Sub-components' lead time optimization in precast concrete house-building industry

A thesis submitted to the Delft University of Technology in partial fulfillment of the requirements for the degree of

Master of Science Construction Management & Engineering

Faculty of Civil Engineering & Geosciences

by

Evangelia Rizopoulou

5351839

August, 2022

Thesis Committee

Prof. Dr. Hans Bakker	Graduation Chair, *TU Delft*
Dr.ir. Maria Nogal Macho	Main supervisor, *TU Delft*
Dr. Martijn Leijten	Secondary supervisor, *TU Delft*
Mr. Karel Kalis	Company supervisor, *Janssen de Jong*

TU Delft

EXECUTIVE SUMMARY

Housing construction industry is plagued by delays, which cannot more be tolerated, owing to population growth and increased congestion on sites. Precast concrete appears to be a promising approach in dealing with these delays, yet long lead times are apparent and need to be dealt with in this industry. Lead time refers to the time that elapses between placing and receiving an order, so the time needed to manufacture and deliver the order. The construction company Janssen de Jong (where this research is conducted), which is not ahead in precast concrete house-building, recognizes the problem of long lead times, naming, specifically, sub-components' long lead times. Sub-components refer to the products being integrated into the precast concrete components (for instance, windows integrated into walls) and they are supplied to the precasting concrete factory by various suppliers. The company seeks to optimize sub-components' lead times, so as to increase its competitiveness. Accordingly, the current research focuses on identifying the sources of sub-components' long lead times in precast house-building industry and optimizing them, in order to improve projects' performance in terms of time and costs. The research draws on literature review, interviews, mathematical optimization modelling and case study.

Literature review and interviews with Janssen de Jong, a precasting concrete factory, a windows and frames supplier and an installation technology supplier revealed the large batch size of batch-and-queue manufacturing method, as the main quantifiable source of long manufacturing (non-value-added) time. This affects significantly the delivery of the sub-components and so, extends their lead time. Batch-and-queue utilizes the equipment to its maximum capacity, yet leads to the creation of stocks of processed products at each step of the production, resulting in large – non-value adding – queues. On the contrary, one-piece-flow manufacturing method (batch size of one), was indicated as a value-adding process worth to approach, yet not easily achievable, not so efficient, due to the increased frequency of set-ups, and more expensive. One-piece-flow refers to moving the product step-by-step through each process step without non-value-added time. The conflicting interests of the suppliers and Janssen de Jong (client)

call for solutions that include both manufacturing methods and provide useful information for the points that could satisfy both time- and cost-related interests.

The mathematical optimization model was built based on the identified conflicting relation between reducing costs and shortening lead times, in relation to the batch size. This was done considering the arguments in favor and against both manufacturing methods and so, the interests of the supplier and client involved. In this way, the bias is reduced as much as possible. Weights are assigned to each of the objectives, denoting their relative importance to the client each time. A set of optimal lead times and costs is obtained, after running the model for each supplier separately, enabling the client to map the solutions and improve the project performance in terms of time and cost, as per the priorities each time.

A recently completed project by Janssen de Jong of precast concrete houses was utilized as a case study for the model validation. Out of the interviewed and involved suppliers, only the windows and frames supplier made some data accessible. This supplier already follows one-piece-flow, so the relevant lead time is known, while process-related data were provided from the past (when they were working with batch-and-queue). Yet, the confidentiality of financial data led to the utilization of a Greek company, as s supplementary one, for obtaining them. This company is active in the same field, mainly follows batch-and-queue and so, is highly representative. The developed model succeeds to yield reasonable results compared to the real figures and literature, with slight deviations, owing mainly to the lack of financial data by the involved windows and frames supplier.

Concluding, the developed model proves to be effective in optimizing sub-components' lead time in precast concrete house-building industry. However, it is recommended the model to be validated using companies from other fields (e.g. installation technology company), as well, and incorporate further information in a future version –complex to include this in the context of the current thesis– to achieve even higher levels of realism and applicability.

ACKNOWLEDGEMENTS

With the current thesis, I finalize my Master of Science degree in Construction Management & Engineering at Delft University of Technology. It has been a long and tough journey, yet with patience and perseverance, I managed to overcome the difficulties on my way. The help certain people gave me contributed to finalizing this thesis. Starting with the academic staff of my thesis committee: Prof. Dr. Hans Bakker, Dr.ir. Maria Nogal Macho, Dr. Martijn Leijten. I would like to thank each and every of you, for the insightful comments and advice you have given me, not only during our official meeting moments, but also whenever I have asked for your help in between these moments.

A special thanks goes out to Dr.ir. Maria Nogal Macho, my main supervisor. Thank you for your support and for always being there when the problems were getting larger and sometimes seemed unsolved. I would like, also, to thank you for introducing me Ms. Yue Shang, a PhD candidate in Engineering Asset Management. I am thankful for meeting you, you are a really kind and smart person. Thank you for always being available when I needed help and for spending hours in reviewing my optimization work and making valuable comments.

Moreover, I feel so lucky for being part of Janssen de Jong during these months and having as my company supervisor Mr. Karel Kalis. Thank you for your help, understanding and guidance during this journey. I deeply appreciate your kindness and your zeal and concern for me to gain experience in this field, by visiting real working environments.

Finally, my biggest gratitude goes out to my beloved ones: my parents and my twin brother for their unconditional love and priceless support. To Nick, you were always there for me. I cannot thank you enough for all that you have done and gone through for and with me. Definitely, studying and completing successfully this master's in Delft, could not have been possible without you.

Evangelia Rizopoulou
Delft, August 2022

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1 INTRODUCTION

Uncertainty and complexity are inherent in construction industry, resulting in being one of the least integrated industries among all major industries (Utomo Dwi Hatmoko et al., 2019). In particular, the involvement of multiple stakeholders, makes it difficult to understand the various processes of construction projects (Elfving, 2003). This leads to miscommunication of information, production and delivery inefficiency, namely non-value adding tasks in the process, causing significant delays (Elfving, 2003). Primayuda et al. (2019) name specifically house-building projects, as the field of construction industry which faces significant delays. Over the years, these delays can no more be tolerated, as population growth and increased congestion on construction sites urge for faster, safer and more efficient project developments, in terms of quality and costs (Tam et al., 2015; Utomo Dwi Hatmoko et al., 2019).

Precast concrete in house-building projects appears to be a promising approach in dealing with the delays, what accounts for the considerable increase of its utilization (Dossche et al., 2016). Nevertheless, the precast concrete house-building industry could not remain completely intact by non-value adding tasks (miscommunication of information, production and delivery inefficiency), owing to the involvement of multiple stakeholders with multiple and sometimes conflicting interests, which, finally, hinder the progress of precast concrete house-building projects. In particular, long lead times, unsmooth flow and embedded process waste are apparent in precast concrete house-building industry, affecting negatively productivity and quality (Xiaosheng & Hamzeh, 2020). Alad and Deshpande (2014) highlight the importance of lead time reduction, so as to reduce waste, while proper Supply Chain Management and lean tools are mentioned as two of the most important allies in this endeavor (Said, 2015; Luo et. Al, 2020).

Lead time is basically the time that elapses between placing and receiving an order. It comprises of the time needed to manufacture and deliver the products, times which belong to manufacturing and logistics fields of Supply Chain Management, respectively. The traditional manufacturing process, batch-and-queue, where large batches are produced, is mentioned as a source of long manufacturing time (Ioana et al., 2020), and so, of non-value-added time in the process. In particular, batch-and-queue refers to the fragmentation of the batch and then, processing each step, utilizing the equipment at its maximum capacity, yet resulting in creation of stocks of processed products (large queues) in the different steps of the process (Ioana et al., 2020). On the contrary, moving towards one-piece-flow appears to be a promising solution to improve manufacturing lead time and so, add value in the process. One-piece-flow refers to moving the product step-by-step through each process without non-value-added time (Ioana et al., 2020). Yet, it is claimed to be more expensive, not easily achievable and not so efficient, due to the frequent set-ups (Marton & Paulová, 2013). As for logistics, significant deviations are found in deliveries (Mishra et al., 2018), which increase the number of non-value adding tasks, namely waiting to move to the next process, having too much inventory, too little inventory or the wrong inventory, moving products and equipment from point to point frequently and so, having excess human movement or reduced productivity levels.

Various attempts have been made in order to reduce lead time, yet there exist gaps and omissions in both fields (manufacturing and logistics), when referring to lead time reduction of sub-components in precast concrete house-building industry. Sub-components refer to the products that are being integrated into the precast concrete components (for instance, windows) and they are supplied to the precast concrete factory by various suppliers, each one having their own operating policy. The need to explore further and provide answers to these gaps and omissions is enhanced by the problem *Janssen de Jong* (the construction company at which the current research is being conducted), is experiencing: long sub-components' lead times, due to the large batch sizes and the involvement of multiple stakeholders with conflicting interests, which bring delays and extra costs in projects' execution. These hinder the efforts of the company to increase its competitiveness in the precast concrete house-building industry.

The multiple stakeholders involved in the examined case are: Janssen de Jong, a precast concrete factory, a windows and frames supplier and an installation technology supplier. Janssen de Jong is the client and then, precast concrete factory is the destination point of sub-components, while windows and frames company and installation technology company supply windows and installation technology sub-components, respectively, to the precast concrete factory. Although the current research collects information from both suppliers for the sake of completeness, the developed approach is validated using only the windows and frames supplier, due to the restricted accessibility to data. It is important to note that a Greek windows and frames company, acting in exactly the same field as the involved windows and frames company and being highly representative of the examined case, is utilized as a supplementary stakeholder – not involved in reality – replacing the non-accessible financial data of the involved windows and frames company.

The exact process that the current research explores starts with Janssen de Jong placing an order for bespoke sub-components needed for a whole project (for instance 100 precast concrete houses) to the supplier. These sub-components are produced at the factory of the supplier, utilizing batch-and-queue manufacturing method, and then they are delivered to the precast concrete factory. Each supplier has their own operating policy, referring to the time and costs involved in their process, which are in conflict with the interests of Janssen de Jong. Specifically, the supplier wants to operate as per their wish (batch-and-queue) in order to not lose efficiency, not have extra costs and be able to serve more clients, while Janssen de Jong demands for shorter lead times (moving towards one-piece-flow), but still aiming for the lowest possible cost. This wish of Janssen de Jong is an oxymoron, as any interference is translated in extra costs in most cases in reality. Therefore, the objective of the current research is to provide a set of optimal lead times and costs for sub-components, considering the arguments against and in favor of both manufacturing methods (batch-and-queue and one-piece flow), and so, the conflicting interests of the suppliers and client (Janssen de Jong) involved. In this way, Janssen de Jong could be informed about the implication of their preference and make a decision in order to improve project performance in terms of time and cost.

The following research methodology is employed in order to fulfill the aforementioned objective:

- *Literature review* in order to partly identify the main contributors to sub-components' long lead times in precast concrete house-building industry and their effects on precast concrete house-building projects' performance.

- *Interviews* with the involved stakeholders in order to further identify the main contributors to sub-components' long lead times in precast concrete house-building industry and their effects on precast concrete house-building projects' performance, based on real working environments.

- *Mathematical optimization model* in order to model mathematically the problem under consideration, based on literature and interview findings. This model will run for each supplier separately and will enable the decision maker to have an overview of the implications of her/his decisions.

- *Case study* in order to validate the developed mathematical optimization problem in reality.

The structure of the current research is as follows:

- *Chapter 2* reviews literature and related work relevant to the current research.

- *Chapter 3* specifies the problem, based on gaps identified in literature and the problem the Janssen de Jong is experiencing. Then, the main research question and the sub-questions are formulated.

- *Chapter 4* presents the research methodology employed in order to address the sub-questions and so, the main research question. Furthermore, a justification for the selection of the mathematical optimization modelling is included.

- *Chapter 5* reviews literature specifically in relation to the definition of sub-components in precast concrete house-building industry, the main sources of their long lead times and the effects of the long lead times on project's performance to address these aspects.

- *Chapter 6* displays interview results and further addresses the main sources of sub-components' long lead times in precast concrete house-building industry and the effects of the long lead times on project's performance.

- *Chapter 7* explains the process to be optimized, based on the findings of previous Chapters, and describes the development of the mathematical optimization model.

- *Chapter 8* employs a recently completed precast concrete housing-project by Janssen de Jong, as a case study. The relevant data obtained by the involved windows and frames supplier and the supplementary Greek windows and frames supplier (as explained above) will be introduced into the developed mathematical optimization model and will be tested whether this model can be useful in reality.

- *Chapter 9* lists the answers to the stated research questions, the conclusions that can be drawn, reflects on the limitations of the current research and provides further recommendations.

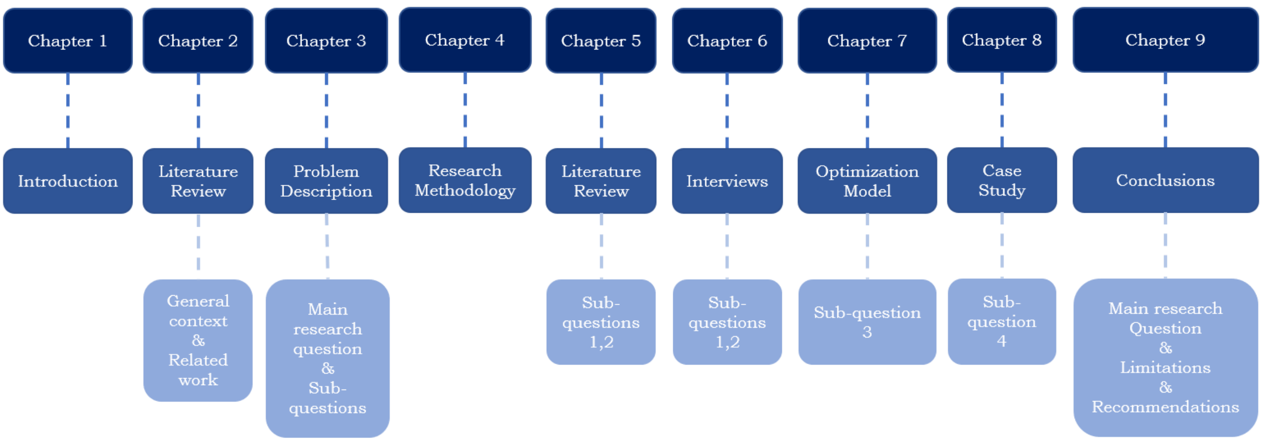

Figure 1-1: Thesis Outline

2 LITERATURE REVIEW – RELATED WORK

This chapter presents the general framework of the current research and reviews related work. The principal role is that of the sub-components' lead time in precast concrete house-building projects. Since the term "lead time" is highly correlated with various terms, it is deemed crucial to follow a deductive reasoning, so as to understand the linkage between them and arrive at the information needed for the current research. Therefore, this chapter is built as follows: first, precast concrete construction in house-building projects is introduced and then, the chapter is divided in two main sub-sections, those of lead time and supply chain management. The rationale behind this division is illustrated below.

Precast construction could be described as the process of designing and manufacturing building elements in factories, shipping them to construction sites and then, assembling them, enabling faster site assembly than typical on-site construction (Smith, 2016; Zhong et al., 2017; Ji et al., 2018). Specifically, the use of precast concrete in housing concerns mainly the creation of components, including beams, walls, columns, floors, staircases and lintels (Glass, 2000). The products that are being integrated into the components, for instance windows being integrated into walls, could be referred to as sub-components.

In recent years, the use of precast concrete in housing has been considerably increased (Dossche et al., 2016), as population growth and increased congestion on construction sites urge for faster, safer and more efficient project developments, in terms of quality and costs (Tam et al., 2015; Utomo Dwi Hatmoko et al., 2019). Nevertheless, long lead times, unsmooth flow and embedded process waste are apparent in precast concrete house-building industry, affecting negatively productivity and quality (Xiaosheng & Hamzeh, 2020). Pan et al. (2012) and El Sakka et al. (2016) are among the researchers who have focused on identifying and improving flow in an attempt to eliminate waste in the process, while Luo et. al (2020) and Said (2015) mention the major role of Supply Chain Management in having successful precast construction projects.

As long lead times pose a problem to the precast concrete house-building industry and Supply Chain Management appears to be the key in improving a precast construction project's performance, both terms are reviewed in the following sub-sections.

2.1 Lead time as a general concept

2.1.1 Definition

Uncertainty and complexity are inherent in construction industry (Utomo Dwi Hatmoko et al., 2019), hence in precast concrete house-building industry, as well. In an attempt to understand and deal with uncertainty in construction projects as a whole, lead time was introduced (Afolabi et al., 2017).

Council of Supply Chain Management Professionals ("SCM Definitions and Glossary of Terms", 2013) defines lead time as "The total time that elapses between an order's placement and its receipt. It includes the time required for order transmittal, order processing, order preparation, and transit.".

2.1.2 Importance of Lead time reduction

Lead time appears to be extremely important for construction projects (Senapati et al., 2012). Alad and Deshpande (2014) highlight the importance of lead time with regards to productivity improvement, while also the need to reduce lead time, so as to reduce waste. In this context, Alad and Deshpande (2014) list the reduction of work in progress, safety stocks, costs and time to market, the improved product quality, the faster response to client need, the increased flexibility and profitability amongst the main advantages of reducing lead time. Except these benefits, short lead time is mentioned as source of competitiveness by De Treville et al. (2014). Senapati et al. (2012) explain that "clients tolerated long lead times which enabled producers to minimize product cost by using economical batch sizes", but "later, when clients began to demand shorter lead times, they were able to get them from competitors".

2.1.3 Tactics for Lead time reduction

Recognition of the importance of lead time reduction in construction projects led to the adoption of four main tactics throughout the years: elimination (removing a procedure), compression (removing time within a process), integration (re-engineering interfaces between successive process) and concurrency (operating processes in parallel) (Mason-Jones & Towill, 1999). These four main tactics and their ramifications mainly refer to lead time reduction of materials and material inventory planning (Mason-Jones & Towill, 1999; Afolabi et al., 2017). Except material inventory planning, Afolabi et al. (2017) emphasize the importance of Supply Chain Management and Lean tools in lead time reduction of all the phases of a construction process and the need to constantly adapt to the needs of construction industry in terms of efficient and effective lead time management.

2.1.3.1 Lean Concept

As mentioned above, Lean tools serve in lead time reduction. Therefore, the relationship between Lean tools and lead time is necessary to be identified.

The fragmented nature of the construction industry, with multiple stakeholders involved, makes it difficult to understand the various processes of construction projects (Elfving, 2003). In Lean construction, the main idea is the involvement of downstream players in upstream decisions, including contractors and suppliers, in order to understand the dependencies of the multiple construction processes and find out the proper way a construction project can be delivered or improved significantly (Elfving, 2003). The inspiration of the Lean construction concept originates from Lean manufacturing, developed by Toyota or Lean Production, which aided Toyota in delivering automobiles faster, at less cost, and creating more value to its clients (Elfving, 2003).

In general, the Lean construction concept aims to improve the efficiency of the production and delivery process, minimize waste (that is, non-value adding activities) in the supply chain and reduce value loss as much as possible (Koskela, 2000; Aziz et al., 2013; Barathwaj et al., 2017). Consequently, these are the goals of manufacturing production and operations management, as well, as these fields utilize the Lean construction concept (Barathwaj et al., 2017).

The eleven principles of Lean construction for flow process design and improvement are (Koskela & Stanford University. Center for Integrated Facility Engineering, 1992):

- Reduce the share of non-value adding activities
- Increase output value through systematic consideration of client requirements
- Reduce variability
- Reduce cycle time
- Simplify by minimizing the number of steps and parts
- Increase output flexibility
- Increase process transparency
- Focus control on the complete process
- Build continuous improvement into process
- Balance flow improvement with conversion improvement
- Benchmark

Waste in construction refers to both residual materials or tools, which are not utilized once the construction is finished and activities which do not provide added value either directly or indirectly, but only raise costs (Hosseini et al., 2012). The seven wastes in every construction process according to Hosseini et al. (2012) are:

- Waste from overproduction (unnecessary work)
- Waste from rejects (defects/unsatisfactory work)
- Waste in transportation (material movement)
- Waste in processing (over processing)
- Waste from inventory
- Waste from waiting (delays)
- Waste from movement (motion)

Non-value adding activities, which are categorized as waste, affect detrimentally construction projects' performance, while value-adding activities contribute to the form, fit or function of the production flow (McManus, 2005).

Elfving (2003) describes the relationship between the value-added time and the lead time (of each of the design, procurement and manufacturing phases), as an inversely proportional one. This means that the greater the lead time of a phase, the lower the value-added time, so the greater the non-value-added time (or the lower the lead time of a phase, the greater the value-added time, so the lower the non-value-added time). Hence, it can be concluded that shortening lead times plays a significant role in the increase of value-adding activities.

2.1.4 Summary & Conclusion

Summarizing Section 2.1, lead time reduction in construction projects and thereby, in precast concrete house-building projects, is urgent. Lead time reduction is strongly related to the Lean construction concept, as both aim for waste reduction (or reducing non-value adding activities) in the construction process. The longer the lead time of a phase, the greater the number of non-value adding activities. Various attempts have been made to reduce lead time in construction, mainly in terms of material inventory planning, yet sub-components' lead times in precast concrete house-building projects seems to be a neglected area. This fact along with the constant change of the construction environment makes lead time reduction an always topical subject for every type of construction project and consequently, for precast concrete house-building projects.

2.2 Supply Chain Management

2.2.1 Definition

Construction industry is considered as one of the least integrated industries among all major industries (Utomo Dwi Hatmoko et al., 2019). In an attempt to integrate construction industry, Supply Chain Management has been widely recognized as one of the significant factors of project success (Utomo Dwi Hatmoko et al., 2019) and for precast concrete house-building projects', as well (Said, 2015).

Several definitions can be found for supply chain and for supply chain management. The current research lists the definitions, as provided by the Council of Supply Chain Management Professionals ("SCM Definitions and Glossary of Terms", 2013).

Supply chain encompasses "the material and informational interchanges in the logistical process stretching from acquisition of raw materials to delivery of finished products to the end user; all vendors, service providers and clients are links in the supply chain." ("SCM Definitions and Glossary of Terms", 2013).

As for Supply Chain Management, the Council of Supply Chain Management Professionals ("SCM Definitions and Glossary of Terms", 2013) defines it as follows: "Supply Chain Management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and clients. In essence, Supply Chain Management integrates supply and demand management within and across companies. Supply Chain Management is an integrating function with primary responsibility for linking major business functions and business processes within and across companies into a cohesive and high-performing business model. It includes all of the logistics management activities noted above, as well as manufacturing operations, and it drives coordination of processes and activities with and across marketing, sales, product design, finance and information technology."

