22,599	823	1,047,814	23,411			1,048,501	23,645	1,997	1,048,445	21,415	3,170		345
W18	1,051,226	28,754	6,745	1,051,584	16,622	17,100		1,052,425	29,593	9,904	1,052,425	29,593	9,904		
W19	1,051,901	34,452	4,552	1,052,215	30,875	6,745	1,520	1,053,038	33,625	8,782	1,055,071	27,542	19,736		107

The experiment with scenario 1 shows that the SME has the capacity for adding one complex project if they accept using overtime in some phases. However, with this analysis in mind, managers might have the opportunity to influence the start date of projects so as to reduce the overtime required.

5.4.4.2 Scenario 2- Adding medium projects

In order to compare scenario 2 with scenario 1 based on similar capacity utilisation, nine medium projects needed to be added to the fifteen projects. The start weeks between each new project were at one-month intervals between weeks 1 and 32. Adding nine medium projects results in overtime costs for design in all models (Figure 31). For models 1, 3 and 4, overtime in carpentry was also needed.



	Model 1	Model 2	Model 3	Model 4
Carpentry overtime	1,488		1,367	227
Design overtime	7,805	16,970	8,487	11,615
Total cost	1,169,213	1,170,943	1,169,339	1,169,729

Figure 31. Comparison of total costs for scenario 2

Testing the second scenario indicates that adding one medium project every month is feasible while some overtime in design and carpentry might be required. Like scenario 1, there is a difference between the total cost of each model but it is not substantial.

5.4.5 Trade-off between models

As it has been shown in the previous section, the four developed models provide comparable results. In particular, the results do not show a significant difference in terms of costs while they all reveal that there is capacity for adding new projects as there are weeks where the production phase does not use its total capacity. Model 1, with the objective of cost minimisation, does not consider press set-up. It would be generally adaptable for SMEs that do not have a bottleneck similar to the one considered in this study. Model 2 and model 4, which aim to reduce the makespan of the projects, might be preferred in SMEs that do not have concerns about keeping final products in stock whereas they might not be suitable when the final product inventory must be kept as low as possible. Model 3 is appropriate for companies which have a bottleneck problem but do not have the possibility of inventory. Model 4 seems appropriate for companies which have a bottleneck problem and the possibility of keeping products in inventory. While the SME under study found that minimising costs seemed an appropriate objective, minimising makespan is not a priority for them. However, they appreciated seeing the impact makespan would have on production planning. Set-up reduction is an issue for this SME and the third objective takes restrictions relating to the resources into consideration to establish the production plan. Therefore, model 3 seems to be a better choice for them, while model 4 provides the opportunity of analysing the option of minimising project makespans. For projects where the SME is responsible for both the production of the structure and the erection of it on-site, makespan minimisation could be an alternative as they are responsible for the production and construction together and are able to adjust the internal due dates.

The results from the two scenarios adding new projects provide an overview of how the idle capacity could be used. According to the cost, adding one complex project costs less than adding numerous projects with medium design complexity. However, the total cost should not be used as the only indicator to decide on the best scenario since total profit could be greater with scenario 2 (i.e. when using an objective function maximising profit instead of minimising costs). Another important aspect of testing these scenarios was to analyse their effect on the efficiency of the resources used. The percentage of capacity used per phase is illustrated in Figure 32 Results show that scenario 2, i.e. adding a medium project per month, makes better use of the capacity. The result is valid for all four models. They also show that the design capacity has been used at a higher rate compared to other phases. This is understandable as design and engineering share the same resources and there are tasks in these two phases in all periods. Furthermore, capacity seems to be better used with models 2 and 4. This is understandable as models 2 and 4 include the objective of minimising the finish time which makes the phases finish sooner. As a result, models 2 and 4 appear promising for SMEs focusing on an effective capacity and resources used when projects involving medium complexity may be added. The experimentation also highlights that when a new project is being considered, predicting the production schedules may guide the bidding process as well as the marketing activities so as to use the production system efficiently.