These definitions hold for all types of industries, so for the construction industry as well. Concerning precast concrete house-building projects, Luo et. al (2020) state that "supply chain involves production, transportation, and assembly linked by a client, a manufacturer, a transporter, a main contractor, and several service/product suppliers, which create value by transforming various materials, products, and components into the precast building project". Despite the fact that a lot of attention has been paid to improving Supply Chain Management for precast concrete house-building projects (by researchers such as Zhong et al. (2017) and Altaf et al. (2018)), there are still gaps in research. In particular, Luo et al. (2020) claim that the investigation and analysis has been limited to only single processes (e.g. logistics or manufacturing) rather than to the supply chain as a whole. Luo et al. (2020) add that the limited data accessibility has posed a hindrance to the collection of real supply chain data, hiding the real picture of Supply Chain in precast concrete house-building projects.

Understanding the significance of Supply Chain Management and relating it to the research gaps above and the current research, it is deemed necessary to move away from the single process investigation. As a starting point, logistics management and manufacturing process could be investigated simultaneously, as they appear to be important processes to a successful Supply Chain Management and consequently to a successful precast concrete house-building project. Therefore, in the following sub-sections, both the components of logistics management and manufacturing process have to be explored and linked to the current research.

2.2.2 Logistics Management

2.2.2.1 Definition

Logistics is described as “the process of planning, implementing, and controlling procedures for the efficient and effective transportation and storage of goods including services, and related information from the point of origin to the point of consumption for the purpose of conforming to client requirements.” ("SCM Definitions and Glossary of Terms", 2013).

As for Logistics Management, the Council of Supply Chain Management Professionals ("SCM Definitions and Glossary of Terms", 2013) defines it as follows: “Logistics Management is that part of Supply Chain Management that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption in order to meet clients' requirements. Logistics management activities typically include inbound and outbound transportation management, fleet management, warehousing, materials handling, order fulfillment, logistics network design, inventory management, supply/demand planning, and management of third-party logistics services providers. To varying degrees, the logistics function also includes sourcing and procurement, production planning and scheduling, packaging and assembly, and client service. It is involved in all levels of planning and execution-strategic, operational, and tactical. Logistics management is an integrating function which coordinates and optimizes all logistics activities, as well as integrates logistics activities with other functions, including marketing, sales, manufacturing, finance, and information technology."

Referring to precast concrete house-building projects, logistics management is summarized as the coordination of suppliers and contractors in order to integrate and optimize supply and operating choices (Said & El-Rayes, 2014; Luo et al., 2020). Effective management and control over supply/demand planning and materials/products transportation are the factors on which the success of construction projects hinges (Karthick et al., 2018). These factors allow the supply chain to operate in an optimal way (Augiseau & Barles, 2017), having better control over productivity and costs (Okeke & Mbabuike, 2020).

2.2.2.2 Delivery deviations

Nevertheless, logistics management practices are being hindered by variability, which, as Arbulu and Ballard (2004) mention, is "omnipresent in any supply system". In particular, this variability is translated in inaccurate warehouse records, missing or delayed deliveries, shortages, overordering, no direct unloading of transporters and misuse of product specifications, resulting in low productivity, delays and cost overruns for the construction project itself, the suppliers and transporters (Golkhoo & Moselhi, 2019; Bäckstrand & Fredriksson, 2020; Okeke & Mbabuike, 2020). Surprisingly, delivery deviations account for 8-25% of non-complete activities (Mishra et al., 2018), as they lead either to congestion in the construction site (vehicles waiting for unloading, inadequate storage locations, deterioration or theft of products) or excessive waiting times (Phan & Kim, 2016; Karthick et al., 2018). This is, what Bertelsen and Nielsen (1997) and Ekeskär (2016) name unnecessary and costly waste or non-value adding tasks. Hence, delivery deviations are worth to be explored further and so, the current research focuses on them, as part of the logistics management.

Reviewing the related work on delivery deviations, Lundesjö (2018) indicates main contractors as those responsible for managing the network of various deliveries of materials, products and resources to the construction site. In particular, Caron et al. (1998) proposed a stochastic model to plan material delivery to a construction site, so that the construction process continues smoothly. Georgy and Basily (2008) developed an approach that employs a genetic algorithm to optimize the material delivery schedule and the associated inventory control. Said and El-Rayes (2014) created an optimization framework for material supply and storage management at construction sites, while Mishra et al. (2018) devised a material delivery model for construction projects with near-term task level scheduling, taking into account the constraints posed by material delivery problems. Recently, Golkhoo and Moselhi (2019) developed an automated genetic algorithm-multilayer perceptron (GA-MLP) method to optimize material delivery schedule on the basis of material requirements planning and the least total material cost. Nevertheless, Nolz (2020) adds that time spent on non-value adding tasks, owing to organizational deficiencies, still poses a major challenge in the field of logistics management in construction.

2.2.2.3 Summary & Conclusion

Summarizing Section 2.2.2, effective logistics management appears to be a prerequisite for the success of a construction project. Many researchers have focused on improving material deliveries in construction projects. Yet, there is room for improvement, as non-value adding tasks are omnipresent in construction logistics management and thereby, in deliveries management. Furthermore, it is remarkable that little to no attention has been paid to product deliveries (the focus was mainly on material deliveries), let alone when referring to the sub-components in the precast concrete house-building industry. Therefore, the current research is triggered in an attempt to explore products', specifically sub-components', deliveries in the precast concrete house-building construction.

2.2.3 Manufacturing

2.2.3.1 Definition

Manufacturing process could be defined as the conversion of raw materials and components into finished goods (Al-tarawneh & Al-Shourah, 2018). The manufacturing process is able to respond to changes in demand and produce various products on time at the lowest possible cost, representing one of the most value-adding activities in the supply chain (Al-tarawneh & Al-Shourah, 2018).

Flexibility in the manufacturing process to be a value-adding activity in the supply chain, illustrates the uncertainty that exists in the manufacturing process. The flexibility of the manufacturing process is highly reflected on the time needed to manufacture a product and consequently, on the moment when this product is ready to be delivered to the client and the actual moment the client receives this product. The higher the uncertainty, the less the flexibility in the process and consequently, the more the negative effects on the various times involved. This is translated in higher uncertainty in Supply Chain Management as a whole and so, in Supply Chain Management of precast concrete house-building construction, as well.

2.2.3.2 Traditional manufacturing process

The traditional manufacturing process is the one of batch-and-queue (Ioana et al., 2020). Ioana et al. (2020) mention that what is typical in this manufacturing environment is the fragmentation of the batch and then, the processing at each step, according to the capacity of the equipment. In this way, the maximum capacity of the equipment is utilized, yet stocks of processed products are created in the different steps, making it difficult to visually detect a quality problem, thereby increasing the rejection rates (Ioana et al., 2020). This type of production (stock creation) leads to longer manufacturing time (Ioana et al., 2020), as the time spent in actual manufacturing of the product is less than 10% of the total manufacturing lead time (Senapati et al., 2012). Hence, the value-added time in the process is reduced significantly.

2.2.3.3 Manufacturing Lead time

Looking into manufacturing lead time, Alad and Deshpande (2014) define it as the sum of the processing time, setup, move and waiting time. Alad and Deshpande (2014) mention that "waiting time is usually largest of the four components, accounting for as much as 90% of manufacturing lead time in some system", while Johnson (2003) adds that waiting time should be targeted first. Equation [1] illustrates the calculation of manufacturing lead time:

$$\begin{gathered} Manufacturing\ Lead\ time \\ = \\ Setup\ time + Processing\ time + Move\ time + Waiting\ time \end{gathered} \quad [1]$$

The term "setup time" refers to the time needed for the changeover when the production is switched from producing a product A to product B (Kumar, 2013). "Move time" is usually included in the term "processing time" and refers to the time needed to properly handle and move equipment (Langstrand, 2016). "Processing time" is basically "the total time required to properly handle an item within a process step", while "waiting time" is referred to as "the time when products or people are idle" (Langstrand, 2016).

In general, various tools have been used for the reduction of each of the times constituting manufacturing lead time. A brief overview is presented below:

- Setup time reduction: Kumar (2013) explains that some of the main benefits from the reduction of setup times regard the batch size, inventory levels and cost of setup, thereby responding to client needs/schedules more flexible, improving on-time delivery and increasing machines capacity. Taiichi Ohno realized that set-up time reduction gave Toyota the opportunity to reduce batch sizes, thereby allowing products to reach clients with less delay (Monden, 2011). Patel et al. (2001) evaluated setup time to examine the type of improvements which can be made in a small company, by utilizing Shingo's Single Minute Exchange of Die (SMED), while the application of this methodology on a CNC machine by Kumar (2013) revealed a significant reduction in the down time, almost by half. Method study was, also, utilized by companies in an attempt to reduce set-up time (Alad & Deshpande, 2014).

- Processing, move and waiting time reduction:
  - Work study techniques, such as Method study and Work measurement, can reduce work content and ineffective time, thereby reducing total lead times (Alad & Deshpande, 2014). The study by Hemanand (2012) revealed a reduction in motion waste and a productivity improvement in automotive industry by utilizing used time, motion study and the Lean concept, yielding considerable total annual savings.
  - Lean tools aid in minimizing waste, referring to non-value adding activities (motion time, waiting time, set-up time etc.). In particular, the combination of Value Stream Mapping (VSM) and Methods-Time Measurement (MTM), as illustrated in the study by Kuhlang et al. (2011), resulted in the reduction of lead time/inventory, the increase in productivity, processes' standardization, accurately determined times, while ensuring the predictability and capability to assess the target status. Ballard et al. (2003) utilized Value Stream Mapping (VSM) to identify non-value adding tasks in precast components manufacturing and they observed a reduced cycle time and lead time.
  - An effective Lead-time Evaluation and Scheduling algorithm (LETSA) was developed by Agrawal et al. (2000) aiming to minimize cycle time, in the context of Production planning and control.

2.2.3.4 One-piece-flow manufacturing process

In an attempt to move away from the traditional manufacturing process of batch-and-queue, and consequently from long manufacturing lead times, Ioana et al. (2020) moved towards the Lean flow, named one-piece-flow, at an improvement project in automotive industry. What one-piece-flow entails is moving the product step-by-step through the process without waiting time (Ioana et al., 2020). According to Krijnen (2007), one-piece-flow meets client requirements on the basis of Just-In-Time methodology (a Lean tool as well), while minimizing waste in the production line. Marton and Paulová (2013) recognize the prevalence of one-piece-flow over batch-and-queue, but also the fact that one-piece-flow is more expensive than batch-and-queue and not always achievable and efficient, owing to the increased frequency of set-ups, the high associated set-up costs and the inefficiency of delivery too small batches. However, Marton and Paulová (2013) note the importance of continually improving manufacturing processes in order to get closer to the original one-piece-flow, leading to lower inventory levels, shorter manufacturing time and better client service.

2.2.3.5 Summary & Conclusion

Summarizing Section 2.2.3, manufacturing process, if not flexible, has significant effects on Supply Chain Management and therefore, on projects' performance. There have been serious attempts to reduce manufacturing lead time within the traditional manufacturing process of batch-and-queue. Moving towards one-piece-flow seems to be the most promising one, yet it is claimed to be expensive and not easily achievable and efficient. However, it is worth noting that nothing is mentioned in relation to the reduction of sub-components' manufacturing lead time in precast concrete house-building industry, but only for the precast components. Therefore, the current research is triggered to explore the capabilities of moving towards one-piece-flow, in the context of improving manufacturing lead time of sub-components and adding value in the supply chain of precast concrete house-building industry.

3 PROBLEM DESCRIPTION

This chapter specifies the problem at hand. First, a general overview of the identified problem in literature is presented, followed by the identified gaps and the problem, as company Janssen de Jong perceives it. Finally, the research questions triggered by the formulated problem are listed.

3.1 Problem identified in literature

As presented in Chapter 2, Supply Chain Management plays a key role in dealing with the uncertain and complex nature of construction industry. Non-value adding tasks, namely delivery deviations and long manufacturing lead times, are omnipresent and account for long lead times and consequently, delays and cost overruns. This problem is ever relevant for the construction industry, as the working environments are becoming more and more congested and urge for shorter duration. The precast concrete house-building industry, as part of the construction industry, could not remain competitive based on long lead times.

3.2 Gaps in literature

The gaps identified in literature are the following:

- The investigation and analysis of Supply Chain Management for precast house-building projects has been limited to only single processes (e.g. logistics only or manufacturing only) rather than to the supply chain as a whole (Luo et al., 2020).

- Limited data accessibility has posed a hindrance to the collection of real supply chain data, hiding the real picture of Supply Chain Management for precast concrete house-building projects.

- Little to no attention has been paid to product deliveries (the focus was mainly on material deliveries), certainly not for the sub-components in the precast concrete construction industry.

- There have been serious attempts to reduce manufacturing lead time within the traditional manufacturing process. However, it is worth noting that nothing is mentioned in relation to the sub-components of precast concrete house-building industry, but only for the precast components.

- In general, various attempts have been made to reduce lead time in construction, yet lead time reduction of precast concrete housing sub-components seems to be a neglected area.

3.3 Problem formulated by the company

The problem described in the first place by the company *Janssen de Jong,* in which the present study is conducted, is indicative of the problem identified in literature. *Janssen de Jong* operates in the field of construction, yet it is not leading in precast concrete house-building projects. As part of the construction the company undertakes projects consisting of a specific number of houses. The company's wish is to reduce the time needed to build one precast concrete house at the precast concrete factory in order to have it on the construction site as per planning. In this way, the overall time needed for the project to be completed will be significantly reduced. However, long lead times and specifically sub-components' long lead times, referring only to manufacturing and delivering to the precast concrete factory and not to the construction site itself, pose a major problem in achieving this goal.

In particular, since each project has unique specifications, posed by the client, the sub-components are bespoke, meaning that they need to be engineered differently compared to the projects of other clients. This leads suppliers to the traditional manufacturing process of batching-and-queuing, in order to prevent setup times, which is in conflict with the wish of the company for moving towards one-piece-flow and shortening lead times. As illustrated in Section 2.2.3.2, the traditional manufacturing process leads to non-value-added time and thereby, long manufacturing times. As a consequence, the delivery of the sub-components to the precast concrete factory is negatively affected. If the long manufacturing lead time and the delay in delivery are added up, then a long lead time arises. The interesting note here, as Janssen de Jong explains, is that there is no substantial delay caused by the precast concrete factory itself. When all the sub-components are available, it takes around twelve hours to produce a complete component.

3.4 Research questions

Combining the gaps in literature with the problem posed by Janssen de Jong, the following main research question and sub-questions can be formulated to improve sub-components' lead times in precast concrete house-building projects: starting with order placement, so the time needed to manufacture the sub-components, and ending with the receipt of goods ordered by the precast concrete factory, so the time needed to deliver the sub-components.

Main Research Question: *How could sub-components' lead times in precast concrete house-building projects be optimized, to improve project performance in terms of time and cost?*

Sub-questions*:*

1. *What are sub-components in precast concrete house-building projects and what are the main sources of long sub-components' lead times?*

2. *What are the effects of sub-components' long lead times on project performance?*

3. *How could the development of a mathematical optimization model aid in optimizing sub-components' lead times in the context of precast concrete house-building projects?*

4. *How could the developed mathematical optimization model be validated using a real precast concrete house-building project, as a case study?*

4 RESEARCH METHODOLOGY

This chapter presents the methodology used to address the formulated problem and answer the research questions. The methods utilized are four in total: literature review, interviews, mathematical optimization modelling and validation through case study.

4.1 Literature review

Literature review method is utilized in order to partly answer the first two sub-questions:

1. *What are sub-components in precast concrete house-building projects and what are the main sources of long sub-components' lead times?*

2. *What are the effects of sub-components' long lead times on project performance?*

As illustrated before, delivery deviations and long manufacturing lead times account for long lead times in construction industry. Yet, little to no attention has been paid to products and specifically, to sub-components' long lead times in precast concrete house-building industry. Therefore, as a first step, it is important to explore the generally recognized sources of long lead times in construction industry in relation to/and adjust them to the problem at hand, and then, identify any other relevant source. Specifically, the traditional manufacturing process, referring either to materials or products, consists of specific steps and its typical shortcomings are common between the various sectors of construction industry. Hence, a conclusion can be drawn for the manufacturing times of sub-components in precast concrete house-building industry, as well. The same holds for delivery deviations. Moreover, any other source of long sub-components' lead times will be identified. Finally, the effects of the long lead times on a construction project's performance will aid in revealing the effects of long lead times on precast concrete house-building project performance, as well.

4.2 Interviews

Interviews with Janssen de Jong, the precast concrete factory and the involved suppliers (the windows and frames supplier and the installation technology supplier) are held in order to complete the puzzle and provide more specific answers to the first two sub-questions. The different perspectives of the practitioners who are directly involved in the process can shed light on these questions. The goal is each and every one of them to explain the reasons behind sub-components' long lead times as they perceive them, how these are translated in time and cost terms for their operations, to what extent they are willing and at which cost to change their way of working in order to meet client's wish and maybe, where an ideal balance could be found.

4.3 Mathematical Optimization Model

Once the information is gathered by literature and interviews, it will be used to describe the exact procedure that needs to be optimized. Afterwards, the variables will be defined. Then, the objective functions and the constraints will be formulated, using mathematical equations. In this way, the problem under consideration will acquire a mathematical substance and then, it will be translated into *Python Programming Language.* This, will enable the search of the optimal or (near-optimal) solutions. Therefore, the mathematical optimization model serves as a tool in answering the third sub-question:

3. *How could the development of a mathematical optimization model aid in optimizing sub-components' lead times in the context of precast concrete house-building projects?*

The overall goal of this model is to be applicable as much as possible. For instance, the precast concrete factory could be substituted in another study by the construction site itself, at which the long material lead times need to be optimized.

4.3.1 Reason for the selected approach

"*Modelling is one of the most appealing areas in engineering and the applied sciences. In fact, engineers need to build models to solve real-life problems. The aim of a model consists of reproducing the reality as faithfully as possible, trying to understand how the real world behaves and obtaining the expected responses to given actions or inputs.*" (Castillo et al., 2002).

The statement by Castillo et al. (2002) illustrates the importance of modelling, in an attempt to find solutions to real-life problems and support the decision-making process. In recent years, various types of models have been developed in order to support decision-making processes. In particular, the complex nature of manufacturing systems, which entails complex decision-making, could be supported in an effective way by simulation models and mathematical optimization models (Caggiano et al., 2015).

Simulation modelling enables decision makers to verify given scenarios, as they can "evaluate the most relevant performance indicators for each problem and obtain valuable data that suggest potential reconfigurations or improvements to enhance the system" (Caggiano et al., 2015). Nevertheless, simulation modelling does not contribute in generating the optimal (or near-optimal) solutions to the examined problem (Caggiano et al., 2015).

On the other hand, mathematical optimization models "serve the aim of determining optimal (or near-optimal) solutions for decision variables by formally describing problems in terms of objective function and constraints to be satisfied" (Caggiano et al., 2015). Therefore, a mathematical optimization model contributes in generating specific solutions to a problem.

In any case, Castillo et al. (2002) mention the importance of selecting the model that reproduces adequately the reality, in order to reach an acceptable solution to a real problem. The current research aims on improving sub-components' lead times in precast concrete house-building projects, starting with the manufacturing process and ending with the delivery of sub-components to the precast concrete factory. Therefore, the manufacturing process is highly involved in the examined case and thereby, both simulation and mathematical optimization modelling could be utilized for modelling the problem (as described in the previous paragraphs). However, the focus is on finding the optimal (or near-optimal) solutions to the problem of sub-components' lead times in precast concrete house-building projects and not just on understanding how the whole system operates by evaluating different scenarios. For this reason, the mathematical optimization modelling, aiming on generating solutions that optimize the objectives of the system, is selected as the approach that best fits in the examined problem.

4.4 Case study

A case study is used in order to answer the fourth sub-question:

4. *How could the developed mathematical optimization model be validated using a real precast concrete house-building project, as a case study?*

Specifically, the manufacturing and then, the delivery of a sub-component to the precast concrete factory will be used as a case study. The data for this project was expected to be provided by Janssen de Jong and the involved suppliers, as discussed at first place when this research started. Unfortunately, it proved that there is limited data accessibility due to confidentiality reasons mainly. Therefore, a further personal research for other relevant suppliers was necessary. Further details are provided in Chapter 8. The collected data will be introduced into the developed mathematical optimization model. In this way, it will be tested whether this model can be useful in reality as opposed to only being useful within research.

5 LITERATURE REVIEW – *Sub-Questions 1,2*

This Chapter aims to partly address the first two sub-questions of the current research:

1. *What are sub-components in precast concrete house-building projects and what are the main sources of long/unnecessary sub-components' lead times?*

2. *What are the effects of sub-components' long lead times on project performance?*

It is divided in three sub-Sections: the first one, defines the sub-components in precast concrete house-building projects and the other two (partly) answer the two sub-questions in relation to Supply Chain Management as a whole and its components (manufacturing and logistics management), respectively.

5.1 Precast concrete house-building: *Sub-components*

A precast concrete house consists of various raw materials, which are transformed into components and sub-components. Precast components include mainly beams, walls, columns, floors, staircases and lintels (Glass, 2000). The products that are being integrated into the components, for instance windows being embedded into walls, could be referred as sub-components. It is obvious that sub-components are provided to the precast concrete factory by various suppliers, while components are produced at the precast concrete factory itself.

5.2 Precast concrete house-building: *Supply Chain Management*

The challenging part of Supply Chain Management for precast concrete house-building projects is that there is more than one production location (various sub-component factories, precast concrete plant and site), which makes the need for coordinating efforts even more crucial, regarding both manufacturing and logistics management (Koskela & Stanford University. Center for Integrated Facility Engineering, 1992; Lessing et al., 2005; Nahmens & Mullens, 2011). Vallet-Bellmunt et al. (2011) and Ji et al. (2018) claim that the success of Supply Chain Management in precast concrete house-building projects hinges on the coordination and relationships between the stakeholders. Effective coordination and strong relationships can enhance stakeholders' competitiveness and add value for the end client (Ji et al., 2018).

Since multiple stakeholders, each one having their own interests and role, and multiple sub-processes are involved in the precast concrete house-building process, it is self-evident that coordination and strong relationships are rather complex to achieve. This complexity is translated into ignorance of each other's practices, poor communication of necessary information, poor workflow and inadequate production planning (Hwang et al., 2018; Niu et al., 2017) and, by extension, increase of non-value adding actions (Luo et al., 2020; Forsman et al. 2012). The most indicative problems are overproduction, excess inventory and long lead times (Forsman et al. 2012; Wu and Low, 2014; Zhai et al., 2016), which result in time and cost overruns. Time and cost overruns affect significantly the reputation of the stakeholders involved, causing even loss of competitiveness (Benjaoran & Dawood, 2006). For this reason, Nahmens and Mullens (2011) mention "the importance of developing and nurturing relationships throughout the supply chain", which is supported by the example of the Japanese, whose efforts to reduce lead time are aided by the strong and lasting relationships they have with their suppliers (Senapati et al., 2012).