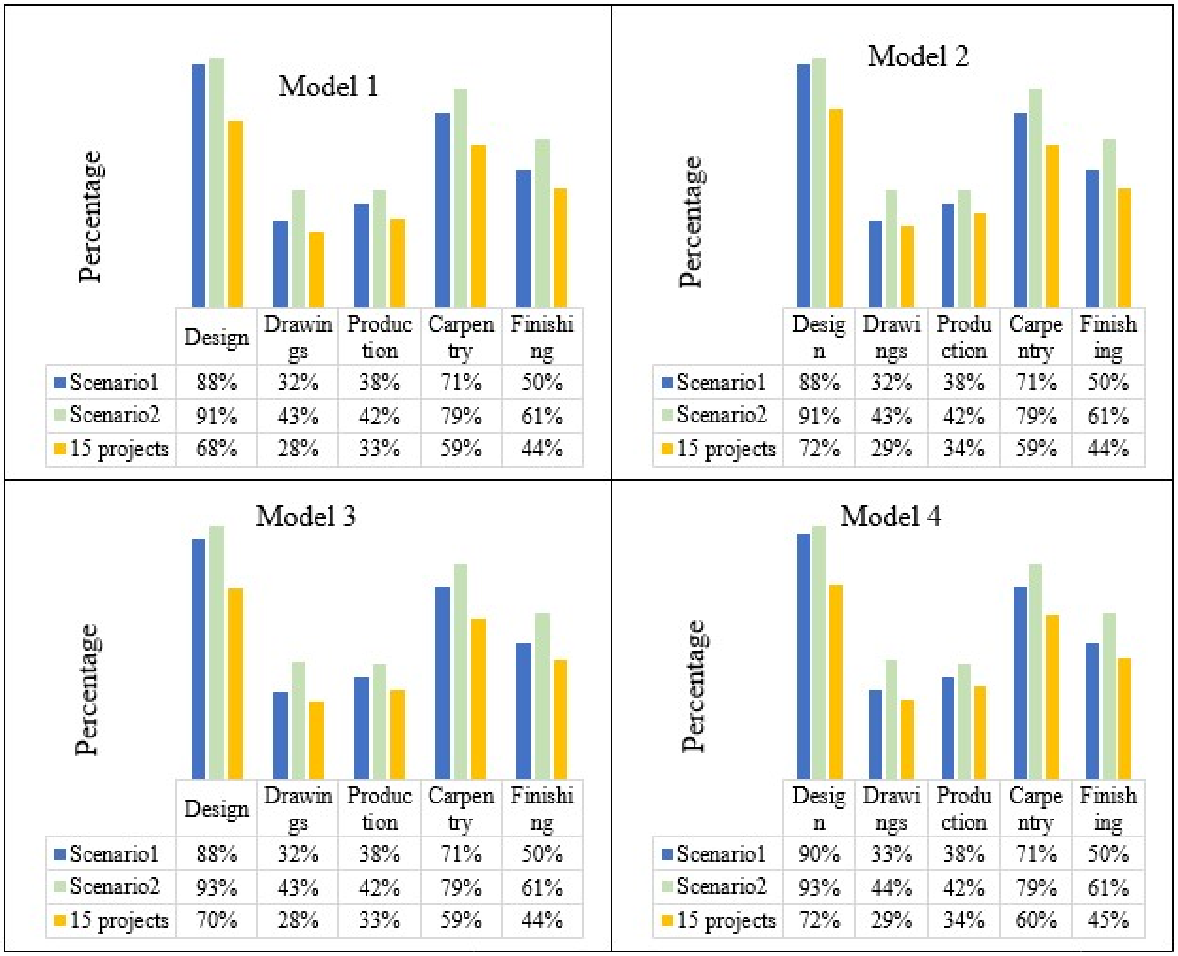


Figure 32. Capacity use of resources in models 1 to 4

5.5 Discussion and managerial insights

5.5.1 Discussion

This section presents a discussion comparing the proposed planning models with what has been found in the literature in terms of works in the forest industry and the project scheduling approach in production planning. This article contributes to the forest industry field by providing planning models for engineered wood production in ETO systems. Regarding the increasing demand for this wood product in North America, Opacic et al. (2018) and Ghiyasinasab et al. (2018) presented simulation models for this industry. These papers provided a system analysis without tackling the lack of tactical planning for simultaneous projects. Works of Farrell and Maness (2005), and Ouhimmou et al. (2008) considered tactical planning for secondary wood products which are not specific for engineered wood products or ETO systems. Compared to the previous studies with a project-oriented approach for production planning, there are technical details in the presented models that contribute to the existing ones. To begin with, the ETO context usually has a confirmation milestone before the start of production, such as design confirmation by an external party in this case. Secondly, in ETO, the design engineer might still need to adjust the design during the production phase. This was therefore modelled as two separate phases (design and engineering) using the same resource. Additionally, a resource assigned to a project can switch from one project to another in the same time period. Therefore, there is more freedom in resource allocation and scheduling which is also based on the reality of this type of production.