5.2.1 Conclusion

It can be concluded that all the aforementioned apply to the examined case of sub-components, as they are part of the multi-stakeholder/agent precast concrete house-building process. As mentioned before, the sub-components are not produced at the precast concrete factory. Therefore, the company, the precast concrete factory and the involved suppliers could be recognized as the "multiple stakeholders involved in the process". All of them consider their own interests and values, yet the actions of each and every one of them affect the overall performance of the project. This automatically highlights the importance of coordination and long-term relationships between them, which if absent result in long lead times, and so in waste (non-value-adding tasks) in the process, time and cost overruns (poor project performance), loss of competitiveness and disappointed clients.

5.3 Precast concrete house-building: *Manufacturing & logistics*

The traditional manufacturing process is the one of batch-and-queue (see Chapter 2). This means that production by batch is used instead of production by piece, which is referred to as one-piece-flow. The size of the batch could be defined as "the number of products to be produced and released to a next process at one time" (Shim, 2011).

Shim (2011) mentions that batch size has been recognized as the principal factor that affects the performance of all kinds of projects in terms of duration and cost. In particular, batch size reduction has proven to raise production performance, thereby shortening lead time and project duration (Sacks & Goldin, 2007; Santos & Powell, 2001). This is because the work completed in one activity is released early to the next activity, reducing the idle resources between activities, and so manufacturing time and delivery time to the end client (Shim, 2011). In support of these arguments, McLean (2017) states that big batch sizes take longer to run and to consume the inventory from large shipments, while the orders of clients are not fulfilled when needed. Nevertheless, suppliers cleave to the idea that producing big batches and shipping full trucks, saves money and freight (McLean, 2017). Therefore, they are afraid and hesitant about reducing the batch size (Ward & McElwee, 2007). What they use as a strong argument against it, is the increase in the number of set-ups and the associated costs (Santos & Powell, 2001). Ward and McElwee (2007) explain that suppliers believe that this kind of change will reduce the efficiency of their work, demand for extra labor force and result in extra costs or/and extended duration.

5.3.1 Conclusion

Concluding, as the traditional manufacturing process refers to all kind of projects, and so to precast concrete house-building projects, it is logical that the conditions and perceptions around the traditional manufacturing and supply environment (big batch sizes and full trucks) apply to the case of sub-components, as well. The sub-components needed for a precast concrete house are various and they are produced at different production environments (factories/suppliers), in which the traditional manufacturing process (big batches) seems to be dominant. It is self-evident how negatively the lead time of each of the sub-components can be affected by the reluctance of the respective supplier to reduce the batch size. Consequently, it is obvious what happens if more (or all) suppliers hesitate to reduce the batch size, owing to their fear of working inefficiently: longer lead times resulting in poor project performance (a lot of idle time in the process, excess inventory, cost and time overruns).

6 INTERVIEWS

This chapter presents the information collected while interviewing the various stakeholders. This information is used to provide more detailed answers to the first two sub-questions, obtained from real working environments. These answers along with general information collected by the interviews, will be utilized to frame the problem at hand using mathematical terms, contributing to the answer of the third sub-question.

The chapter is divided in four sub-sections, each one corresponding to one of the four involved stakeholders: Janssen de Jong Bouw (construction company), Van de Vin (windows and frames company), Geelen Beton (precast concrete factory), "Anonymous Company" (installation company).

6.1 Janssen de Jong Bouw B.V. – *Construction Company*

Interviewee A was the first interviewee on behalf of *Janssen de Jong* (transcript of this interview is included in Appendix D).

According to Interviewee A, although *Janssen de* Jong is a large construction company, it is not ahead in precast concrete house-building. It is stated that "the main concern of *Janssen de Jong*, in the field of precast concrete house-building industry is the inefficiency in the unbalance of workflows. Because we are dealing with companies that have individually optimized their processes, there is a lot of waiting between the different tasks. As a construction company, our objective is to bring all these parties together in the most efficient way for the project, not just the individual tasks".

Referring to long lead times in precast concrete construction, the company mentions the delivery of sub-components in large batches as the main contributor. Interviewee A adds that the individual lead times of engineering and manufacturing of sub-components, prolong the total lead time of sub-components and the total lead times of the concrete components, as well. As Interviewee A explains, this owing to the fact that sub-components are bespoke (since every project is unique and has different specifications), meaning that there are variations in their form, which specify different engineering/processing times.

Except the prolonged total lead times of the concrete components, which is the direct consequence of long sub-components' lead times, Interviewee A adds that "the main effect is that big parts of the project are constantly waiting for the next task to be performed. Since as a construction company we manage the schedule of all subcontractors and suppliers on site. The longer this takes the less projects we can execute. The lead time shortening therefore, gives us the opportunity to execute more projects and the leverage of exponentially increased turnover".

6.1.1 Conclusion

Looking back to the first two sub-questions of this research and summarizing the answers provided by the company in relation to them: it is clear that the manufacturing process and the delivery of sub-components in large batches significantly affect the lead times of the sub-components themselves, but also the lead times of the concrete components in which the sub-components are to be embedded. The consequence of these lead times is the omnipresent waiting time, which acts as a hindrance for the timely and in-budget completion of projects and to the ability to execute more projects.

6.2 Van de Vin ramen en kozijnen B.V. - *Windows & frames Company*

Interviewee B was the second interviewee, on behalf of *Van de Vin ramen en kozijnen B.V.* (transcript of this interview is included in Appendix D).

According to Interviewee B, their lead time, as a window company, is ten weeks: six weeks to get the definite drawings for the windows to produce, four weeks to order the materials needed (like glass) and about one week to actually produce the windows. Interviewee B adds that someone may argue that the company is a bit more expensive than other companies in this field which operate differently, but his counterargument is that the company "can offer shorter lead times, which is also money".

Surprisingly, when Interviewee B was asked about the minimum and maximum batch sizes they use and their way of working, he said that they already follow one-piece-flow manufacturing method. In this way, as Interviewee B states, they managed to reduce most of the waiting times involved in their processes. The only waiting times that still hinder their processes are related to the drawings of the windows. Interviewee B notes that, for six weeks, the drawings come back and forth to them and the client, in order to be checked and verified. This happens because the process of making the drawings is not standardized. The clients (and so Janssen de Jong), as Interviewee B describes, would save them a lot of time if they used the sub-components (windows or doors) that are presented by Van de Vin in their 3D models. Except waiting times, Interviewee B argues that they managed to reduce the variability in deliveries, as well. This can be attributed to the fact that most of their clients work with the same precast concrete factory, so the company can easily combine deliveries of different clients on a daily basis and deliver them to this specific location. Of course, there exist cases in which they have to deliver only one order of one client or different orders to different locations. What Interviewee B notes is that one truck per client is more common in other companies, as clients want to protect their products and think they save time.

It is worth noting that the company does not refer to large batch size as a contributor to sub-components' lead times, as Janssen de Jong did. This is due to the fact that they work in an already optimized way, as described above, yet this is not the case for all the companies nowadays. Interviewee B claims that people keep insist on working horizontally (processing the products at each step of the process, so basically batch-and-queuing) and non-vertically (vertically means moving step-by-step through a process, so following one-piece-flow) and this has to change. Interviewee B explains that ten to twelve years ago, when they also started producing, they used to work with large batch sizes. And so, they had large queues and great amount of stock, leading to high costs and non-satisfied clients.

6.2.1 Conclusion

Looking back to the first two sub-questions of this research and summarizing the answers provided by the company in relation to them: although the company, when referring to their current way of working, did not recognize the batch size, but the waiting time in making, checking and verifying the drawings, as the main contributor to lead times, three important conclusions can be drawn. The first one is that the batch size did pose a problem to them in the past, leading to excessive times and costs, and still poses a problem to many other companies, which have not optimized their processes. The second conclusion is that there is no problematic situation in the company in relation to the batch sizes and delivery of the windows, which is described as one of the problems by Janssen de Jong. Therefore, there is no room for optimization in the case of this company in relation to the current research. Of course, it is important to bear in mind that the company delivers mostly to one specific place, what favors their whole process of making and delivering small batches to different clients with the same truck. Yet, this is not how other companies work. The final conclusion is that the implementation of one-piece-flow in reality proved to be effective, yet its implementation might be more expensive than the traditional manufacturing method.

6.3 Geelen Beton - Precast Concrete Factory

Interviewee C and Interviewee D were the next two (third and fourth) interviewees, on behalf of *Geelen Beton Wanssum en Posterholt* (transcript of this interview is included in Appendix D).

As the interviewees at the precast concrete factory describe, according to their experience throughout the years, the sub-components' long lead times stem from the large batches that the window and installation companies deliver to them. They explain that the large batches can cause delay and disruptions in their way of working, which are not desirable, as time is money. In particular, they claim that the tactic of large batches still hinders their process, when referring to the installation companies. The installation companies usually deliver to precast concrete factory sub-components for about ten houses at the same time, because for the installation company this is one truckload, while for the precast concrete factory it corresponds to around sixty components. However, this is not the case for the window company (they work with the window company presented before), as this company has already optimized its process towards one-piece-flow and so, it delivers small batches. One of the interviewees specifically states that "we managed with Van de Vin to get it in the order we want it and just a small time before we need it. So not the whole project at the same time, but in batches. And we prefer small batches, but Van de Vin also needs to drive as few times as possible, so the batches cannot be too small". The last part of Interviewee's C statement illustrates the importance of making small batches, but up to the point at which the delivery of them is still efficient, implying that too small batches are not efficient and should be avoided. Moreover, they note as an additional contributor to the long lead times the fact that they have to educate over and over again different installation companies, as they are usually different from project to project.

As for the consequences of sub-components' long lead times, the interviewees clarify that they do not really affect their schedule itself, when they are informed in advance about them. And their ability of not being affected that much by delays, for which they are being informed timely, stems from their continuous efforts to have a stable production per day (approximately six houses per day). However, the consequences of sub-components' long lead times are evident when referring to the inventory at their place, as they end up with a lot of sub-components waiting, when delivered belatedly and massively for many projects.

6.3.1 Conclusion

Looking back to the first two sub-questions of this research and summarizing the answers provided by the two interviewees in relation to them: they recognize the large batches as the main contributor to sub-components long lead times. Thus, they highlight the importance of small batches, as far as they enable efficient deliveries. In this way, they will not lose space, as they do now, owing to the large batches send mainly by the installation companies (installation suppliers).

6.4 Anonymous Company – Installation Technology

Interviewee E was the fifth interviewee, on behalf of *anonymous installation company"* (transcript of this interview is included in Appendix D). The anonymity of the company is preserved upon their request.

This company is specialized in Heating, Ventilation, Air Conditioning (HVAC) and plumbing systems. The company works with a batch size of one, meaning that they follow one-piece-flow manufacturing method. In this way, they can shorten lead time and work more efficiently in comparison with working with large batches. It is, also, mentioned that by utilizing internal transportation, so their own trucks, the small batches are efficient to be delivered. In any other case, they need an external company and the costs are different. Yet, Interviewee E recognizes that the perception of minimum batch differs per company, meaning that not all companies have moved towards reduction of the batch size. Interviewee E adds that not all clients understand that receiving their products faster affects (increases) the amount of money to pay.

It is important to note that this company cannot be deemed as a purely manufacturing company, which has optimized its process towards one-piece-flow, or be used as a paradigm for how similar companies in this field (should) work. This is because, as the Interviewee E implies, the company did not really experience the actual difference between batch-and-queue and one-piece-flow in their process, in terms of set-ups, inventory and waiting times. Specifically, the Interviewee E explains that the actual manufacturing part (cutting to length the airducts) is being done at another factory, which is not a common scenario for other installation companies. And of course, the effects of batch-and-queue are evident in the process and lead times of this factory, but they are kind of hidden in the lead time of the company. The manufacturing part of the latter is only about airducts being mounted together and it is reasonable, that one-piece-flow is easier to be approached when the cutting part has already been done.

6.4.1 Conclusion

Looking to the first two sub-questions of this research and summarizing the answers provided by Interviewee E in relation to them: Interviewee E indirectly recognizes the large batches as the contributor to sub-components long lead times, as they negatively affect time-efficiency, while directly highlights the time-efficiency of small batches. Yet, Interviewee E implies an increase in the price, as a natural consequence of faster operations, which is still not understandable by most of clients. While referring to one-piece-flow in the case of this company, it is important to bear in mind that this choice is significantly favored by the fact that another company is responsible for the manufacturing part. This means that a large part of the manufacturing related to set-ups, inventory, manufacturing lead times is removed from the work of the former. Hence, one-piece-flow cannot be considered as a given and/or easily feasible method in another installation technology company, which is responsible for the manufacturing as a whole.

7 MATHEMATICAL OPTIMIZATION MODEL

The goal of this Chapter is to answer the third sub-question:

3. How could the development of a mathematical optimization model aid in optimizing sub-components' lead times in the context of precast concrete house-building projects?

The answers to the first two sub-questions of the current research indicate that the batch size and the miscommunication of information, along with the absence/presence of strong relationships between the various stakeholders, are the main contributors to the long sub-components' lead times in precast concrete house-building industry. Nevertheless, the latter contributors cannot be taken into account in building this optimization model, because of the complexity to model and quantify these aspects. Thus, the batch size is the main variable around which the optimization model can be developed. The relevant information gathered denote that:

– The traditional manufacturing method (batch-and-queue) and specifically, the large batch size accounts for long waiting times, excess inventory, inefficient deliveries and finally, long sub-components' lead times in precast concrete house-building industry. These long lead times affect negatively the performance of a project in terms of time and costs. However, batch-and-queue utilizes the equipment at its maximum capacity and only few set-ups are needed, and so fewer set-up costs.

– On the other hand, moving towards one-piece-flow manufacturing method (batch size of one) appears to be a promising approach, yet it has shortcomings, as well. As Janssen de Jong describes, "the inefficiency of extra transportation or inactivity due to too small batches can lead to higher costs, with minimum benefit on the project". Explicating this statement: it is reasonable that the client wants to build houses faster, in order to undertake more projects and increase profit. On the contrary, the fear of working inefficiently and having extra costs drive the decision of suppliers to follow the traditional manufacturing method. And this decision is even more justified for them, when they have to produce bespoke sub-components. Specifically, if they follow the wish of the client for smaller batches, they claim that they will have more set-ups in between the production, which will reduce the efficiency of their work, will increase the demand of workforce and so, the costs, and bring them delays in producing other orders. Therefore, their fear is that their efficiency and profit will be jeopardized. This is the reason why a company, in such case, ends up being more expensive than other companies (which still operate as per their own wish), in an attempt to manage these risks and feel economically safe. The window company and the installation technology company serve as a real evidence, that shortening lead times, by producing and delivering smaller batches, results in additional costs.

Hence, it can be concluded that there is a clear conflicting relation between reducing costs and shortening lead times (reducing batch size), which stems from the conflicting interests of the client and the suppliers. So, the optimization model should consider the arguments against and in favor of both manufacturing methods and so, the interests of the client and the supplier, and include a range of the batch sizes a supplier can provide along with the time and costs involved in the production and delivery. In this way, the client will be able to map the cost- and time-related implications of minimizing lead time and costs simultaneously.

In the following sub-sections, an overview of the process to be optimized is presented along with the development of the mathematical optimization model.

7.1 Overview of the process to be optimized

This section includes an overview of the process to be optimized. The scope is limited to the manufacturing (production) and transportation of house-building projects' sub-components to the precast concrete factory. It is important to clarify that:

- The transportation of the houses to the construction site is out of the scope of this research, as the longest lead times are found in the production and transportation to the precast concrete factory, according to the company (Janssen de Jong).

- The design lead time is not included, as the designs are already specified when the order is made.
- The supply of raw materials to the respective suppliers is out of the scope of this research as this sector cannot be really influenced. Moreover, the supply of raw materials to the precast concrete factory (cement, gravel, sand, aggregates etc.) is not taken into consideration, as these materials have short lead times. Therefore, in any case, raw materials are deemed available when an order is placed.
- The contribution of this research to the construction community is limited to the results obtained by the optimization model, which can be used as a guide in order for the client to understand the implications of her/his preference each time. Assigning works (such as ordering or delivering) to specific dates or making further decisions, based on the model's results, is out of the scope of the current research.

Below, the description of the process to be optimized is introduced in steps:

1. The client places the order for the various types of sub-component needed for the whole project (for instance, 75 houses) to the supplier. To illustrate, if the total number of houses to be built is 75 and each house needs 10 windows (3 of type I, 3 of type II, 4 of type III), the client places an order to the window (sub-component) supplier for:

$$10\ (windows) * 75\ (houses) = 750\ \ windows\ for\ the\ whole\ project$$

Or

$$[3\ (windows\ of\ type\ I) + 3\ (windows\ of\ type\ II) + 4\ (windows\ of\ type\ III)] * 75 (houses) = 750\ \ windows\ for\ the\ whole\ project$$

2. The supplier starts the production of the different types of sub-component in large batches. The size of each of the batches usually equals the quantities ordered per type and the number of batches equals the number of types. Referring to the example above, for three types of windows, the number of

batches will be three, as well. The size of batches will be 225, 225 and 300, respectively.

3. The batches are loaded on truck(s) and delivered to the precast concrete factory.

4. The process ends when the demand is satisfied, that is when the batches of all the types of the sub-component are successfully delivered by the supplier to the precast concrete factory.

7.2 Development of the mathematical model

The current section concerns the development of the mathematical model. As an introductory note, the rationale behind the design of the model is explained. Then, the assumptions made for its development are introduced. Afterwards, the parameters, variables, objective functions and constraints are presented.

7.2.1 Rationale behind model designing

As explained, the wishes of the client and the suppliers should be taken into consideration in order to capture the various time- and cost- scenarios and provide realistic information to the decision maker (client). Therefore, the optimization model aims to minimize the two conflicting objectives of lead time and total cost, based on the variations of the batch size. The lead time refers, basically, to the supplier's practices, while the total costs refer to the revenues of the supplier, so the amount of money the client has to pay, based on the relative importance of each of the objectives (shortening lead time and reducing cost) to her/him, each time.

The aforementioned suggest that the optimization model should run for each and every supplier, separately. The client's request to the respective supplier involves, basically, a request for changing/adjusting the latter's way of working (reducing the batch size, that is approaching one-piece-flow). Therefore, it is important for the client to understand how such a request is translated into time and money in each case and draw conclusions which will be useful for future projects, as well. An additional reason that justifies the choice of not including all the suppliers in the optimization model simultaneously, is that the suppliers work independently and the way the one works does not depend on the others' way of working. The time they all need for production and delivery cannot be added up, because in this case, each supplier will wait for the other in order to start the production, which does not happen in reality.

7.2.2 Assumptions & Simplifications

Since every optimization model cannot approach absolutely the reality, some assumptions and simplifications have to be made. The assumptions and simplifications in the model of the current research are listed below. More specifically:

- The client places the order of the various types of a sub-component to the respective supplier for the whole project. This is how the orders are placed in reality.
- The manufacturing method (operating tactic) the suppliers utilize is similar to that of batch-and-queue.
- Having as a basis the batch-and-queue manufacturing method, the one that the model tries to explore and approach is the one-piece-flow.
- Only one supplier can supply a sub-component and its various types. For instance, only one supplier can provide all the different types of windows needed for the project execution.
- Each supplier has her/his own operating policy, that is a range in the batch size that she/he can produce.
- There is no availability of the sub-components at the respective supplier when the order is placed, as sub-components are bespoke and not catalogued.
- The raw materials needed to produce the sub-components are available at the respective supplier and also, at the precast concrete factory.
- Each supplier has one assembly line, as the worst-case scenario, and there is a continuous flow of production.
- The model does not look into the orders of other clients, as the sub-components are bespoke and cannot be used elsewhere. The model pays attention only to the production of this specific order placed by one client.

- The production of different types of sub-components does not start immediately after the placement of the order in all cases in reality, so an indicative delay is included in the model.
- The various types of a sub-component are assumed to share the same number of production runs. The term “production runs” refers to the number of steps needed to produce a type of sub-component. Furthermore, the time needed to process one unit of a type at each production run is assumed to be the same for all production runs of this type.
- The model focuses on the variations in production time of the various types owing to the various batch sizes. Therefore, except the set-up time in between the production, the rest of the waiting times involved in the process of producing all the different types, which are present irrespective of the batch size, are summarized in a parameter (Δ) and an average value is used for them.
- The batch size that the optimization model selects each time is only one for each supplier, irrespective of the number of types. That is, the various types of sub-component are assumed to share the same batch size.
- The transportation/delivery of the sub-components to the precast concrete factory refers to ground transportation only.
- The delivery of the quantities of the different types of a sub-component needed for the whole project is not done all at once, but by installments. The number of itineraries each time is related to the capacity of the truck.
- Each supplier utilizes one specific type of truck for the deliveries and the full truckload service is applied. This means that the truck is loaded with the order of one client only and there are not intermediate stops between the point of departure and the destination point, as would happen in the case of mixing orders from different clients. So, time is saved. The capacity of the truck for each supplier is fixed.
- In a full truckload service, the client pays a standard price for leasing the whole truck, irrespective of the percentage in which the truck is loaded. So, this is the fixed delivery cost per truck (T). The quantities ordered for the different types and the size of the truck determine the number of trucks that will be used for the whole order and the final total costs. Furthermore, the distance to be covered (and many other terms, such as the vehicle depreciation, the

maintenance costs, the fuel price, the salary of the driver) is already included in the standard delivery cost that the transportation company asks for each time. For this reason, the distance is not included as an extra term in the delivery cost calculation in this model.

- The distance to be covered, so the time needed for the deliveries is not affected by the variations in the batch size, as it is fixed and it can be obtained by several map platforms. This choice is based on the fact that in the full truckload service the trucks are utilized by one client only, that is there are no intermediate stops between the point of departure and the destination point. Therefore, the distance is fixed, it has negligible contribution to the time and so, in the time equation.
- The term “inventory” refers to the inventory that is created between the production runs in the batch-and-queue manufacturing method, owing to the waiting time involved in the process. In reality, the inventory cost is fixed per day, meaning that there is standard average value per day (not per piece). Therefore, in the current research it is given as fixed per day, as well (I). So, the greater the waiting time, the greater the total inventory costs.
- Except the set-up costs and the inventory costs, which are affected by the variation in the batch size, the summation of other costs such as the price of raw materials, the labor costs, electricity used to operate the equipment, are given as a fixed price per type of sub-component.

7.2.3 Parameters

The parameters, that is the data used as inputs in the development of the mathematical optimization model, are listed below. They can be grouped in four main categories for better comprehension:

- General: this category provides general information about the suppliers and their operating policy;
- Quantity-related: this category provides information about the order (quantity of the different types) a client makes to the supplier;
- Time-related: this category provides information about the various times involved in sub-components' lead time;
- Cost-related: this category provides information about the various costs involved in producing and delivering the sub-components.

Table 7-1 below summarizes the parameters corresponding to each category along with their range of definition and a description.

Table 7-1: List of parameters

CATEGORY	PARAMETER	DESCRIPTION
General	$t \in \mathbb{Z}^+$	*Types of sub-component*
	$\beta \in \mathbb{Z}^+$ (in pieces)	*Minimum batch size that supplier can produce (operating policy)*
	$B \in \mathbb{Z}^+$ (in pieces)	*Maximum batch size that supplier can produce (operating policy)*
	$r \in \mathbb{Z}^+$	*Number of production runs on the assembly line*
	$k \in \mathbb{Z}^+$ (in pieces)	*Maximum truck capacity*
	$d \in \mathbb{R}^+$ (in km)	*Distance from the supplier to the precast concrete factory*
	$v \in \mathbb{R}^+ (\frac{\text{km}}{\text{h}})$	*Average velocity per truck*
Quantity-related	$q_t \in \mathbb{Z}^+$ (in pieces)	*Quantity of sub-component ordered per type* ***t*** *for the whole project*

Time-related	$\delta \in \mathbb{R}^+$(in days)	*Average delay measured from the moment the order is placed until the production starts*
	$\tau_t \in \mathbb{R}^+$ (in min/unit)	*Time needed to process one unit of type **t** at each production run **r**. All production runs of a type **t** share the same time*
	$s \in \mathbb{R}^+$ (in min)	*Time needed for every set-up on the assembly line*
	$\Delta \in \mathbb{R}^+$ (in min)	*Total other waiting times ("standard delays") at the supplier's factory non-related to the actual production of the types*
Cost-related	$c_t \in \mathbb{R}^+$ (in €)	*Standard costs of raw material and other relevant costs (for example labor and electricity) to produce a type **t***
	$C \in \mathbb{R}^+$ (in €)	*Set-up cost on the assembly line*
	$I \in \mathbb{R}^+$ (in €/day)	*Inventory cost per day*
	$T \in \mathbb{R}^+$ (in €)	*Transportation cost per truck*

7.2.4 Relation between parameters

The mathematical relation between some of the parameters can be expressed as indicated in Table 7-2:

Table 7-2: Relation between parameters

RELATION BETWEEN PARAMETERS	DESCRIPTION
$\sum_t \boldsymbol{q_t}$	*Total quantity of the different types* **t** *of sub-component ordered for the whole project*
$\left\lceil \frac{\sum_t \boldsymbol{q_t}}{\boldsymbol{k}} \right\rceil$	*Number of trucks of used in order to deliver the quantities of the different types* **t** *of a sub-component. As reasonable, the number of trucks cannot be a float number, so in case there is not an exact division, the result should be rounded up to the nearest integer*
$\left\lceil \frac{\sum_t \boldsymbol{q_t}}{\boldsymbol{k}} \right\rceil * \boldsymbol{T}$	*Total delivery costs for the delivery of the total order of sub-component*
$\left\lceil \frac{\sum_t \boldsymbol{q_t}}{\boldsymbol{k}} \right\rceil * \frac{\boldsymbol{d}}{\boldsymbol{v}}$	*Total delivery time for the delivery of the total order of sub-component from the supplier to the precast concrete factory*
$\sum_t (\boldsymbol{q_t} * \boldsymbol{c_t})$	*Total standard costs to produce all the different types* **t** *of a sub-component ordered by the client*

7.2.5 Design Variables

The main design variable, that is the output of the mathematical optimization model, is the size of the batch. In particular:

- $b \in \mathbb{Z}^+$: Size of the batch produced
- $j_t \in \{0,1\}$: Binary variable equal to 1 if all types $\boldsymbol{t}$ are delivered; otherwise, 0

7.2.6 Other Variables

The "other variables" refer to those variables which depend on the size of the batch. These are listed in Table 7-3 and they are further explained under Section 7.2.7:

Table 7-3: List of other variables

OTHER VARIABLES	DESCRIPTION
$\boldsymbol{P_t}(\boldsymbol{b}) \in \mathbb{R}^+$	*Total time to produce a complete batch of type **t** (referring only to the production process of this type)*
$\boldsymbol{W_t}(\boldsymbol{b}) \in \mathbb{R}^+$	*Waiting time to produce a complete batch of type **t** (referring only to the production process of this type)*
$\boldsymbol{A_t}(\boldsymbol{b}) \in \mathbb{R}^+$	*Actual time needed to produce a complete batch of type **t** (referring only to the production process of this type)*
$\boldsymbol{n}(\boldsymbol{b}) \in \mathbb{Z}^+$	*Number of set-ups on the assembly line*
$\boldsymbol{x_t}(\boldsymbol{b}) \in \mathbb{Z}^+$	*Number of batches per type **t** of a sub-component produced by supplier*

7.2.7 Objectives & Constraints

The situation under exploration in the current research consists two conflicting objectives, time and cost, resulting in a multi-criteria decision-making process. Consequently, the optimization to be done is clearly a *multi-objective* one, as more than one objective have to be optimized simultaneously (Chang, 2014). Nevertheless, the preferences of the decision maker should be articulated, otherwise the problem to be optimized in this kind of optimization is underdetermined. In general, the preferences can be articulated:

- *A Priori*: by translating the multiple objective function into a single optimization problem, using the *weighted objective function* method, and indicating the relative importance of the desired goals by setting weights, before running the optimization algorithm (Chang, 2014);

- *A Posteriori*: by translating the multiple objective function into a single optimization problem, using the *weighted objective function* method, and assigning different values to the weights, so as to cover all the possible combinations (Chang, 2014). Then, the decision maker can make a decision after mapping all these potential solutions.

The aforementioned suggest that the *A posteriori* methods provide the decision maker interesting information of the implication of her/his decisions (Chang, 2014). Since, in the current research, it is of high importance for the decision maker to first have access to all the possible scenarios (solutions) and then, make a decision, the *A posteriori* methods are utilized. In particular, weights are assigned to each of the objectives, which basically indicate how important these objectives are to the decision maker. These weights are non-negative and their summation is equal to 1 (Chang, 2014). The larger the weight, the greater the importance of the respective objective to the decision maker. Then, by altering the values of the two weights, that is by covering all the possible combinations (for instance 5%-95%, 10%-90% and so on), the optimization algorithm provides the set of the different solutions corresponding to the different weights (Chang, 2014). Afterwards, the solutions are plotted (Pareto front) and they are all considered equally good. Then, the decision maker can choose one of the optimal solutions of the Pareto front, based on her/his need at this specific point of time.

First, the two objectives are introduced and explained below, separately:

1. **Minimize total lead time for producing and delivering the quantities of all the different types of a sub-component ordered by the client.** *The lead time consists of:*
   i. *an <u>initial delay</u> from the moment of placing the order until the start of production;*
   ii. *the <u>total time needed for the production</u> of the batches of all the different types;*
   iii. *the <u>total set-up time for the production</u> of the batches of all the different types;*
   iv. *<u>total other waiting times</u> at the supplier's factory non related to the actual production of the batches of all the different types*;
   v. *<u>total time needed to deliver</u> the total order of sub-component from the supplier to the precast concrete factory (see Section 7.2.4).*

Equation [2] presents the objective function of the total lead time to be minimized:

$$\min_b f_1(b) = \min_b \; \delta + \textstyle\sum_t P_t(b) + s * n(b) + \varDelta + \left\lceil \frac{\sum_t q_t}{k} \right\rceil * \frac{d}{v} \qquad [2]$$

2. **Minimize total costs for producing and delivering the quantities of all the different types ordered by the client.** *The total costs consist of:*
   i. *the <u>total standard costs</u> to produce all the different types of a sub-component ordered by the client (see Section 7.2.4);*
   ii. *the <u>set-up costs</u> to produce all the different types of a sub-component on the assembly line;*
   iii. *the <u>inventory cost</u> involved in the production of all the different types of a sub-component. The term "inventory" refers to the stock that is created between the production runs in the batch-and-queue manufacturing method, owing to the waiting time involved in the process. Hence, the inventory costs for the production of all the different types can be calculated by multiplying the inventory cost per day by the waiting time included in the production;*

iv. *the <u>delivery cost</u> to deliver the total order to the precast concrete factory (see Section 7.2.4);*

Equation [3] presents the objective function of the total cost to be minimized:

$$\min_b f_2(b) = \min_b \ \sum_t (q_t * c_t) + \ C * n(b) + I * \sum_t W_t(b) + \left\lceil \frac{\sum_t q_t}{k} \right\rceil * T \qquad [3]$$

Looking at Equation [2] and Equation [3], it is obvious that the terms which are not expressed as a function of the design variable $\boldsymbol{b}$, do not affect the result of the optimization. However, they are included in the objective functions, as it is important for the decision maker to have an overall picture of the total costs and total time in the process.

The weighted objective function which results from the two objective functions (see Equation [2] and Equation [3] above) is formulated as follows:

$$\min_b \ w * f_1(b) + (1 - \ w) * \ f_2(b) \ , \qquad [4]$$

where $w \in [0,1]$ is the weight used to articulate the preference of the decision maker, as described in the beginning of the current Section.

Subject to:

- <u>Batch size of sub-component produced has to be equal or smaller than the maximum batch size and equal or larger than the minimum batch size that supplier can produce (operating policy)</u>.

$$\beta \leq \ b \leq B \qquad [5]$$

- <u>Batch size of sub-component produced has to be equal or smaller than the minimum quantity ordered per type of sub-component for the whole project</u>. *This constraint makes sure that the programming algorithm will not choose a batch size which is larger than the minimum quantity ordered, preventing the inventory of a type at the supplier's factory. Since these types are bespoke,* *they cannot be further used in the order of another client, so this kind of inventory needs to be avoided.*

$$min\,(q_t) \geq b \quad [6]$$

- Total time to produce a complete batch of a type (referring only to the production process of this type). *This time equals the sum of the waiting time and the actual time needed to produce a batch of a type.*

❖ *The obvious way to calculate the $P_t(b)$ is the following*:

$$P_t(b) = (b * \tau_t) * r \quad \forall\, t$$

*However, the reason why it is analyzed into its component parts, $\boldsymbol{W_t(b)}$ **and** $\boldsymbol{A_t(b)}$, is justified by the fact that the first term represents the non-value-added time, while the second term represents the value-added time in the process. In the current research, it is of high importance to show the variation in these two terms depending on the batch size. Therefore, the following equations is formulated:*

$$P_t(b) = W_t(b) + A_t(b)\ \forall\, t \quad [7]$$

- Waiting time to produce a complete batch of a type (referring only to the production process of this type). *Mimicking the **batch-and-queue manufacturing method**, the waiting time is basically the time the first ready unit at each production run waits for the other units to be completed. This non-value adding process is repeated until the last production run, where the first unit is finally completed and all the other units are completed, as well.*

$$W_t(b) = (b * \tau_t - \tau_t * 1) * (r - 1)\ \forall\, t \quad [8]$$

- Actual time needed to produce a complete batch of a type (referring only to the production process of this type). *Mimicking the batch-and-queue manufacturing method, the actual time needed to produce a complete batch of a type is the one that adds value in the whole process and refers* *to the real **one-piece-flow**, where there is no waiting time. Practically, only in the beginning of each production run, where the first unit is being processed, and in the last production run, when all the units of the batch are completed, there is value-added time.*

$$A_t(b) = (\tau_t * 1) * (r - 1) + b * \tau_t \quad \forall t \qquad [9]$$

- <u>Number of set-ups on the assembly line.</u> *The number of set-ups refers to the number of times the production process has to switch from producing a product A to product B (Kumar, 2013). This number can be found as the up-rounded quotient of the division between the total quantity of the different types to be produced on a line and the batch size.*

$$n(b) = \left\lceil \frac{\sum_t q_t}{b} \right\rceil \qquad [10]$$

- <u>Number of batches per type of a sub-component produced by supplier.</u> *The number of batches per type can be found as the quotient of the division between the quantity of type ordered and the batch size. This means that each type will have a number of batches* $\boldsymbol{x_t(b)}$ *of size* $\boldsymbol{b}$*. As reasonable, the number of batches cannot be a float number, so in case there is not an exact division, the result should be rounded up to the nearest integer.*

$$x_t(b) = \left\lceil \frac{q_t}{b} \right\rceil \quad \forall t \qquad [11]$$

- <u>The delivery of the batches of the different types of a sub-component should stop once all the batches of all types have been delivered.</u> *The demand, so the quantities ordered by the client should be satisfied. This is satisfied only when the result of the multiplication between the number of batches of each type* $\boldsymbol{t}$ *and binary variable* $\boldsymbol{j_t}$ *equals the number of batches for each type (so, variable* $\boldsymbol{j_t}$ equals to 1).

$$x_t(b) * j_t = x_t(b) \quad \forall t \qquad [12]$$

- The batch size cannot exceed the capacity of the truck. *The batch size selected by the optimization algorithm should fit in the truck of the supplier.*

$$\frac{k}{b} \geq 1 \quad [13]$$

The logical constraints, referring to the range of definition of each and every parameter and variable, are presented in Sections 7.2.3, 7.2.5 and 7.2.6, respectively. Hence, no further elaboration on them is included in the current Section.

7.2.8 Overview of the optimization process

After introducing all the elements of which the mathematical optimization model consists, a description of the way the model works is presented. Specifically:

- The design variables and their range of definition are already introduced in the model by the model developer.
- The two objectives of cost and time are already combined in the model in a single objective function by the model developer (see Section 7.2.7).
- The inputs (parameters) given in Section 7.2.3 are introduced in the model by the client and so, the relation between the parameters can be defined.
- The client alters the value of the weight in the weighted objective function.
- The optimization algorithm runs and a set of optimal solutions is obtained. The main output of each set is the value of design variable ***b***, which determines the value of the weighted objective function. In addition, the values of the variables which depend on the design variable ***b*** can be accessed, namely:
  - the time needed to produce the batches of all the types;
  - the waiting time in producing the batches of all the types in batch-and-queue manufacturing method;
  - the actual processing time to produce the batches of all the types in the real one-piece-flow;
  - the number of setups;
  - the number of batches per type;

- The client maps all the possible solutions and based on her/his needs, she/he makes a decision.

8 CASE STUDY

The current chapter serves in answering the fourth sub-question:

4. How could the developed mathematical optimization model be validated using a real precast concrete factory, as a case study?

First, the case and the available data are introduced. Afterwards, the results obtained by running the optimization algorithm are presented. Finally, these results are discussed.

8.1 Case Description

The project used in the current research is one of those Janssen de Jong completed recently: *23 woningen Dijkstraten Best*. The relevant procedures for the project execution started on 21/02/2020 and the project was finally delivered on 31/05/2022. It consists of three blocks of 23 precast concrete houses in total. All these houses are built at the precast concrete factory, where the sub-components arrive from the involved suppliers. Once the houses are completed, they are transported to the construction site.

The involved stakeholders are:

- Construction Company - *Janssen de Jong*
- Precast concrete factory - *Geelen Beton*
- Windows and frames Company - *Van de Vin ramen en kozijnen B.V.*
- Installation Technology Company – *Anonymous*

Amongst them, the suppliers of sub-components to the precast concrete factory are:

- Windows and frames Company - *Van de Vin ramen en kozijnen B.V.*
- Installation Technology Company – *Anonymous*

The construction company would like to have an overview of the time and costs involved in optimizing the process of manufacturing and delivering the sub-components to the precast concrete factory, in order to use this knowledge in future projects.

As explained in Section 4.4, the aforementioned involved suppliers did not share data as expected and so, the non-availability of all the relevant data required further personal research on other relevant suppliers. The personal research was successful in the case of the windows and frames only, as there was generally reluctance on behalf of the companies to respond and provide, even approximately, some data. Hence, only the supply of windows and frames is used to answer the fourth sub-question, yet it is still a highly representative and sufficient case. In the following section, the procedure followed to collect the necessary data for windows and frames is explained thoroughly.

8.2 Windows & frames

As described in Chapter 6, the windows and frames company has already optimized its process towards one-piece-flow, so no further optimization is needed. However, the way they used to work could be used to check whether the mathematical optimization model yields similar results while moving to the current situation. Some of the data required for the model are provided approximately or not at all, owing either to the inability of the windows and frames company to specify them accurately or to the confidentiality of data, respectively. Specifically, the non-accessible data, which are cost-related parameters, are filled in the model based on research in a relevant window company in Greece (XYLOSYSTEM, see Appendix A). This company is specialized in wooden windows and frames, as well, and works with bespoke sub-components. The company utilizes mainly the batch-and-queue manufacturing method, presents similar process- and time-related data with the way the involved company used to work and so, is a highly reliable representative of the situation under exploration. The steps to collect this data were the following:

- Janssen de Jong provided the definitive windows and frames drawings for the 23 houses, as received by the involved windows and frames company
- The involved windows and frames company provided time-related and process-related data, approximately
- Based on the drawings, the quantities, dimensions, details (single/double/triple element etc.) and operating system (fixed glazing, open to left, turn-and-tilt left, tilt etc.) of the windows and frames were obtained. Then,

a list of them was created and a request for offer was made to the Greek company. The drawings from the involved windows and frames company were not shared with the Greek company or anyone else.

- The Greek company made an offer for the sub-components. The costs are related to the *standard costs of raw materials and other relevant costs for production, set-up costs and inventory* (see parameters c_t, C, I). It is reasonable that for this company as well, cost-related information is confidential. Therefore, the company selected to share this data after multiplying them all by a constant factor (unknown to the researcher), ensuring that neither the data is public nor the quality of the data compromises the end result of the optimization model. In the Appendix (see Appendix A), a proof of requesting and receiving this data is included.
- Now, all the data needed for the model is available.

8.2.1 Assumptions & Simplifications

The examined case has to be coincided with the assumptions and simplifications listed in the Chapter 7.

8.2.2 Data (Parameters)

This Section lists the data (parameters) provided by the involved supplier of windows and frames and the Greek windows and frames company in Table 8-1.

Table 8-1: Data - Windows & frames Company

CATEGORY	VALUE OF PARAMETER	DESCRIPTION
General	$t = 9$	<u>*Types of sub-component:*</u> *Type 1: Door (1.10 m * 2.50 m)* *Type 2: Window (1.55 m * 1.40 m)* *Type 3: Door (3.00 m* 2.50 m)* *Type 4: Window (0.55 m * 1.40 m)*

		*Type 5: Window (0.55 m * 1.40 m)* *Type 6: Window (1.60 m * 2.15 m)* *Type 7: Window (1.20 m * 1.50 m)* *Type 8: Window (1.60 m * 1.50 m)* *Type 9: Window (0.55 m * 0.90 m)*
	$\beta = 1$	*Minimum batch size that supplier can produce*
	$B = 80$	*<u>Maximum batch size that supplier can produce:</u> based on the capacity of one assembly line at the factory*
	$r = 9$	*<u>Number of production runs on the assembly line:</u>* *Cut wood, profile, assembly, sand, paint, sand, glass, final assembly, check*
	$k = 60$ pieces	*<u>Maximum truck capacity:</u> The typical size of truck used is 40 feet (ft) or ≈12 meters (m) and its maximum capacity in pieces of windows is on average 60 pieces per truck*
	$d = 50$ km	*<u>Distance from the supplier to the precast concrete factory:</u> Distance to Geelen beton obtained by map platforms*
	$v = 60\ \frac{\text{km}}{\text{h}}$	*Average velocity per truck*

Quantity-related	$q_1 = 23$ pieces $q_2 = 24$ pieces $q_3 = 24$ pieces $q_4 = 13$ pieces $q_5 = 27$ pieces $q_6 = 17$ pieces $q_7 = 30$ pieces $q_8 = 15$ pieces $q_9 = 10$ pieces	*Quantity of sub-component ordered per type **t** for the whole project*
Time-related	$\delta = 10 \text{ days} = 14400 \text{ min}$	*Average delay measured from the moment the order is placed until the production starts*
	$\tau_1 = 280\ min/piece$ $\tau_2 = 240\ min/piece$ $\tau_3 = 320\ min/piece$ $\tau_4 = 170\ min/piece$ $\tau_5 = 170\ min/piece$ $\tau_6 = 300\ min/piece$ $\tau_7 = 160\ min/piece$ $\tau_8 = 230\ min/piece$ $\tau_9 = 135\ min/piece$	*<u>Time needed to process one unit at each production run **r**</u>: This time is given approximately as an average value and all production runs of a type **t** share the same value (see Section 7.2.2)*
	$s = 250 \text{ min}$	*<u>Time needed for every set-up on the assembly line:</u> This time is given approximately as an average value for all the machines involved in the process*

	$\Delta = 21600\ \text{min}$	*Total other waiting times ("standard delays") at the supplier's factory non-related to the actual production of the types:* *These delays are estimated to (around) 15 days and may include: possible repair due to unexpected breakdown of machines, time to modify the drawings if a mistake is detected while producing, time to tidy the completed products within the factory and prepare them for delivery and/or public holiday*
Cost-related	$c_1 = 1450$ € $c_2 = 1700$ € $c_3 = 2500$ € $c_4 = 800$ € $c_5 = 800$ € $c_6 = 1820$ € $c_7 = 945$ € $c_8 = 1490$ € $c_9 = 850$ €	*Standard costs of raw material and other relevant costs to produce a type* ***t***
	$C = 500$ €	*Set-up cost on the assembly line*
	$I = 150$ €/day $= 0.11$ €/min	*Inventory cost per day*
	$T = 400$ €	*Transportation cost per truck*

8.2.3 Relation between parameters

The mathematical relation between the parameters is indicated in Table 8-2.