The models presented here do not necessitate complex input data processing as the only input dates needed are start and due date of the projects, the best start and finish times of each activity being calculated by the model. As a result, the input data can be a user-friendly table in an Excel file. The previous works in this category of literature typically consider one objective which is either project makespan or production costs while the models proposed in this paper consider multi-objectives. In conclusion, the contribution of the models presented in this research is to integrate a RCPSP with multi-project, multi-objective models, including set-up reduction. Furthermore, it addresses the ETO environment and engineered wood production for construction projects.

5.5.2 Managerial insights

The findings presented provide a set of managerial insights into adjusting the schedule factors and the SME's multi-objective production planning. Since the optimisation results are provided in Excel files, they are accessible for analysis by managers in a user-friendly interface. Managers could use models to plan the execution of the projects based on project due dates, the predicted amount of time required per phase and the expected design confirmation date. This would allow managers to evaluate the capacity and requirement of overtime or outsourcing. Moreover, they could analyse their resource usage and idle time. As four distinct models are presented, managers could compare the impact of combining objectives. By using model 2, they could compare the costs, idle time of resources and the possibility of releasing the projects before their due date. Besides the tactical planning, the models can provide a weekly action plan for each phase and be used by the production manager to manage the entire production. Once the final design of a project is approved, managers could use models 3 and 4 to update their upcoming production plan so as to maximise the use of their bottleneck equipment, in this case, the press. Managers would be able to compare the results with the previous models before choosing the set-up reduction strategy. Finally, the optimisation models could be used as decision support tools to analyse different scenarios such as bidding on a new project or expanding production or marketing activities.

The results obtained from this research were presented to the SME's CEO and the production planner. As none of the employees has modelling experience, they noted the advantage of having an Excel interface to manage the input and results of the proposed models. Their objective is to use the maximum capacity and to accept more projects even if it adds extra cost. Once the models will have been modelled using a free solver (in progress), it will be implemented in the SME's system. The company plans to use it for two purposes: weekly operational planning and validating capacity before adding new projects.

5.6 Conclusions

This research provides a production scheduling approach in an ETO production context for construction projects. The methodology includes the analysis of the case of a SME in this domain from both the tactical level such as project acceptance and the operational level such as production processes and press set-up. Four optimisation models were proposed with the combination of minimising cost, project makespan and set-up times. Historical data from the SME covering fifteen projects in a 40-week time frame were applied to the models and the results were analysed and compared with the actual production data. Furthermore, the models were used to schedule the production to analyse the impact of adding one or more projects in this same time frame. Two scenarios were developed to verify the capacity of the system if adding complex or medium projects, how many could be added and when it was more profitable to add them.

Some limitations in this research could be extended in future work. Firstly, historical data was used as input data so uncertainties in forecasts have not been considered in the scope of this study. Another limitation which could be considered in future work would be to allow backorders as this was not modelled to reflect the SME's reality. The model could be expanded and be tested for other aspects such as the optimum release time to reduce the inventory cost of finished or under process products. Moreover, integrating the uncertainty such as machinery breakdowns and unpredicted fluctuation in demand could add value to the provided work. In addition, the proposed model was developed for a SME producing engineered wood used in wood construction projects. However, the objective functions and constraints are general and valid for multi-project ETO production systems. There are some constraints which are customised for the studied system such as using the same resource for design and engineering which are added in separate constraints to keep the general function of the models. Therefore, it would be interesting to expand this study by applying the model in other similar systems. Besides the scenarios tested in this study, the models could be applied to other scenarios that might be of interest to managers. For instance, integrating an MTO product with a pre-designed structure which would eliminate the design time.

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General conclusion and perspectives

General conclusion

In this research, we studied the production of engineered wood for construction projects with the aim of increasing productivity and facilitating production of current and future products. The research was conducted in collaboration with a SME located in the province of Quebec in Canada, which produces glulam for construction projects.