Table 8-2: Relation between parameters

RELATION BETWEEN PARAMETERS	DESCRIPTION
$\sum_t \boldsymbol{q_t} = 183$	*Total quantity of the different types* ***t*** *of windows ordered for the whole project*
$\left\lceil \frac{\sum_t q_t}{k} \right\rceil = \left\lceil \frac{183}{60} \right\rceil = 4$	*Number of trucks used in order to deliver the quantities of the different types* ***t*** *of windows*
$\left\lceil \frac{\sum_t q_t}{k} \right\rceil * T = 4 * 400 = 1600\,€$	*Total delivery costs for the delivery of the total order of sub-component*
$\left\lceil \frac{\sum_t q_t}{k} \right\rceil * \frac{d}{v} = 4 * \frac{50}{60} = 3.3\,h = 200\,min$	*Total delivery time for the delivery of the total order of windows from the supplier to the precast concrete factory*
$\sum_t (q_t * c_t) = 256290\,€$	*Total standard costs to produce all the different types* ***t*** *of windows ordered by the client*

8.2.4 Objective function & Constraints

After introducing the parameters in Equation [2], the objective function of the total lead time to be minimized is formulated as follows:

$$\min_b f_1(b) = \min_b \; 14400 \; + \sum_t P_t(b) + 250 * n(b) + 21600 \; + 200$$

After introducing the parameters in Equation [3], the objective function of the total cost to be minimized is formulated as follows:

$$\min_b f_2(b) = \min_b \; 256290 \; + \; 500 * n(b) + 0.11 * \textstyle\sum_t W_t(b) + 1600$$

Then, these two objective functions can be replaced in the weighted objective function (see Equation [4]).

$$\min_b \; \boldsymbol{w} * [14400 + \textstyle\sum_t P_t(b) + 250 * n(b) + 21600 + \; 200\,] \; +$$
$$+ \, (\mathbf{1} - \boldsymbol{w}) * [256290 + \; 500 * n(b) + 0.11 * \textstyle\sum_t W_t(b) + 1600]$$

Afterwards, the parameters are introduced in the constraints (wherever necessary):

- $1 \leq \; b \leq 80$ [5]
- $10 \geq \; b$ [6]
- $W_1(b) = (b * 280 - \; 280 * 1) * (9 - 1), \ldots, W_9(b) = (b * 135 - \; 135 * 1) * (9 - 1)$ [8]
- $A_1(b) = (280 * 1\,) * (9 - 1) + b * \; 280, \ldots, A_9(b) = (135 * 1\,) * (9 - 1) + b * \; 135$ [9]
- $n(b) = \left\lceil \frac{183}{b} \right\rceil$ [10]
- $x_1(b) = \left\lceil \frac{23}{b} \right\rceil, \ldots, x_9(b) = \left\lceil \frac{10}{b} \right\rceil$ [11]
- $\frac{60}{b} \geq 1$ [13]

8.2.5 Results

This section presents the results obtained after running the developed mathematical optimization model. Python programming language (*Python 3.9.13*) is utilized and specifically, Visual Studio Code (*Version: 1.67.2*) as a free source code editor (see Appendix B). The optimization algorithm used is SciPy (Scientific Python), which “provides functions for minimizing (or maximizing) objective functions, possibly subject to constraints” ("Optimization and root finding (scipy.optimize) — SciPy v1.8.1 Manual", 2022). A graphical user interface is developed in Visual Studio Code, as well, in order to communicate easily and efficiently the way the model works to everyone with no prior experience with programming (see Appendix C).

The results are illustrated in figures: first, the values of the variables which depend on the main design variable ***b*** are demonstrated (Table 8-3, Table 8-4, Table 8-5). Afterwards, the relation between the main variable ***b***, the preference (weight w) and each of the objectives is presented (Figure 8-1 and Figure 8-2), and then, the Pareto front is plotted (Figure 8-3). For better comprehension, explanatory tables with the corresponding values accompany the figures (Table 8-6, Table 8-7 and Table 8-8, respectively).

Table 8-3: Number of set-ups on the assembly line

Weight (w)	**Batch size** (b)	**Number of set-ups** $n(b)$
0.0	8	23
0.1	6	31
0.2	5	37
0.3	4	46
0.4	3	61
0.5	3	61
0.6	3	61
0.7	3	61
0.8	2	92
0.9	2	92
1.0	2	92

Table 8-4: Number of batches per type t

Weight (w)	**Batch size (b)**	***Number of batches per type t of a sub-component produced by supplier $x_t(b)$***								
		Tp. * *1*	*Tp. 2*	*Tp. 3*	*Tp. 4*	*Tp. 5*	*Tp. 6*	*Tp. 7*	*Tp. 8*	*Tp. 9*
0.0	8	3	3	3	2	4	3	4	2	2
0.1	6	4	4	4	3	5	3	5	3	2
0.2	5	5	5	5	3	6	4	6	3	2
0.3	4	6	6	6	4	7	5	8	4	3
0.4	3	8	8	8	5	9	6	10	5	4
0.5	3	8	8	8	5	9	6	10	5	4
0.6	3	8	8	8	5	9	6	10	5	4
0.7	3	8	8	8	5	9	6	10	5	4
0.8	2	12	12	12	7	14	9	15	8	5
0.9	2	12	12	12	7	14	9	15	8	5
1.0	2	12	12	12	7	14	9	15	8	5

* Abbreviation for *Type*

Table 8-5: Times for the production of the all types t

Weight (w)	Batch size (b)	Total time to produce the batches of all types (in min) $\sum_t P_t(b)$	Total waiting time to produce the batches of all types (in min) $\sum_t W_t(b)$	Total actual time to produce the batches of all types (in min) $\sum_t A_t(b)$
0.0	8	144360	112280	32080
0.1	6	108270	80200	28070
0.2	5	90225	64160	26065
0.3	4	72180	48120	24060
0.4	3	54135	32080	22055
0.5	3	54135	32080	22055
0.6	3	54135	32080	22055
0.7	3	54135	32080	22055
0.8	2	36090	16040	20050
0.9	2	36090	16040	20050
1.0	2	36090	16040	20050

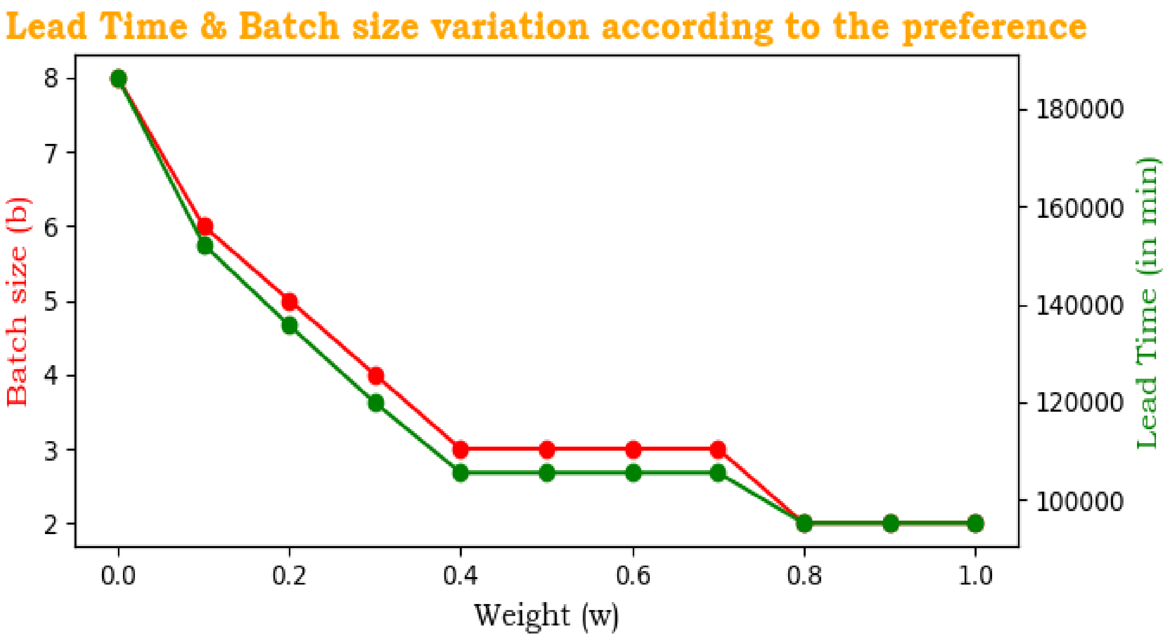

Figure 8-1: Lead Time & Batch size variation according to the preference

Table 8-6: Lead Time & Batch size variation according to the preference

Weight (*w*)	**Batch size (*b*)**	**Lead Time (in min)**	**Lead Time (in days)**
0.0	8	186310	130
0.1	6	152220	106
0.2	5	135675	95
0.3	4	119880	84
0.4	3	105585	74
0.5	3	105585	74
0.6	3	105585	74
0.7	3	105585	74
0.8	2	95290	66
0.9	2	95290	66
1.0	2	95290	66

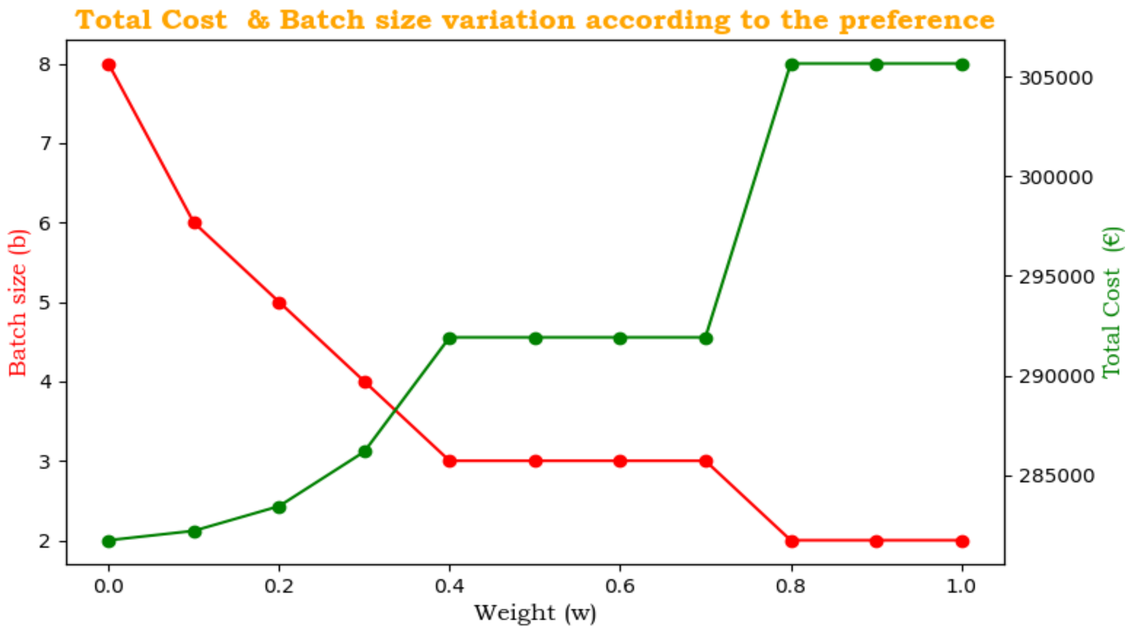

Figure 8-2: Total Cost & Batch size variation according to the preference

Table 8-7: Total Cost & Batch size variation according to the preference

Weight (w)	**Batch size (b)**	**Total Cost (in €)**
0.0	8	281740.8
0.1	6	282212
0.2	5	283447.6
0.3	4	286183.2
0.4	3	291918.8
0.5	3	291918.8
0.6	3	291918.8
0.7	3	291918.8
0.8	2	305654.4
0.9	2	305654.4
1.0	2	305654.4

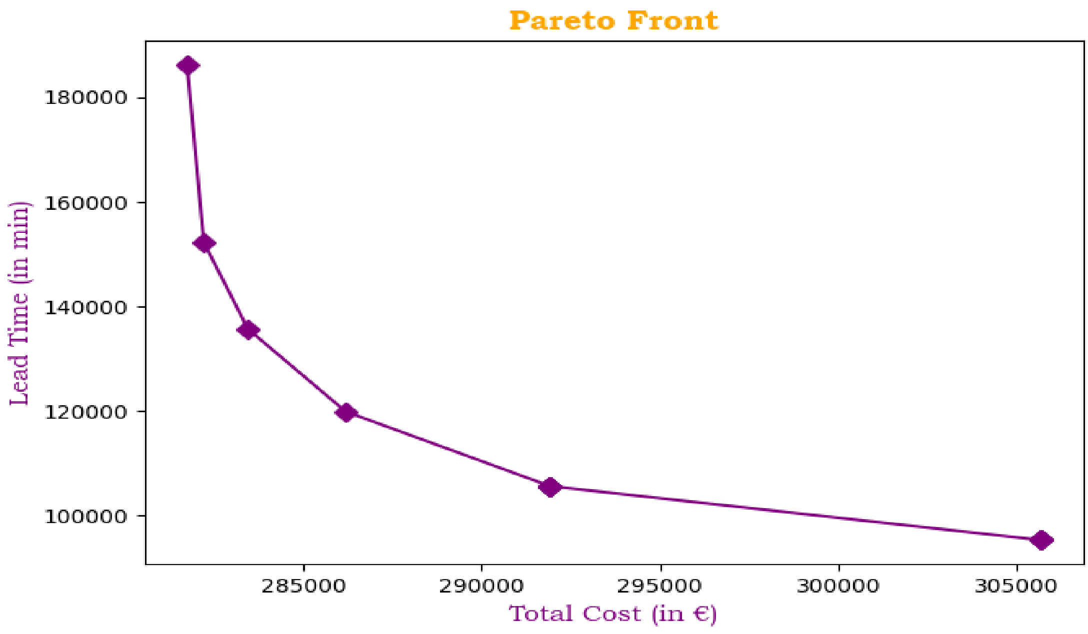

Figure 8-3: Pareto Front – Plotting 1st objective against 2nd objective

Table 8-8: Pareto Front – Optimal design value according to preference

Weight (w)	**Batch size (b)**	**Total Cost (in €)**	**Lead Time (in min)**	**Lead Time (in days)**
0.0	8	281740.8	186310	130
0.1	6	282212	152220	106
0.2	5	283447.6	135675	95
0.3	4	286183.2	119880	84
0.4	3	291918.8	105585	74
0.5	3	291918.8	105585	74
0.6	3	291918.8	105585	74
0.7	3	291918.8	105585	74
0.8	2	305654.4	95290	66
0.9	2	305654.4	95290	66
1.0	2	305654.4	95290	66

8.2.6 Discussion

8.2.6.1 Optimal solutions

As explained under Section 7.2.7, all the solutions in the Pareto front (or boundary) are considered equally optimal. Improving one of the objectives affects the improvement of the other objective, meaning that none of them can be improved without degrading the value of the other. This is explained below and illustrated further in Figure 8-4:

– lead time must get “worse” (namely, get longer), so that the total cost can be “improved” (namely, get lower);
– total cost must get “worse” (namely, get higher), so that the lead time can be improved (namely, get shorter).

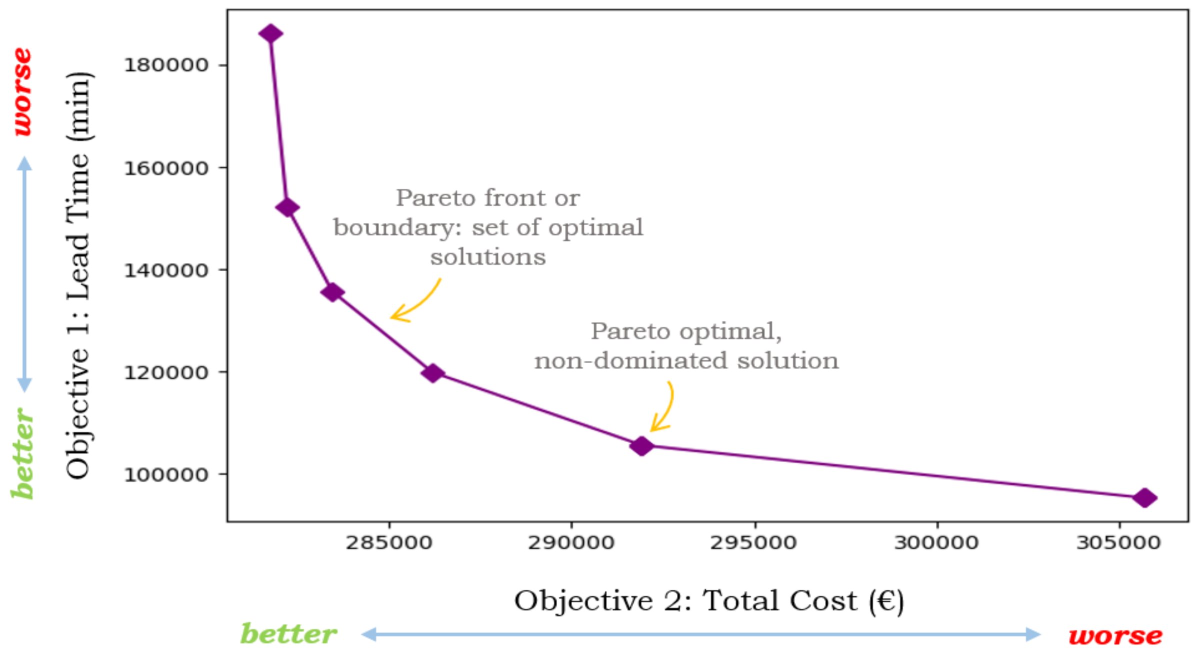

Figure 8-4: Pareto Front – Explanation

Once the decision maker decides on the importance of the two objectives (lead time minimization and total cost minimization), the optimal design values can be retrieved. These values, corresponding to the importance of the objectives each time, are summarized in Table 8-8. In particular:

a. For *weight 0*, meaning that the decision maker desires to pay full attention on total cost minimization, the optimization algorithm yields a batch size of 8. This batch size corresponds to a *total cost* of *281740.8 €,* which is the lowest cost amongst the total costs in Table 8-8, and a *lead time* of *130 days*, which is the longest time amongst the times appearing in Table 8-8. These values are reasonable (refer to the explanation above): the decision maker desires to "improve" to the greatest possible extent the total cost (lowest cost), resulting in "worsening", to the greatest extent, the lead time (longest lead time).

b. For *weights 0.1, 0.2, 0.3, 0.4* meaning that the total cost minimization is more important to the decision maker, but lead time minimization increases gradually in importance, the optimization algorithm yields a *batch size* of *6, 5, 4* and *3*, respectively. The greater the attention lead time minimization starts receiving (lead time is "improving", so it is getting shorter), the "worse" the total cost (it is getting higher), as a result of the conflicting relation between the two objectives. So, for *weight 0.1*, the *total cost* is *282212 €* and the *lead time* is *106 days*, while for *weight 0.4*, the *total cost* is *291918.8 €* and the *lead time* is *74 days*.

c. The highlighted row in Table 8-8 corresponds to *weight 0.5*. *Weight 0.5* means that the objectives are *equally* important to the decision maker. Therefore, in order for both of them to get equally "improved", it is important to get equally "worse" at the same time. The *batch size* that satisfies this preference is *3* and yields a *total cost* of *291918.8 €* and a *lead time* of *74 days*.

d. For *weights 0.6, 0.7, 0.8, 0.9*, meaning that the lead time minimization is more important to the decision maker and total cost minimization decreases gradually in importance, the optimization algorithm yields a *batch size* of *3, 3, 2* and *2*, respectively. The lower the attention paid on total cost minimization (total cost is getting "worse", so it is getting higher), the "better" the lead time (it is getting shorter).

e. For *weight 1.0*, meaning that the decision maker desires to pay full attention on lead time minimization, the optimization algorithm yields a *batch size* of *2*.

This batch size corresponds to a *total cost* of *305654.4 €,* which is the highest cost amongst the total costs in Table 8-8, and a *lead time* of *66 days*, which is the shortest time amongst the times appearing in Table 8-8. These values are reasonable, again: the decision maker desires to "improve", to the greatest possible extent, the lead time (shortest lead time), resulting in "worsening", to the greatest extent, the total cost (highest total cost).

An important comment on the observations above: It can be noticed that for *weights 0.4, 0.5, 0.6, 0.7*, the optimization algorithm yields the same results. Shortly before the lead time minimization becomes more important to the decision maker, as well as when it starts increasing even more in importance, the outcome is the same. *Weights 0.8, 0.9* and *1.0*, share the same results, as well. This means that while approaching the real one-piece-flow (batch size 1), there is no substantial difference in the lead time and total cost. The similarity of results in both cases can be attributed to the fact that the algorithm is constrained to a largest batch size of 10 (see constraint [6]), so basically to a set of 10 values. It is reasonable that at some point the algorithm will not be able to further optimize the objectives, so it will start yielding the same results.

Finally, commenting on the components (Table 8-3, Table 8-5) constituting the final results above:

- The difference between the lowest and highest number of set-ups is noteworthy. The set-ups quadruple when selecting the smallest possible batch size (for *batch size 8,* the *number of set-ups* is *23*, while for *batch size 2,* the *number of set-ups* is *92*), highlighting the possibility of increased inefficiency in the working environment due to the more frequent set-ups.

- The difference between the values of total waiting time (non-value-added time) and total actual time (value-added time) is interesting. As the batch decreases in size, the share of total waiting time in the total time gradually decreases, until the point when batch size is 2. At this point, the actual time has a greater share in the total time, denoting that the value-added time in the process, while approaching one-piece-flow, is dominant.

8.2.6.2 Suggestion by the researcher

A personal assessment by the researcher: the difference between the lowest and the highest total cost (*23913.6 €*) could not be deemed so extreme, while the difference between the shortest and the longest lead time (*91020 min or 63 days or 2 months, approximately*) could be deemed more extreme for the progress of a project. It seems that moving towards one-piece-flow, at least for the case under consideration, is not so expensive, as to make its application prohibitive, and can save almost two months of waiting time (non-value-added time).

Understanding the difficulty of getting familiarized with a practice different than the one used to work with for years (referring to suppliers), as well as the wish to make and save money (referring both to suppliers and client): the researcher, as a first step, would suggest a *batch size* of *3,* which equally degrades the two objectives and facilitates a smoother transition from one practice (and so, time- and cost-related aspects) to another.

8.2.6.3 Effectiveness & Validity of the model

The effectiveness and validity of the mathematical optimization model could be confirmed by the fact that the model yields reasonable, and similar to reality, lead time, for approaching one-piece-flow. In particular, for a *batch size of 2*, the l*ead time* obtained by the model is *66 days* and approaches the real lead time of the involved windows and frames company, as described in interviews: *10 weeks (or 60 days, 6 working days per week)* for the real one-piece-flow, that is a batch size of 1. It is noticeable that if the real one-piece-flow had been achieved, then the lead time would be less than *66 days*, and so, closer or even equal to the real *60 days*. Moreover, the lead time corresponding to the largest batch size resembles the lead time of the batch-and-queue manufacturing environment of the Greek windows and frames company. When visiting their factory, they roughly estimated that for around *200 pieces* and a *batch size* of 10, they would need *25 weeks* (*or 150 days, 6 working days per week),* approximately. Comparing these figures to the ones of the model, it can be concluded that *130 days* with *a batch size of 8* is reasonable for the examined case (*183 pieces*), as a consequence of the batch-and-queue manufacturing method. Any slight deviation is anticipated and acceptable, as there will be always a point in reality that cannot be captured 100%, especially since the cost data by the involved supplier are not provided.

The effectiveness and validity of the mathematical optimization model could be further confirmed by the fact that the model yields reasonable, and similar to reality, total costs, for the real batch-and-queue manufacturing method. The roughly estimated total cost by the Greek company for around *200 pieces* and a *batch size of 10* (as described above) was *290000 €*, while the model for *183 pieces* and a *batch size of 8* conduces to a *total cost* of *281740.8 €*. As for one-piece-flow, which is utilized by the involved windows and frames company, no costs, even approximately, were provided. Yet, their claim that "someone would say that we probably are a bit more expensive than others. However, my answer to this is that can offer shorter lead times, which is also money" could be deemed as real evidence of/enhances the result obtained: one-piece-flow is indeed more expensive, but this is justifiable, taking into consideration the time and consequently, the money might be lost when utilizing batch-and-queue manufacturing method.

Concluding, the validity and effectiveness of the model is confirmed by the fact that as long as the model yields reasonable results for the case study under consideration, it can yield reasonable results for any other real case, as well.

8.2.6.4 Sensitivity to external factors

While formulating the weighted objective function in Chapter 7, it was noted that: the terms which are not expressed as a function of the design variable $\boldsymbol{b}$, do not affect the result of the optimization. However, they are included in the objective functions, as it is important for the decision maker to have an overall picture of the total costs and total lead time in the process. Consequently, it is important to consider that any fluctuation in the values of these external terms (factors) affects significantly this picture of total costs and total lead times. Especially, fluctuations in relation to political and so, economical aspects. Two indicative, and more frequently encountered, examples are:

- A sharp increase in the fuel price (which is a topical subject, owing to the ongoing war) will increase significantly the transportation cost T per truck and so, the share of the total transportation cost in the total cost calculation. On the contrary, a decrease in the fuel price will reduce the share of the total transportation cost in the total cost calculation.

- A sharp increase in the total standard costs to produce all the different types of a sub-component (related to raw materials' purchase, labor costs, electricity costs), owing to unexpected and mainly, bleak circumstances, will increase significantly the share of total standard costs in the total cost calculation. Accordingly, a decrease in the total standard costs will lead in lower total costs.

9 CONCLUSION

This chapter presents the conclusions of the current research in relation to the main research question, after revisiting each of the sub-questions (see Chapter 3). Then, the limitations of this research are discussed and finally, recommendations for further research are made.

9.1 Answer to sub-questions

In Chapter 3, four sub-questions have been formulated contributing to the answer of the main research question. Each of the sub-questions has been answered at first place, utilizing different tools of research methodology, yet an articulate reference to them is necessary.

9.1.1 Sub-question 1

What are sub-components in precast concrete house-building projects and what are the main sources of long sub-components' lead times?

As identified in literature, the products that are being integrated into the precast concrete components (beams, walls, columns, floors, staircases and lintels), for instance windows being embedded into walls, could be referred as sub-components. These sub-components are produced in different location than the precast concrete components. The former are produced and delivered to the precast concrete factory by various suppliers, while the latter are produced at the precast concrete factory itself.

The main sources of sub-components' long lead times in precast concrete house-building projects, as identified in literature and interviews with relevant stakeholders, are:

- Ineffective coordination and absence of strong/long-term relationships between the various stakeholders involved in the process (construction company, precast concrete factory, various suppliers), which conduce to plethora of non-value adding actions in the supply chain, compromising the success of Supply Chain Management in precast concrete house-building projects.

- The traditional manufacturing environment of batch-and-queue, where large batch sizes are produced, stocks of processed products are created in the different steps of the process, leading to long waiting times (non-value adding times) and so, longer manufacturing times and delays in deliveries. Therefore, the not so flexible nature of the traditional manufacturing environment further compromises the success of Supply Chain Management in precast concrete house-building projects.

- The persistency of the involved suppliers to follow the traditional manufacturing method of batch-and-queue (production of large batch sizes) and consequently, their reluctance to move towards one-piece-flow (production of a batch with size one, where there is almost no non-value adding time), owing to their fear of working inefficiently and having extra costs, due to the more frequent set-ups and extra labor force needed.

- The delivery of sub-components in large batches, as a consequence of the batch-and-queue manufacturing method.

9.1.2 Sub-question 2

What are the effects of sub-components' long lead times on project performance?

The identified effects of sub-components' long lead times on project performance are the time and cost overruns. In particular, a lot of idle (waiting time) and significant loss of space (inventory creation), owing to the belated and massive (large batches) arrival of the sub-components to the precast concrete factory, are observed. These two factors conduce to significant delays in integrating the sub-components to the precast concrete components and so, delivering the complete precast concrete houses to the construction site itself and finalizing the project. Reasonably, lagging behind schedule results in excessive costs, referring not only to this specific project, but to the economic loss from the inability of executing other projects, as well. It is interesting to mention as an indirect, and not so quantifiable, effect of the sub-components' long lead times on project performance, the identified fact that they can defame the stakeholders involved (lead to loss of competitiveness) and so, partly to downgrade the project.

9.1.3 Sub-question 3

How could the development of a mathematical optimization model aid in optimizing sub-components' lead times in the context of precast concrete house-building projects?

As described in Section 4.3.1, the development of a mathematical optimization model is ideal for modelling a manufacturing process, as long as the focus is on finding optimal (or near-optimal) solutions that optimize the objectives of the system. The focus of the current research is on optimizing sub-components' lead times in the context of precast concrete house-building projects. Therefore, the effectiveness and appropriateness of an optimization model, in such a case, are confirmed at a theoretical level.

In practice, the answers to the first two sub-questions indicated the non-easily quantifiable and the quantifiable aspects of the problem. The former aspects, such as the absence of strong relationships between the stakeholders involved and the miscommunication of information, were excluded from the model, due to complexity to model them. The latter aspects, namely the batch size, time and cost are involved in manufacturing (batch-and-queue, one-piece-flow-manufacturing method) and delivery of the sub-components to the precast concrete factory.

A clear conflicting relation was identified in literature and interviews between reducing costs and shortening lead times (moving from batch-and-queue with large batch sizes to one-piece-flow with batch size one) in relation to the batch size: the costs refer to the revenues of the supplier (the amount of money the client has to pay), while the lead time refers, basically, to the supplier's practices, in which the client wants to interfere. Therefore, the main variable of the system is the batch size, while the conflicting objectives of the system are lead time and total cost minimization. Weights are assigned to the objectives, summing up to one, which reflect the importance of each of the objectives to the decision maker each time. Altering the weights, enables the decision maker to obtain useful information about the implications of her/his decision with respect to one specific supplier each time. Improving one of the objectives (assigning greater weight) affects the improvement of the other objective, meaning that none of them can be improved without degrading the value of the other. The constraints of the system concern mainly the production process and operating policy of the supplier and take into consideration the arguments in favor and against both manufacturing methods. In this way, the bias is reduced as much as possible. Specifically, the arguments in favor of batch-and-queue are the low number of set-ups, the low set-up costs, the utilization of the maximum capacity of the equipment, while those against batch-and-queue are the long waiting times and the excess inventory. As for the arguments in favor of one-piece-flow, these are the absence of waiting times, the shorter manufacturing time and the lower inventory levels, while the arguments against one-piece-flow are the increased frequency of set-ups, the high associated set-up costs and the inefficiency of delivering too small batches.

Hence, it can be concluded that the development of a mathematical optimization model with the specifications above can indeed aid in optimizing sub-components' lead times in precast concrete house-building industry. It can provide a set of optimal lead times and costs for each supplier separately, taking into account equally the interests of the client and the supplier.

9.1.4 Sub-question 4

How could the developed mathematical optimization model be validated using a precast concrete house-building project, as case study?

The case study utilized in answering this question was presented in Chapter 8. Comparing the results obtained by the model to the ones provided partly by the involved windows and frames company and partly by the Greek windows and frames company, it can be concluded that the model yields reasonable and close to reality results. There exist slight deviations, owing to the fact that the reality cannot be captured 100% and to the lack of cost information from the involved windows and frames company. If the exact cost figures for one-piece-flow were accessible, then it could be estimated accurately to what extent one-piece-flow is more expensive compared to batch-and-queue manufacturing method (as it has been proved that it is indeed more expensive). Concluding, the selected case study proves that the developed model is valid. As the model yields reasonable results for the case under consideration, it can yield reasonable results for any other real case and achieve higher levels of accuracy if all the data needed is available.

9.2 Answer to the main research question

After revisiting the fourth sub-questions in the previous sections, the main research question can be addressed in the current section. The main research question, as formulated in Chapter 3, is the following:

How could sub-components' lead times in precast concrete house-building projects be optimized, to improve project performance in terms of time and cost?

The current research named the large batch size (batch-and-queue manufacturing method) as the main quantifiable source of long sub-components' lead times in precast concrete house-building projects. These long lead times account for significant time and cost overruns.

It was revealed, in the first place, that the process (manufacturing and delivering) behind sub-components' lead times and the conflicting interests of the stakeholders involved (make and/or save money) acquires mathematical substance. Then, the developed model proved that the lead times can be optimized, as it yielded valid and reasonable results for the selected case study. The fluctuations, with respect to the batch size, in values such as the total waiting time, total actual time and the number of set-ups, were noteworthy, as a consequence of the conflicting relation between lead times and costs.

By making accessible all the sets of optimal solutions (batch size and corresponding lead times and costs), the model enables the decision maker to judge for each supplier separately, whether the shortest lead time is worth the greatest expenditure, the longest lead time is worth the lowest expenditure, the in-between lead time is worth the in-between expenditure and so on. Hence, the decision maker can indeed improve the project performance in terms of time and cost, as per her/his priorities each time.

9.3 Limitations & Recommendations

The current section lists some recommendations for future possible improvements on the examined topic, taking into account those elements which were considered out of the scope of this research and also, certain limitations. The section, also, lists a recommendation referring to Janssen de Jong and the unavailability of data and proposes a way to resolve it. The goal of these recommendations is to achieve even higher levels of realism and applicability. In particular:

- Assign different time (needed to process a unit of a type) to each production run. The current study assumes that the time needed to process one unit of a type at each production run is the same for all the production runs of this type. This assumption is based on the fact that manufacturing industry is not ideal and not so much attention is paid on each separate process but on the process as a whole, as observed while interviewing the practitioners (this is highly related to the lack of data). In a future version of the model, when the utilization of robots will (probably) gain more ground in the manufacturing industry, one could argue that the exact times at each production run will be easily retrievable and so, available for application in the model. Introducing different times for each production run in the model will demand for modifications in the mathematical definition/calculation of the waiting times, actual processing times and so, total times to produce a batch of each type. As a personal assessment, this change/addition will add complexity in the calculation, yet it is feasible (provided that data will be available, otherwise this addition will not be value-adding).

- Incorporate the time needed for the supply of raw materials to the supplier's factory into the lead time. This study assumes that the raw materials are available at the supplier's factory when the order is placed, due to the complexity to model this aspect in the current thesis, as well. Yet, especially in the period of crisis the humanity is going through, the time needed for raw materials' supply presents significant fluctuations, affecting the lead time. Therefore, this time could be taken into consideration in a future version of the model, as well as the supplier of raw materials should be considered as an additional stakeholder. This recommendation is triggered by the words of the installation technology company. The company highlighted that the outbreak of COVID-19 in the past two years along with the ongoing war in Ukraine, affected significantly the supply of materials to the company and so, their lead time. Practically, this addition in the model means that all the materials needed to produce a sub-component should be identified (for instance, wood and glass for the wooden windows). The number of the various materials will determine the number of the suppliers (for instance, one supplier for the wood, one supplier for the glass) and subsequently, the number of extra time terms to be included in the lead time calculation. The model should compare these time terms and include the longest one in the lead time calculation, as this is the one that determines when the production can start (for instance, the wood supplier has a lead time of 15 days, while the glass supplier has a lead time of 10 days, so 15 days will be added in the windows' lead time calculation). The costs for the supply are already included in the model (as described in Chapter 7) and any fluctuations can be reflected directly on their value, without introducing extra cost terms.

- Add assembly lines. One assembly line is assumed to be available for the production of all types of a sub-component, as it is important to capture the worst-case scenario. In reality, most suppliers have more than one assembly line in their factories. Practically, this addition in the model could be approached as follows: the number of assembly lines could be introduced as an extra input in the model along with a binary variable reflecting whether an assembly line is available (or not). A constraint in the model should make sure that at least one assembly line is available each time in order the production to be feasible. Then, some conditions could be checked:
  - Condition 1*: if all the assembly lines are available and the number of types of a sub-component to be produced equals the number of the assembly lines, then each type will correspond to each assembly line and so, all the types will be produced in parallel.*
  - Condition 2*: if the number of available assembly lines is greater than the number of types to be produced, then, not all of the assembly lines are needed*

and so, only some of them (equal to the number of types) will be utilized for parallel production. For instance, if the number of available assembly lines is 3 and the number of types is 2, then only the two assembly lines will be utilized.

– Condition 3*: if the number of available assembly lines is lower than the number of types to be produced, then, all the assembly lines will be utilized in parallel corresponding to some of the types. Once a type is completed, then the production of one of the remaining types will start. For instance, if the number of available assembly lines is 3 and the number of types is 5, then the production of the first three types will start on the three assembly lines in parallel. Once, the production of a type is completed, then type 4 will utilize the assembly line. Then, the same will happen with type 5. So, this procedure stops once all the types enter an assembly line.*

It is self-evident that this approach is way more complex compared to the aforementioned recommendations, yet it could be explored in a future version, if desired.

- Incorporate the project planning (dates) into the model. As it is now, the model is used as a guide in order for the client to understand the implications of her/his preference each time. An interesting addition could be the communication of a 4D BIM (Building Information Modeling) model with the optimization model. A 4D model adds the time (fourth) dimension in a 3D model, making accessible time-related information for each component and each phase of a project. Therefore, the desired dates of having available each of the sub-components at the precast concrete factory could be retrieved from the 4D model. A common practice to retrieve data is to extract it from the 4D model in a comma-separated values (csv) file format and then, introduce ("read") it in any kind of editor in Python programming language. Furthermore, the model (programming code) should be updated in order the sub-component to be linked with the right date in the comma-separated values file. The model should automatically calculate back the more efficient date to place the order, according to the preference each time. Namely, once the optimization algorithm runs and provides a set of optimal solutions, each of the optimal times should be subtracted from the date retrieved by the comma-separated values (csv) file. This would enable the decision maker to have prompt access to the exact – optimal each time – dates for placing an order, avoiding extra calculations. An important note here is that Python serves ideally in building and solving this and any kind of models, owing to the plethora of available libraries. It highly supports and enables the desired interoperability. On the contrary, using Microsoft Excel is not recommended by the researcher. It has been used (by the researcher) in solving simple linear problems only, yet the developed model is complex and not implementable in the Microsoft Excel environment. Of course, this is a personal assessment and the possibility of introducing the model as an "add-in" in Microsoft Excel with some modifications could be explored in a future research, if desired.

- Validate the model using other companies, such as installation technology companies. Although an interview was conducted in the current research with a company in this field, no data was made accessible. Therefore, it could be interesting to explore the behavior of the model in this case, where the perception of small batch size may differ (one-piece-flow could correspond to 30 cables, if referring to a cable company, therefore the smallest batch would be 30).

- "Assume" inputs for the model, if data is not accessible. This recommendation refers basically to the decision maker and everyone who wants to implement and then, run the developed model. Data is important for the model to run and reliable data is important for the model to yield reliable results. However, in some cases data is lacking. If the real data cannot be accessed in any way, then a recommendation by the researcher is to assume this data. "Assume" refers to conducting a mini research: searching in literature, asking different people (not referring to the company or supplier that the model has to run for, but to someone in the same field) who have been involved in manufacturing for years, and then, based on the collected information, introduce an average value for this data.

A final comment by the researcher: it is of high importance to bear in mind that a model and so, a programming code should be built step by step, so that is easier to identify and handle possible errors, which are an integral part of programming. Therefore, any increase in the level of complexity should be done gradually and carefully.

9.4 Data availability statement

All the data used in order to validate the developed model is provided in the current thesis in Chapter 8. The executable file with the developed graphical user interface is located at: https://drive.google.com/drive/folders/1PJDKQysb-f-QsLG1NDwogW8awlAvUIXg?usp=sharing

PERSONAL REFLECTION

Searching for a thesis and trying to arrange everything around the thesis has been a great challenge, long and tough journey during the past ten months; probably, the greatest and at some points, most distressing period of my life. Fortunately, with patience and perseverance, I managed to get everything in line and produce a worthwhile result. I am extremely proud of myself and my work, as I had little experience with programming and manufacturing process, yet I managed to build not only an optimization model from scratch, but also a graphical user interface. If I was asked to do this over again, I would not choose to do anything different with respect to the model and the thesis itself. Of course, out of the context of the thesis and the time-pressure, even higher levels of complexity could be added in the model (as explained in the Limitations & Recommendations Section), thing which is not feasible in a 6-month period and if done imprudently, may compromise the result of the work. The only thing I would change is all the stress and pressure the difficult circumstances exposed me to. In any case, it was a constructive journey, I thank everyone who contributed to my efforts and I hope other people find my work interesting and source of inspiration for further research.

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APPENDIX A: XYLOSYSTEM

This Appendix holds the proof of requesting and receiving data from the Greek windows and frames company, *XYLOSYSTEM.*

Website: https://xylosystem.com/

Email: xylosystem.com@gmail.com

ΞΥΛΟ SYSTEM
ΚΟΥΦΩΜΑΤΑ | ΚΟΥΖΙΝΑ | ΝΤΟΥΛΑΠΑ

To: *Whom it may concern*

The purpose of the current document is to confirm that Ms. Evangelia Rizopoulou contacted our company in order to collect data, in the context of her graduation research.

Ms. Rizopoulou visited our factory in Elassona, where our operating policy was thoroughly presented and explained. We hope that all her questions have been answered adequately. At her request, our company provided information about our operating costs, supply and production costs, as well as other relevant costs involved in the production process.

As the financial data of our company are confidential, the data were multiplied by a constant factor (unknown to Ms. Rizopoulou) before being disclosed to Ms. Rizopoulou, without compromising the result of her work. Still, we would appreciate it if this financial data is kept for the development of her model only and not be further disclosed to anyone else.

We are at your disposal for any clarification.

Sincerely yours,

Vasilis Pangos

Contact person

ΒΑΣΙΛΕΙΟΣ Α. ΠΑΓΓΟΣ
ΠΟΛΙΤΙΚΟΣ ΜΗΧΑΝΙΚΟΣ Τ.Ε.
ΑΡΙΘΜ. ΜΗΤΡΩΟΥ Τ.Ε.Ε. 20368
ΣΟΧΑΙΝΗ 1 ΣΥΚΙΕΣ - Τ.Κ. 566 25
ΑΦΜ. 151914151 - ΔΟΥ: ΣΤ' ΘΕΣ/ΝΙΚΗΣ
ΚΙΝ: 6980127727

- Ξύλινες πόρτες & παράθυρα
- Ξύλινα γερμανικά κουφώματα
- Ξύλινα έπιπλα κουζίνας
- Πέργκολες
- Σκάλες
- Παντζούρια

- Ντουλάπες
- Ξύλινες επενδύσεις
- Ανακλινόμενα παράθυρα
- Μπαλκονόπορτες
- Πόρτες ασφαλείας
- Κουφώματα PVC

Μύκονος | Τήνος | Άνδρος | Σύρος | Λάρισα
Αθήνα | Θεσσαλονίκη | Κρήτη | Χαλκιδική
Κέρκυρα | Ελασσόνα | Πήλιο | Ιωάννινα

Website: https://xylosystem.com/
Email: xylosystem.com@gmail.com

Figure A: Proof of contacting XYLOSYSTEM

APPENDIX B: Programming Code in Visual Studio Code

This Appendix holds the programming code written in Visual Studio Code. The code, except the optimization problem, includes the code for the development of the Graphical User Interface (GUI).

```python
from tkinter import *
from tkinter import ttk
from docx import Document
import tkinter.messagebox
import datetime
import time
import customtkinter
from PIL import Image, ImageTk
import os
from scipy.optimize import minimize
import math
import matplotlib.pyplot as plt


class Warehouse(customtkinter.CTk):

    def __init__(self,root):
        self.root = root
        self.root.title(60*" "+"Sub-component's optimization")
        self.root.geometry("750x800+100+0")
        # self.root.resizable(width=False,height=False)
        self.root.configure(bg='white')

        MainFrame = customtkinter.CTkFrame(self.root,corner_radius = 10,fg_color='light grey')
        MainFrame.grid()

        TitleFrame = customtkinter.CTkFrame(MainFrame,corner_radius = 10,fg_color='light grey')
        TitleFrame.grid(row=0,column=0)
        TopFrame3 = customtkinter.CTkFrame(MainFrame,width=600,height=600)
        TopFrame3.grid(row=1,column=0)

        LeftFrame = customtkinter.CTkFrame(TopFrame3,  width=600,height=600)
        LeftFrame.pack(side=LEFT)
        LeftFrame1 = customtkinter.CTkFrame(LeftFrame,width=200,height=180,)
        LeftFrame1.pack(side=TOP)
```

```python

        # =============================================Images=============================================

        PATH = os.path.dirname(os.path.realpath(__file__))

        # =============================================Legend=============================================
        # In programming, it is important to work with easily understandable names, otherwise the code is not easilry readable.
        # Therefore, here, all the names of variables and parameters used corresponding to the names of variables and parameters used in
        # the thesis document, are illustrated:

        # production_run = r
        # truck_size = k
        # distance = d
        # velocity = v
        # Type1, ..., Type9 = qt
        # avg_delay = δ
        # t_one = τr
        # setup_time = s
        # other_waiting_times = Δ
        # cost_type = ct
        # setup_costs = C
        # inv_costs = I
        # truck_cost = T

        optimization_image = ImageTk.PhotoImage(Image.open(PATH + "/optimization.png").resize((40, 40), Image.Resampling.LANCZOS))
        # =============================================Variables=============================================
        Type1 = StringVar()
        Type2 = StringVar()
        Type3 = StringVar()
        Type4 = StringVar()
        Type5 = StringVar()
        Type6 = StringVar()
        Type7 = StringVar()
        Type8 = StringVar()
        Type9 = StringVar()
        Weight = StringVar()
        Plot = StringVar()