The thesis started with the initial research questions on: Are timber gridshell structures used in the construction industry? How were the samples built? What would the potential market for this structure be? To answer these questions, we conducted a literature review on published articles which were mostly technical and scarce from the process analysis point of view. Therefore, we extracted a number of samples around the world and investigated the existing information about their production processes and involved partners. By combining the scientific and grey literature, we made categorisation of samples and provided process charts to describe their production and involved parties. Finally, we analysed the market opportunities as well as challenges and barriers for production of this structure.

Afterwards, we focused on the improvement of glulam production as prefabricated parts for wood structures and construction projects in ETO systems. We analysed the general production process of glulam in the SME under study and built a simulation model as a decision support tool in process analysis and scenario testing. We tested the scenarios of applying lean tools for process improvement purposes. Identifying and measuring key performance indicators of production time and waiting time showed improvements by applying the methods in the model. According to the limitations in the SMEs to invest in complete elimination of waste, the scenario of partial elimination of non-value-added activities was also analysed. The results showed considerable potential for improvement that could encourage decision-makers to follow the suggested steps to increase productivity.

In the third part of the thesis, we aimed to plan and schedule glulam production for an ETO context more efficiently. We developed four models to cover a combination of objectives. The objective of model 1 was to minimise the total production costs. In model 2, we tried to minimise projects' makespan by minimising finish time of projects. In the third model, we aimed to reduce set-up times. In model 4, we combined the three objectives. Normalisation techniques were adopted to ensure that the three objectives were being treated equally and the weighted sum method was applied to solve the models. Testing the models for the developed case study in a forty-week horizon showed the characteristics of the models in terms of total cost and resource usage. The models were also applied to test scenarios of adding new projects in the same time horizon. In order to make an accessible framework for the SME managers, the results were designed to be presented in Excel files and be used for future modifications.

This study starts with the introduction of gridshell structure and investigates its production and market. The thesis consists of three articles with separate and independent contributions which follow the main objective of the research and complete each other. The first article considers an innovative structure and aims to expand the existing technical literature from a managerial point of view. In the second phase, we focused on production of glulam because it is an appropriate material for gridshell production. Therefore, the second objective of the study was defined to make improvements in the glulam production in SMEs by applying lean approach and providing production planning. Ultimately, improvement in glulam production facilitates the production of gridshell as a new structure that has not been introduced to the market in the Quebec province as well as in Canada.

This research aimed to put theory and practice together and therefore followed a methodology that links the production of glulam in the SME under study to the production of gridshell. The results of each phase of the thesis have been presented to the president and production manager of the SME. They started to adopt primary steps to make improvement by changing the factories layout to a U-shape layout. They also added an employee to the inspection station to reduce the waiting time for the next stations and the total production time.

Recommendations for future work

According to the reviewed literature for this thesis, very few studies have addressed the production of engineered wood products in terms of system analysis and provided decision support tools to support its planning. In particular, production of prefabricated parts for construction projects in the context of ETO does not seem to have captured researchers' attention yet. Although this production system is similar to the manufacturing environment, the low productivity in the construction industry confirms the requirement to pay special attention in this sector to take more steps in standardisation in construction. The future work of this study could include a thorough analysis of this system and on its specifications in general.

In particular, according to the results of the three papers presented in this thesis, the recommendations for future works could include the following items:

- In the concept of innovative structures such as gridshells, more interdisciplinary works are required to consider the market, production and design specifications;
- The developed simulation could be adapted for other systems and companies and be applied for testing other scenarios;
- The developed multi-objective models could be expanded by considering uncertainties;
- Input data for the models were based on historical data and prediction theories were not considered in this study which could be complementary future work;
- The optimisation models in this study were concentrated on production. Analysis of the supply chain and procurement of raw material could add value to the provided works;
- The presented simulation model in this study contains the stations of production as well as breakdowns in machinery and other details that are not considered in the optimisation models. In complementary research, providing a combination of simulation and optimisation could provide a more comprehensive model.

Specific future research for the SME would involve the analysis of the production system after applying the re-engineering steps and adding the gridshell structure in their production. The collaboration between all involved stakeholders in a construction project is one of the other points to be considered especially for products with a complex design.

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