```

```python
    # ============================================Functions============================================

    def start_process():

        def objective_fun(x):
            global cost
            global total_time
            global no_trucks
            batch_size = x[0]
            batch_time = x[1]
            no_setups = sum([y for x,y in order.items()]) / x[0]
            sum_wait_time = cost_qty_type = 0

            for k,v in order.items():
                for k1,v1 in supplier1.items():
                    if k == k1:
                        cost_qty_type += v*v1['cost_type']

            for k,v in supplier1.items():
                for x in range(v["production_run"]-1):
                        sum_wait_time += v["t_one"] * batch_size - v["t_one"]

            no_batches = 0
            for k,v in order.items():
                no_batches += math.ceil(v/batch_size)

            no_trucks = math.ceil(sum([y for x,y in order.items()])/truck_size)

            cost = (cost_qty_type + setup_costs*no_setups + \
                    (sum_wait_time)*inv_costs/(60*24)+ no_trucks*truck_cost)


            total_time = avg_delay + batch_time + setup_time*no_setups + \
                other_waiting_times + no_trucks*(distance/velocity)/60

            #Weighted objective function
            return weight*(avg_delay + batch_time + setup_time*no_setups + \
                other_waiting_times + no_trucks*(distance/velocity)/60) + (1-weight)*(cost_qty_type + setup_costs*no_setups + \
                    (sum_wait_time)*inv_costs/(60*24)+no_trucks*truck_cost)

        #Waiting time
        def constraint1(x):
            batch_size = x[0]
            wait_time = x[2]
            result = 0

            for k,v in supplier1.items():
                for x in range(v["production_run"]-1):
                        result += v["t_one"] * batch_size - v["t_one"]
            return wait_time - result

        #Actual processing time
        def constraint2(x):
            batch_size = x[0]
            process_time = x[3]
            result = 0
            t_one =[]

            for k,v in supplier1.items():
                for x in range(v["production_run"]-1):
                    if x== 0:
                        t_one.append(v["t_one"])
                    result += v["t_one"]

            t_one = sum(t_one)
            return process_time - batch_size*t_one - result
```

```python
    #Batch time
    def constraint3(x):
        wait_time = x[2]
        process_time = x[3]
        batch_time = x[1]
        return batch_time - process_time - wait_time

    #Number of set-ups
    def constraint4(x):
        return sum([y for x,y in order.items()]) /x[0]-1

    #No zero input (quantities of types introduced in the model belong to positive integers)
    def constraint5(x):
        batch_size = x[0]
        no_batches = {k:math.ceil(v/batch_size) for k,v in order.items()}
        result = []
        data = [result.append(v) for v in no_batches.values()]
        return all(result) - 0.5

    #At least one batch should fit in the truck
    def constraint6(x):
        batch_size = x[0]
        return  (truck_size/batch_size -1)
```

```python
    #Demand is satisfied, all batches are delivered - so, the remaining quantities of all types are 0
    #This corresponds to the constraint with jt, that all batches are delivered
    def constraint7(x):
        global order1
        batch_size = x[0]
        truck_space = int(truck_size/batch_size)
        order1 = order.copy()
        for k,v in order1.items():
            order1[k] = math.ceil(v /batch_size)

        while all(value <=0 for value in order1.values())==0:
            for k,v in order1.items():
                if v >0:
                    order1[k] = v - 1
                    truck_space = truck_space - 1
                    if all(value <=0 for value in order1.values())!=0 and truck_space != int(truck_size/batch_size):
                        break
                    elif truck_space < 1:
                        truck_space = int(truck_size/batch_size)

        return int(all(value <=0 for value in order1.values())) -0.5

    #Batch size has to be equal or smaller than the minimum quantity ordered - for ex. if min=10, I cannot have batch_size of 20.
    def constraint8(x):
        batch_size = x[0]
        return  (min(order.values()) - batch_size)
```

```python
    #Plotting costs
    def plot_cost():
        fig,ax = plt.subplots()
        # make a plot
        ax.plot(weights, batch_size_list, color="red", marker="o")
        # set x-axis label
        ax.set_xlabel("Weight (w)",fontsize=12, font ='bookman old style')
        # set y-axis label
        ax.set_ylabel("Batch size (b)",color="red",fontsize=12, font ='bookman old style')
        ax2=ax.twinx()
        # make a plot with different y-axis using second axis object
        ax2.plot(weights, cost_list,color="green",marker="o")
        ax2.set_ylabel("Total Cost (in €)",color="green",fontsize=12, font ='bookman old style')
        ax.set_title("Total Cost & Batch size variation according to the preference",color="orange",fontsize=14, font ='bookman old style

        #Plotting table
        plt.rcParams["figure.figsize"] = [7.00, 3.50]
        plt.rcParams["figure.autolayout"] = True
        fig, axs = plt.subplots(1, 1)
        columns = ("Weight (w)","Batch size (b)","Total Cost (in €)")
        data = [([round(weights[x],2),round(batch_size_list[x],2),round(cost_list[x],2)]) for x in range(11)]
        axs.axis('tight')
        axs.axis('off')
        the_table = axs.table(cellText=data, colLabels=columns, loc='center',cellLoc='center')
        plt.show()

```

```python
    #Plotting time
    def plot_time():
        fig,ax = plt.subplots()
        # make a plot
        ax.plot(weights, batch_size_list,color="red", marker="o")
        # set x-axis label
        ax.set_xlabel("Weight (w)",fontsize=12, font ='bookman old style')
        # set y-axis label
        ax.set_ylabel("Batch size (b)",color="red",fontsize=12, font ='bookman old style')
        ax2=ax.twinx()
        # make a plot with different y-axis using second axis object
        ax2.plot(weights, time_list,color="green",marker="o")
        ax2.set_ylabel("Lead Time (in min)",color="green",fontsize=12, font ='bookman old style')
        ax.set_title("Lead Time & Batch size variation according to the preference",color="orange",fontsize=14, font ='bookman old style'

        #Plotting table
        plt.rcParams["figure.figsize"] = [7.00, 3.50]
        plt.rcParams["figure.autolayout"] = True
        fig, axs = plt.subplots(1, 1)
        columns = ("Weight (w)","Batch size (b)","Time (in min)")
        data = [([round(weights[x],2),round(batch_size_list[x],2),round(time_list[x],2)]) for x in range(11)]
        axs.axis('tight')
        axs.axis('off')
        the_table = axs.table(cellText=data, colLabels=columns, loc='center',cellLoc='center')
        plt.show()

    #Plotting Pareto Front
    def plot_pareto():
        fig,ax = plt.subplots()
        # make a plot
        ax.plot(cost_list, time_list,color="purple", marker="D",ms=7)
        # set x-axis label
        ax.set_xlabel("Total Cost (in €)",fontsize=12, font ='bookman old style')
        # set y-axis label
        ax.set_ylabel("Lead Time (in min)",fontsize=12, font ='bookman old style')
        ax.set_title("Pareto Front",color="orange",fontsize=14, font ='bookman old style', fontweight = 'bold')

```

```python
    #Plotting table
    plt.rcParams["figure.figsize"] = [5.00, 3.50]
    plt.rcParams["figure.autolayout"] = True
    fig, axs = plt.subplots(1, 1)
    columns = ("Total Cost (in €)","Lead Time (in min)","Lead Time (min)")
    data = [([round(cost_list[x],2),round(time_list[x],2)]) for x in range(11)]
    axs.axis('tight')
    axs.axis('off')
    the_table = axs.table(cellText=data, colLabels=columns, loc='center',cellLoc='center')

    plt.show()

order = {
    'Type_1':int(Type1.get()),'Type_2':int(Type2.get()),'Type_3':int(Type3.get()), 'Type_4':int(Type4.get()),
    'Type_5':int(Type5.get()), 'Type_6':int(Type6.get()), 'Type_7':int(Type7.get()), 'Type_8':int(Type8.get()),
    'Type_9':int(Type9.get())
}

supplier1 = {
    'Type_1': {'t_one':280,'setup_time':250,'production_run':9,'cost_type':1450},
    'Type_2': {'t_one':240,'setup_time':250,'production_run':9,'cost_type':1700},
    'Type_3': {'t_one':320,'setup_time':250,'production_run':9,'cost_type':2500},
    'Type_4': {'t_one':170,'setup_time':250,'production_run':9,'cost_type':800},
    'Type_5': {'t_one':170,'setup_time':250,'production_run':9,'cost_type':800},
    'Type_6': {'t_one':300,'setup_time':250,'production_run':9,'cost_type':1820},
    'Type_7': {'t_one':160,'setup_time':250,'production_run':9,'cost_type':945},
    'Type_8': {'t_one':230,'setup_time':250,'production_run':9,'cost_type':1490},
    'Type_9': {'t_one':135,'setup_time':250,'production_run':9,'cost_type':850}
}

```

```python
#Parameters
inv_costs = 150 # €/day
setup_time = 250 # minutes
other_waiting_times = 21600 #minutes
avg_delay = 14400 #minutes
setup_costs = 500 #per setup
weight = float(Weight.get())
truck_size = 60
truck_cost = 400 #€ per truck
distance = 50 #km
velocity = 60 #km/h

# Initializing values
batch_size = 10
batch_time = 10000
wait_time = 7000
process_time = 3000
positive_infinity = float('inf')

#Guess
x0 = [batch_size, batch_time, wait_time, process_time]

#Bounds
bounds_batch_size = (1,80)
bounds_batch_time = (20,positive_infinity)
bounds_wait_time = (10,positive_infinity)
bounds_process_time = (10,positive_infinity)
bnds = (bounds_batch_size,bounds_batch_time, bounds_wait_time, \
    bounds_process_time)

```

```python
        #Constraints
        con1 = {'type':'eq','fun':constraint1}
        con2 = {'type':'eq','fun':constraint2}
        con3 = {'type':'eq','fun':constraint3}
        con4 = {'type':'ineq','fun':constraint4}
        con5 = {'type':'ineq','fun':constraint5}
        con6 = {'type':'ineq','fun':constraint6}
        con7 = {'type':'ineq','fun':constraint7}
        con8 = {'type':'ineq','fun':constraint8}
        cons = [con1, con2, con3, con4, con5, con6, con7,con8]

        global result
        result = minimize(objective_fun, x0, method='SLSQP',\
            bounds=bnds,constraints=cons, options = {'maxiter':1000})
        tkinter.messagebox.showinfo("Sub-component's optimization",result['message'])
        document = Document()
        self.text_box.delete('1.0',END)
        self.text_box.insert(END,20*' '+'Results\n',result)
        self.text_box.insert(END,result)
        ts = time.time()
        st = datetime.datetime.fromtimestamp(ts).strftime('%d/%m/%Y - %H:%M:%S')
        document.add_paragraph(f'{st}\n {result}')

        # print("no_trucks",no_trucks)
        global total_time
        global cost
        print("no_trucks",no_trucks)
        print(order1)

        weights=[i*0.1 for i in range(11)]
        batch_size_list = []
        cost_list = []
        time_list = []

```

```python
        #Solution
        for weight in weights:
            result1 = minimize(objective_fun, x0, method='SLSQP',\
                bounds=bnds,constraints=cons, options = {'maxiter':1000})
            batch_size_list.append(result1.x[0])
            cost_list.append(cost)
            time_list.append(total_time)


        def plot_selection():
            if Plot.get() == 'Batch_size - Cost':
                plot_cost()
            elif Plot.get() == 'Batch_size - Time':
                plot_time()
            elif Plot.get() == 'Pareto':
                plot_pareto()
                # plot_time()
                # plot_cost()
        plot_selection()
        self.plot_selction = customtkinter.CTkButton(LeftFrame1,text="Plot Selection",text_font=('bookman old style',12,'bold'),text_color='w
        self.plot_selction.grid(row=7,column=2,sticky=E,pady=5)

        document.save('python.docx')

```

```python
        # ===============================================Labels and Entries===============================================
        self.lbltitle=customtkinter.CTkLabel(TitleFrame,image=optimization_image,compound='left',text_font=('bookman old style',20,'bold'),text="Sub-component's optimizat
        self.lbltitle.grid(row=0,column=0,ipadx=75)
        self.lbltitle.image = optimization_image

        self.lblWindows = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',14,'bold'),text="Windows & Frames Supplier", text_color = "brown")
        self.lblWindows.grid(row=1,column=0,sticky=W,ipadx=0)

        self.lblMess = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',11,'bold'),text="▷ Enter the quantities per type needed", text_color = "green")
        self.lblMess.grid(row=2,column=0,sticky=W,ipadx=0)

        self.lblType1 = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',12,'bold'),text=" Type 1: Door (1.10m*2.50m)     ")
        self.lblType1.grid(row=3,column=0,sticky=W,ipadx=0)
        self.entType1 = customtkinter.CTkEntry(LeftFrame1,text_font=('bookman old style',12,'bold'),corner_radius = 20,width=120,justify='left',textvariable=Type1)
        self.entType1.grid(row=3,column=1,sticky=W,padx=5)

        self.lblType2 = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',12,'bold'),text="Type 2: Window (1.55m*1.40m)       ")
        self.lblType2.grid(row=4,column=0,sticky=W,padx=5)
        self.entType2 = customtkinter.CTkEntry(LeftFrame1,text_font=('bookman old style',12,'bold'),corner_radius = 20,width=120,justify='left',textvariable=Type2)
        self.entType2.grid(row=4,column=1,sticky=W,padx=5)

        self.lblType3 = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',12,'bold'),text="Type 3: Door (3.00m*2.50m)       ")
        self.lblType3.grid(row=5,column=0,sticky=W,padx=5)
        self.entType3 = customtkinter.CTkEntry(LeftFrame1,text_font=('bookman old style',12,'bold'),corner_radius = 20,width=120,justify='left',textvariable=Type3)
        self.entType3.grid(row=5,column=1,sticky=W,padx=5)


        self.lblType4 = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',12,'bold'),text="Type 4: Window (0.55m*1.40m)       ")
        self.lblType4.grid(row=6,column=0,sticky=W,padx=5)
        self.entType4 = customtkinter.CTkEntry(LeftFrame1,text_font=('bookman old style',12,'bold'),corner_radius = 20,width=120,justify='left',textvariable=Type4)
        self.entType4.grid(row=6,column=1,sticky=W,padx=5)


        self.lblType5 = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',12,'bold'),text="Type 5: Window (0.55m*1.40m)       ")
        self.lblType5.grid(row=7,column=0,sticky=W,padx=5)
        self.entType5 = customtkinter.CTkEntry(LeftFrame1,text_font=('bookman old style',12,'bold'),corner_radius = 20,width=120,justify='left',textvariable=Type5)
        self.entType5.grid(row=7,column=1,sticky=W,padx=5)


        self.lblType6 = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',12,'bold'),text="Type 6: Window (1.60m*2.15m)       ")
        self.lblType6.grid(row=8,column=0,sticky=W,padx=5)
        self.entType6 = customtkinter.CTkEntry(LeftFrame1,text_font=('bookman old style',12,'bold'),corner_radius = 20,width=120,justify='left',textvariable=Type6)
        self.entType6.grid(row=8,column=1,sticky=W,padx=5)


        self.lblType7 = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',12,'bold'),text="Type 7: Window (1.20m*1.50m)       ")
        self.lblType7.grid(row=9,column=0,sticky=W,padx=5)
        self.entType7 = customtkinter.CTkEntry(LeftFrame1,text_font=('bookman old style',12,'bold'),corner_radius = 20,width=120,justify='left',textvariable=Type7)
        self.entType7.grid(row=9,column=1,sticky=W,padx=5)


        self.lblType8 = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',12,'bold'),text="Type 8: Window (1.60m*1.50m)       ")
        self.lblType8.grid(row=10,column=0,sticky=W,padx=5)
        self.entType8 = customtkinter.CTkEntry(LeftFrame1,text_font=('bookman old style',12,'bold'),corner_radius = 20,width=120,justify='left',textvariable=Type8)
        self.entType8.grid(row=10,column=1,sticky=W,padx=5)


        self.lblType9 = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',12,'bold'),text="Type 9: Window (0.55m*0.90m)       ")
        self.lblType9.grid(row=11,column=0,sticky=W,padx=5)
        self.entType9 = customtkinter.CTkEntry(LeftFrame1,text_font=('bookman old style',12,'bold'),corner_radius = 20,width=120,justify='left',textvariable=Type9)
        self.entType9.grid(row=11,column=1,sticky=W,padx=5)

        self.lblMess2 = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',11,'bold'),text="▷ Introduce your preference", text_color = "green")
        self.lblMess2.grid(row=12,column=0,sticky=W,ipadx=0)

        self.lblWeight = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',12,'bold'),text=("Weight ∈ [0,1]"))
        self.lblWeight.grid(row=13,column=0,sticky=W,padx=5,ipadx=7)
        self.entWeight = customtkinter.CTkEntry(LeftFrame1,text_font=('bookman old style',12,'bold'),corner_radius = 20,width=120,justify='left',textvariable=Weight)
        self.entWeight.grid(row=13,column=1,sticky=W,padx=5)

        self.lblPref = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',11,'italic'),text="  0: cost minimization most important")
        self.lblPref.grid(row=14,column=0,sticky=W,padx=5,ipadx=7)

        self.lblPref = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',11,'italic'),text="  1: time minimization most important")
        self.lblPref.grid(row=15,column=0,sticky=W,padx=5,ipadx=7)

        self.lblPlot = customtkinter.CTkLabel(LeftFrame1,text_font=('bookman old style',12,'bold'),text="Plot          ")
        self.lblPlot.grid(row=16,column=0,sticky=W,padx=5)
        self.cboPlot = ttk.Combobox(LeftFrame1,font=('bookman old style',12,'bold'),width=14,state='readonly',textvariable=Plot)
        self.cboPlot['values'] = (' ','Batch_size - Cost','Batch_size - Time','Pareto')
        self.cboPlot.current(0)
        self.cboPlot.grid(row=16,column=1)
        # ================================================Text Box================================================

        self.text_box = Text(LeftFrame, height =20, width=50)
        self.text_box.pack(expand=True)
        self.text_box.insert(END,20*' '+'Results')

        # # ================================================Buttons================================================
        self.process = customtkinter.CTkButton(LeftFrame1,text="Start Process",text_font=('bookman old style',14,'bold'),text_color='white',corner_radius=10, fg_color="pu
        self.process.grid(row=6,column=2,sticky=E)


if __name__=='__main__':
    root = customtkinter.CTk()
    application = Warehouse(root)
    root.mainloop()
```

Figure B: Programming code in Visual Studio Code

APPENDIX C: Graphical User Interface (GUI)

This Appendix holds the developed graphical user interface (for better comprehension of the developed model) in Python. Figure C is obtained after entering the quantities, the weight and pushing the button “Start Process”. The message, which appears in the white frame, informs whether the optimization was successful or not and provides the corresponding results. Furthermore, the message “Orden has been delivered successfully!” appears and informs the user regarding the status of the order: if all the batches of all types have been delivered. Then, by clicking on the dropdown list “Plot”, three options appear for plotting: Batch size – Lead Time, Batch size – Total Cost, Pareto. By clicking on “Plot Selection” the respective plot is illustrated along with a table for better comprehension. In Figure C, the quantities entered correspond to the case study used to validate the model, while the resulting figures and tables are those presented under the Results Section in Chapter 8.

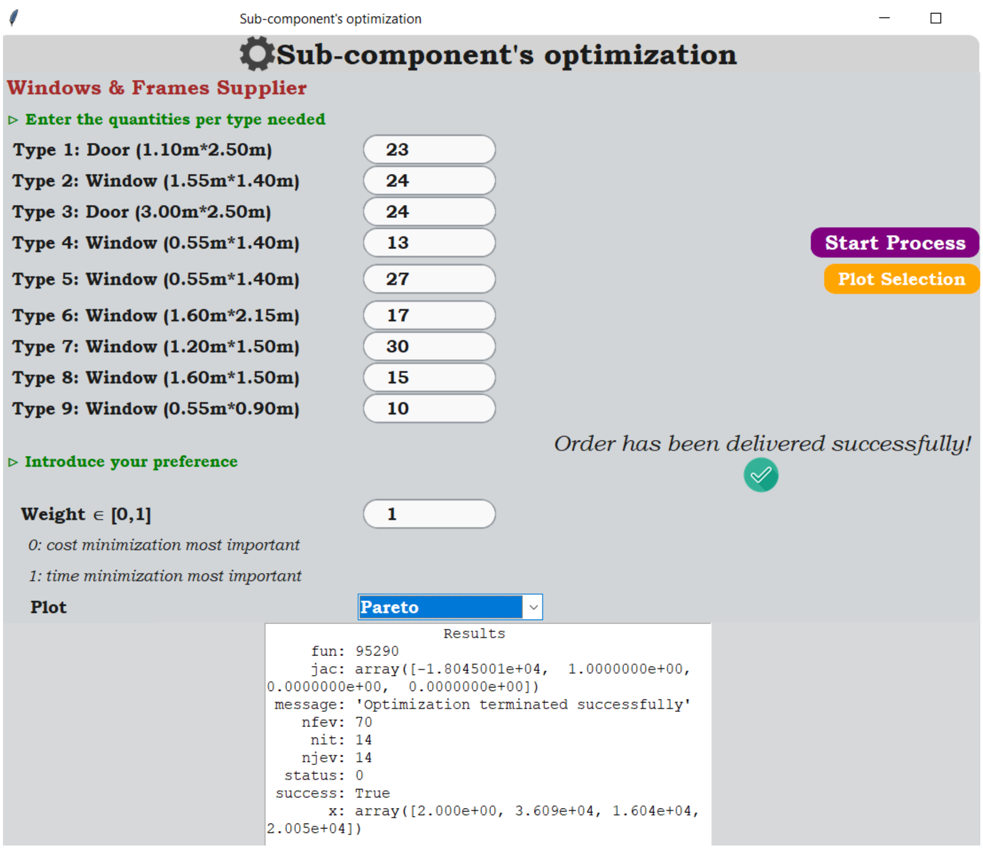

Figure C: Graphical User Interface – Results after starting the process

APPENDIX D: Interviews

Janssen de Jong Bouw B.V. – *Construction Company*

Interviewer: Evangelia Rizopoulou

Interviewee A

1. <u>Could you please describe me the current situation at *Janssen de Jong* concerning the precast concrete house-building industry?</u>

We are a large construction company, but for the scale of the company not ahead in precast concrete house building. We build about 300-500 houses each year, where our competition is building more in the region of 3000-5000 houses per year. We have to innovate to be able to get ahead of competition.

2. <u>Who are the main stakeholders (people/companies/factories) involved in the precast concrete house-building industry (e.g. precast concrete factory, window factory etc.)?</u>

There are a few, let me sum them up per category:

– Competitive construction companies/products:
  - Van Wijnen “Fijn Wonen”
  - Dura Vermeer “Blokje om”
  - Volker Wessels “Morgen wonen”

– Companies that Janssen de Jong uses as subcontractors are:
  - Geelen beton (precast factory)
  - Prefab houtconstructies Hardenberg (wood framed prefab roofs)
  - Van de Vin kozijnen (windows)

There are more concrete casting companies, window factories and the like. I don’t have relevant information about their way of working or their scale. Imagining that around 80.000 houses are built annually in the Netherlands, and a lot of those are concrete, we can see that the supply is ample.

3. What are the problems you are experiencing in this field of construction industry? In terms of money, time, reputation, communication with the other stakeholders involved.

The main concern is the inefficiency in the unbalance of workflows. Because we are dealing with companies that have individually optimized their processes, there is a lot of waiting between the different tasks. As a construction company, our objective is to bring all these parties together in the most efficient way for the project, not just the individual tasks.

4. Referring specifically to the problem of long lead times, which are the main contributors to long lead times in precast concrete construction in general and which are specifically the main contributors to long lead times of the sub-components?

The main contributors for long lead times are the subcomponents that are delivered in large batches. Not only the long lead times of the subcomponents itself, but also the engineering time for the subcomponents before manufacturing can start. So, within the total lead times of the concrete elements, there are individual lead times of engineering and production of subcomponents.

5. Which are the effects of long lead times on you as a company (client), on the rest of the stakeholders (e.g. precast concrete factory) and on the project performance?

The main effect is that big parts of the project are constantly waiting for the next task to be performed. Since, as a construction company, we manage the schedule of all subcontractors and suppliers on site. The longer this takes, the less projects we can execute. The lead time shortening therefore, gives us the opportunity to execute more projects and the leverage of exponentially increased turnover.

6. What is the ideal situation for you to be achieved and what is the more realistic scenario to start "solving" this problem? In other words, what should be paid attention to in order to reduce lead times to a reasonable extent? As we need to

be as realistic as possible, what are the advantages and disadvantages for all the stakeholders involved? Can we end up with a win-win situation for all, in practice?

Ideally, we can. The theoretical approach is to make one house at a time in a one-piece-flow order. In practice, the inefficiency of extra transportation or inactivity due to too small batches can lead to higher costs, with minimum benefit on the project. The optimum can only be found if all these factors are included in the equation. The win-win situation occurs when we can find the minimum quantity of products being produced/transported/processed close to a one-piece-flow orientation, without the extra cost of under freight, increased setup costs etc. and even if any of these extra costs would be the case than they should integrally be reviewed whether they benefit the total project or not.

7. What's your opinion on building strong and long-term relationships with the other stakeholders involved in the process? Is it something you are just taking for granted or you are trying as far as you can to maintain and enhance your relationships with them? If the former holds: why are you doing so (for example: do you maybe think that they will "always be available" when you need them because they want to sell their products and make money, so you don't have to be close to them)? If the latter holds, in which ways you are trying to maintain and enhance your relationships with them?

The relationship with expert partners should be strong in order for them to help us in optimizing our combined process. This means, we challenge them in improving the process, we ask them for commitment and priority for our projects, and reward them on the other hand by giving them continuity in contracts/projects and a steady revenue.

This only counts for partners that are of influence in the project process in terms of complexity, number of manhours on site of product lead times. Commodity goods (a box of nails or a can of paint) don't necessarily have to be obtained from partners with which we have strong relationships.

8. Suppose that we have a project consisting of 500 houses. The sub-components needed for the whole project will be ordered at the same time. Is that right? It

might seem reasonable, but can you explain briefly why are you ordering massively for (for example) 1-year time horizon and not at regular intervals?

It would be ideal to order in smaller quantities for a few benefits; engineering can be done in smaller batches and therefore, having a shorter lead time. It could, also, benefit from possible improvements, that can be adapted in future batches. Ideally, we would purchase on basis of an annual blanket order and order Just in time on-demand.

The fact that we order in larger batches has to do with our method of purchasing. We buy per project or maybe for multiple projects in order to get a lower price per m^2 or per window. This does not (yet) account for the benefits that smaller batches provide us. We need to change this as soon as we can quantify these benefits.

9. Could you describe me a "typical" procedure that is followed once the 3D simulation of a project is ready? For example, we make the drawings and the 3D model of the whole project and then, we have to add the dimension of time (4D). At this point, do you check the lead time of each supplier and then you add the dimension of time?

In this process, we do not yet have the optimization of the lead times. What we do, is we provide the suppliers with a list of the components assigned to a certain date of assembly on site. For now, we just try to make the 4D planning way ahead of execution. Ideally, the lead times would be included in the metadata of the components in the BIM model. So that we can place the whole 4D planning in time. Not only for the construction, but also in what period the construction can be executed regarding the lead times.

Van de Vin ramen en kozijnen B.V. – *Windows & frames Company*

Interviewer: Evangelia Rizopoulou

Interviewee B

1. What’s your lead time as a company? According to your experience as a company, which are the main contributors to long lead times for you to produce a window? So, is it for example, the fact that you don't have the materials you need on time in your factory in order to start producing or are the steps that you follow in the assembly line in order to make the windows? Also, how your lead time could be translated in monetary terms?

We have a lead time of approximately ten weeks starting from the moment we get the order until the moment we deliver the first window. In these ten weeks, we use about six weeks to get drawings to produce the windows, and four weeks to actually order the materials like glass, and all the other products we need for the windows. And then, we have about one week to actually make the window. If we talk about costs, someone would say that we probably are a bit more expensive than others. However, my answer to this is that can offer shorter lead times, which is also money. And shorter lead time is a gain.

2. So, as you just described, you need only 1 week to produce all the windows, but there are like 9 or 10 weeks in which you are basically waiting for other things to be done. What are the effects of these waiting times on you, as a company?

We gather the drawings, or maybe a 3D model from you (Janssen de Jong). And then, we make the drawings for the windows and we send them back to Janssen de Jong, so they can check them._So, we need maybe two weeks, one and a half week to make this rolling, then we send them to check and to verify if it's all in order. Then, Janssen de Jong needs maybe one and a half week, as well and afterwards, they sent the drawings back. And_maybe there are some changes we need to make on the drawings. Then, we make those changes and send them again back as definitive drawings. So, we need about four or five weeks_to get to the specification in order to make the windows, and then we can start buying our products like glass and wood. So, we can order all these products and the factories have about three weeks to deliver all these products to us._And the fourth week, we start making the window frames. And after a week, we can deliver them.

3. So, the actual production takes one week. And the rest time of the time is basically out of your control in some way. For this research, we are not looking into these suppliers (glass factory for example), because that would make the whole research very complicated due the time limitation. But, your point of you and how you are experiencing it is important.

Indeed, the time needed by the rest of the suppliers is out of our hands. It's a big component of the time. We have to wait before they deliver all them, because we order all these materials custom-made, as every window frame is different. So, most of the waiting time comes from the delivery of raw materials to us.

4. Do you have maybe an idea of how you can improve/reduce the waiting time in your process?

Well, the most of the waiting time is in producing the drawings. So, because it takes six weeks, in the whole process of ten weeks, we need six weeks to get to definite drawings. We could make arrangements; we can raise some standards in how to make these window frames.

5. So, because there are a lot of projects, they're all different projects. So, if you can standardize processes, you can shorten the lead time.

Yes. And why yes? Because you (Janssen de Jong) choose for Geelen, as a factory to make the concrete walls. A lot of variables are gone, because they have a standard way of making the walls and how to put the window frames in the concrete. So, that saves a lot of variables. And maybe a part of that, is the 3D models we get from you (Janssen de Jong). And the way you make these models. If you use components, which are presented by us to make these 3D models, then it saves us a lot of time, searching which window frames are where and how are they.

6. So, whole let's say the drawing process that takes a few weeks is something that we want to eliminate, but let's assume that this has been eliminated. So, we're going to focus on production and supply and then, I think the variability is the types of windows that go into one house.

Well, as we can see later on, our production is computer-managed, so we produce one piece at a time. So, we don't need to make a lot of window frames which are all the same. We follow one-piece-flow. So, it doesn't matter if we make ten different window frames or ten same window frames. On a daily basis, we make about one hundred window frames, which can be different all one hundred. And we produce on a daily basis for about six different clients. So, each batch, each production batch is about fifteen to twenty window frames.

7. So, the minimum batch size is fifteen and the maximum batch size is around twenty?

Actually, there is no minimum batch size for us. Yeah, one window frame. But if you say we want to make one house per day, we can make the window frames for one house in one day, in that day. So, there are transportation costs, if we have to drive to Geelen (precast concrete factory) every day. But the way we work now is if a client wants fifteen window frames today, we deliver them and if he says, next week, I want the same amount, the same amount of frames, we deliver them next week. So, we don't say we have a truck, and it's got to be full. We deliver on a daily basis, different clients with the same truck. So, we drive from A to B to C and back. So, we don't need to deliver a minimum of fifteen window frames to one place. We combine, them so that truck is full and the driver has a certain route to route to drive.

8. Suppose that you don't have so many clients on a day and you have to deliver this amount of fifteen or twenty windows for one house for one client with one truck.

It happens, it happens. We say: to deliver a window frame to client it costs about maybe 20 euros. We try to do it as efficient as possible. But that's how we select to work as a company. We don't say, it has to be a minimum of that and otherwise, you'll get to pay extra.

9. <u>So, there's a fixed average price per window, which is already included in the cost that you offer to Janssen de Jong?</u>

Yes. Because we have different clients, who work with Geelen (precast concrete factory), it can be that we deliver frames from Janssen de Jong and from other clients at the same time to Geelen (precast concrete factory).

10. <u>Well, that makes sense. So, let's say your goal is to have a full shipment of windows to more than one client. And in case you have to deliver, let's say, windows for one client, then the price depends on the fixed price per window, right?</u>

We use a fixed price for delivery. And it doesn't matter if we have to deliver ten window frames or fifty.

11. <u>I searched a bit some sites of window factories, to see the standard delivery costs and have a rough idea. They have standard delivery costs for a specific amount. So, either me as a client asks you to make one window, I have to pay standard delivery costs of let's say, one hundred euros. These standard delivery costs are the same until a specific amount of, let's say, twenty windows, but above twenty windows, there is a kind of discount in the delivery costs. And I would like to ask you, if something like that happens in reality in your case, in case you have to deliver more than the regular or normal capacity of the truck, it can offer you a discount, in a way that both sides can save money. Is there something like that happening?</u>

Minimum is maybe five buildings; houses they make or ten or more. There's always a certain amount of window frames. But if there's a situation where we have to deliver just one or two window frames to a certain place, in Holland, then we say, well, then we have to charge you extra delivery costs.

12. So, the advantage in your case, is that many of the windows are delivered to Geelen (precast concrete factory), which is not too far away from here. It's a fixed distance that fits on the routes that you have daily. But that's different than different construction sites throughout the country. So, in this case, then it works for you to work with an average price per window.

It doesn't matter if we deliver the window frames to Geelen or maybe to Rotterdam or another place, we look at the distance from here to the delivery place. And then, we say that's a fixed price for that number of kilometers. So, if it's far away, we charge a little bit more per window frame to deliver the window frames.

13. And is there a kind of maximum capacity for the truck? I have to deliver to these clients. And I have the constraint that I have to load the truck until its maximum capacity. Is there an indicative number of maximum capacity or it happens that in every case you can use another truck?

We, as a company, don't have our own trucks. We use a transportation company, and they are limited in their capacity. So, some days we have no trucks at all, and some days we have two or three or more.

14. So, there's kind of, let's say, price list for the distance and the kilometers. Is that the case for other companies as well or it is your practice because you work with one-piece-flow?

Yes. I believe that one-piece-flow makes things easier for us to do it in this way, yet what is more common is to see clients preferring a truck for themselves only, in order to protect their products and avoid, let’s say unnecessary stops. So, I believe most companies are being asked to do so, especially where clients are on a hurry. There is a fixed price per truck, which is given by the transportation company.

15. What’s the difference between your way of working now and few years ago?

I have been wondering why are people building twenty houses, twenty concrete slabs, and then twenty walls. Why not vertical, but horizontal. In the past years, we were already looking at the product: how should it be made. And nowadays, we look more and more about how is the process.

16. In this model, we should find the balance between the cost and the time. What we can find in literature is that if we have large batches (batch-and-queue), we need more time to produce the windows or everything we need produce, we have more waiting times and inventory. Many argue that this way of producing costs less compared to the situation when you ask for smaller batches, which will cost you more, because this then will affect the number of set-ups and the delivery of the products. What's your opinion?

Yes, what you described holds, but in our case, that's not the case, as we also use robots.

17. Yes, I can understand that and it is really impressive. Your processes are already optimized. However, the problem is that not all people think in the way you do and they insist on the traditional way of working. If we go back to the years, I suppose that you were also working in the traditional way. After searching about the way this way of manufacturing works, I found that there are some steps, production runs in order to produce a window and there are different processing times at each step. Is that right?

Yes.

18. So, back again to the production around 10 years or 12 years ago. What was the average set up time? Because, I suppose, you were not so optimized as you're today. Could you somehow measure the setup time you needed in order to produce the different batches?

You are right. At that time, we didn't work with the same batches as now. Because then we would make a series of ten or fifteen same window frames. We had stocks everywhere.

19. So, in the more general situation, how many steps we can find in the production of the window?

Cut and profile them, then we have to assembly. After that, they are painted. The next step is to put glass, doors, PVC slabs. So, final assembly.

20. I would say in the old-fashioned way, you had set up times in between all, so you had to change the size of the cutting, the color of the paint and so on. There's a lot of variability in set up times between all these processes. And you did eliminate them. But when referring for example to paint, if all the windows have different colors, there's no minimum batch or setup anymore?

Yes. We use small cans of paint. So, we can easily change the color. Of course, when we have to make window frames for five different clients, it's easier to make first client A and client B, because they have the same color. Separate batches, but one after the other.

21. The model I am developing has to be general. Of course, the ideal situation, as you described it, is to say that we don't have setups/large setup times, because of the robot or the computer and there is also no variation in delivery costs. But this is not the case for all the companies, right?

Yes, indeed this is not the case for all.

22. So, just to sum up this discussion and draw a conclusion. In this case, you, as a window company, seem to not have, let's say, a problem that it is of interest for the optimization model. You have already improved your way of working and it’s really impressive, as I haven’t heard of someone else that did so. In the thesis, I am trying to solve a problematic situation. And I don't think that here we have a problematic situation.

Yeah, I understand. The waiting times, we reduce them, because we don't want waiting times, because the client doesn't want to pay for waiting. So, about 10-12 years ago, we started with lean manufacturing. And in this time, every day, we make the process better. So, we have every day less waiting time and we have a pull planning, we don't have stock between one production unit and the other. Because that's waiting time. And that's why we have no stock from our suppliers, and no stock from window frames we deliver to Janssen de Jong. Because if we produce them and we can deliver them, they cost money, because we have made them and so what we have to deliver next week, we make this week and we put them on a truck and deliver. So, if you say what's the difference between producing one or five or ten, there's no difference, because it's all one flow. So, it's already optimized, there's no batch and queue, waiting times and stock, that is costing money. And that's normally based because of the setup time. And it is important to know, in the beginning of the process, which window frames have to be together in order to put them in the same steel frame and deliver them.

23. Can I have an indicative list of the costs involved in the lead time?

Well, we calculate the exact price for one for each and every window. Let’s say material costs, labor etc. And then we add them up. And that's the total.

Geelen Beton – Precast Concrete Factory

Interviewer: Evangelia Rizopoulou

Interviewee C

Interviewee D

1. In the context of my research, which is about sub-components' lead time optimization in precast concrete house-building projects, I am trying to figure out which are the main contributors to long lead times and what are the effects of them. So, I would like your opinion on that, according to your experience. Last week we visited (Mr. Karel Kalis and I) Van de Vin company and they said that were able to produce and deliver to you per house, and they can combine different windows on one frame. Could you please explain how was your experience before Van de Vin, which seems to be really optimized?

We started out with a window company just delivering all types in one time or more in houses at the same time. And then we had to pick one out, but that's not possible because another window is leaning against it. So, we had to produce in the order they left it or we had to get the windows and the fabric and then, there were four windows, we needed one, we were going back outside and so on and so on. So, that takes a lot of time and effort in the factory, which we don't want; time is also money. But we managed with Van de Vin to get it in the order we want it and just a small time before we need it. So not the whole project at the same time, but in batches. And we prefer small batches, but Van de Vin also needs to drive as few times as possible, so the batches cannot be too small.

2. So, one window is too small and not efficient right?

Yes, that's too small, there's a lot of driving. So, we don't want that.

3. So, this is the goal of my optimization; to see what is the most efficient number of windows and but also all the other sub-components. So, you want as small batches as possible, but not to make it not extremely more expensive and inefficient. So, where is the optimum that is that is the core of the of the research. I suppose that you have several truckloads for one house, right?

In concept housing, it's two truckloads for the walls and two for the floors, so four truckloads per house.

4. So how much time in other words on average it takes you to build the house, if you have all the components available here?

We can make approximately six houses a day. Two with the walls and two to three with the floors per day.

5. And in case you don't have everything you need in order to build these houses, what's the average delay that the delay of delivering these components brings to you, as a company, and how this affects your way of working?

In case there are delays, we do know that a lot before, so we can manage that in the schedules. We can produce other things, for which we have the components already. And we put them in front of the other one, the other goes backwards.

6. So, you already know beforehand, which components will be delivered later than you expect them. So, you're trying to adjust your way of working based on that?

It doesn't happen often. But if it happens, we know it in time, so we can change our schedule. So, for the windows, for example, we produce the walls without the windows sometimes. So, the builder gets the walls without the windows and has to put the windows on the construction site on the walls.

7. So how much time in advance do you check whether or not you have all the sub-components to be able to make sure that you can produce?

One week before for production. This is the time when the windows have to be on site. And if they're not there, then we start changing the schedule. But we don't need them one week before, but one day only. We say one week before, because one day before we can’t change the schedule. And one week before we can change the schedule. So, we need to know one week before. That's why.

8. What happens if a project is delayed?

When a project is delayed, we don't always delay our production. Because we need a production that is really stable. We can't produce three houses a day, and next week, nine houses a day. It needs to be fixed. We don't do this always, sometimes we do, because we don't have the drawings or the windows or the installation sub-components. But if we have, usually we decide to produce anyway, because we need a stable batch. In other situations, the builders built the exact amount as we can produce. But usually, that's not the case in the summer when more or less will be built than in the winter, because there are weather conditions and these types of delay. So, that's why also we need a big terrain to store the produced elements. Sometimes they go to the construction site in a week, but sometimes it takes five weeks before they are delivered. And that's a big challenge for us, that the planning of the builders doesn't follow our production planning.

9. By visiting Van de Vin, I can imagine that the way Van de Vin works is not something that every company does, if we're talking about window companies. So, I was surprised, by the way there have organized everything in order to be able to produce more batches and deliver them to you. Are you working in an optimized way, as well?

We always recommend Van de Vin. Indeed, it's one of the few ones. They are far into this one-piece-flow way of working. Our working is based on one-piece-flow. So, we don't need a series of exact same components or elements. So, if it's three times the same wall, we can produce them on Monday, Tuesday, one directly after the other. So. it's not necessary. It's real one-piece-flow in the factory, but the one house is usually ten walls and six places. So, it's sixteen elements. That's why it's four truckloads.

10. So, you are fitted for the one-piece-flow, and so does Van de VIN. How about the installation companies?

There is a problem with the installation sub-components, that usually come for ten houses at the same time, which is ten times six elements, sixty elements. We don't need them all ten at once, two batches of five is also good or four or two or three. Housing is also good. But they say this is not possible. The batch is so different, because they can load a truck and this batch can correspond to fifty elements for us. So, we have a lot of inventory let's say of the installation parts, which do not want it.

11. What if the builder on the construction site changes the production flow/the order of the houses to be built?

The builder asks for construction and we produce them in that way he asks for. But if six weeks before delivery, they change the order they want to follow, we can change our production also still, but we need to know that before, because that that makes how the load is stacked.

12. How much time it takes to produce one element?

It's usually two hours, and then it needs drying time of a minimum of six hours, when we work in three shifts. Now we work in two shifts, it's 12 hours. So, one day, 12 hours later, you can extract it from the molds.

13. I suppose that there's a difference between the production of specific types of housing and the production of bespoke houses. Is that right?

If you have a housing type, we call it type A or B or C and then, you know exactly in three weeks we need two houses of type A and B. In the most ideal situation, we have the drawings and we already have the calculations for the rebars. We just pick them out and then we can produce, this is the most ideal situation. But there are also unique houses. So, we need the engineering, it is not even there, because it has to be unique for the unique house. If the houses are sold and not rented, the client can choose some options. So, that usually has effect on the process. Because the options are not standard anymore. You can choose where to put the lighting and that makes the elements unique. So, the elements are shaped exactly the same. But if one component is in another place, it makes it unique.

14. Are you producing in batches of houses?

When you have a batch of nine buildings, it's not efficient to do the engineering for each one, so we need a batch of maybe 9-10 houses to 15 houses is ideal.

15. And if you have a batch of let's say nine and the project is 74 houses, then you have eight batches or something. So, can you completely separate them and say we do the engineering of these nine houses and get them into production and then, do the engineering of the next nine houses and so on?

We do that, but there will be some overlap.

16. What about working with the same companies over and over again? How this adds/or not to your process?

If you want to reduce your process, you need to work with the same companies over and over again. And this is usually a problem, because mainly the installation company is different from project to project, so we need to start over and over again and educate another installation company each time.

17. Are there ways in which you can standardize the options a client has, even in bespoke houses?

Yes, you can make also the wishes of the client standard. So, if you restrict the clients in the options they have and say them that they can choose for four different options, then you need to engineer them only once. So, there are many different ways in which you can standardize the options as well as the wishes of the client.

Anonymous Company – Installation Technology

Interviewer: Evangelia Rizopoulou

Interviewee E

The anonymity of the company is preserved upon their request.

1. Could you please introduce the company? At the precast concrete factory and the window company we visited during the past two weeks, they said that the installation parts are the ones that extend lead times. What is the batch size you work with as a company? Is there a minimum and maximum?

The company is specialized in HVAC and plumbing systems. We are doing single housing, apartment buildings and concept housing for different contractors. Our process includes standardization, digitalization, prefabrication and optimization of logistics. We are trying to reduce the variability of the supply, so we are trying to improve the prefabrication part. Currently, we are working with a batch size of one, which saves us a lot of time and effort, compared to large batches.

2. How does this batch size affect the way you deliver these parts either to the precast concrete factory or the construction site itself? Both in terms of trucks cost and the number of batches you are delivering? Is there a specific, let's say, catalogue with delivery costs? Is there a specific truck with a specific capacity that delivers all these products?

We have our own truck, which is up to a certain amount of volume. My colleague has the experience with it and so we can give you these numbers of the capacity and cost of the truck. And if batches are larger, then we need an external company to do that. But it’s better to assume that they can all be transported by our own truck or our own transportation station. Do you maybe remember what the best batch amount is for Geelen beton (precast concrete factory)?

3. I think they can do it per element. But of course, Janssen de Jong, as Mr. Karel explained, orients per house. So, I think their minimum is one house, but this is several truckloads for Geelen, I think six or eight elements of concrete. So, the minimum differs per company.

Okay, indeed, the perception of minimum differs per company, but even for companies which are specialized in the same field. Also, the perception of what is expensive and it is reasonable to be more expensive, is something that many people still find difficult to understand. Most of clients do not really understand that when asking for something to be done faster, they have to kind of "reward" your operations. Instead, they demand for both shorter times and lower prices, which is not feasible. You cannot, let's say, interfere in the way someone works without compensating for that.

4. Referring to the transportation cost, I found that the way the transportation companies charge the client is based on the full truckload service mainly, that is a client pays a specific truck and uses it for themselves irrespective of the quantity of products that is going into this truck. Is that the case in your way of working?

We have internal transportation and external transportation. So, in internal the cost is fixed per truck, while in external, the cost is calculated per palette or batch size. We mostly work with internal transportation, as it is more efficient.

5. I suppose that before moving towards one-piece flow there were a lot of setups in the way you were working right. So, now these have been kind of eliminated?

There are no specific set up times in our factory, as we order the air ducts in this specific length for specific projects. That means here, these air ducts need only to be mounted together, so that's why we don't have set up times here.

6. That’s interesting. So, you have basically moved the set-ups and so, the set-up times to another factory. So, the existence of set-ups in their way of working results in more waiting, right? I suppose this is not the way most companies in this field work.

Yes, the existence of set-ups is obvious in their process and in their lead time. We don’t have really experience on that, so in this sense we cannot say whether they have or not optimized their process. They usually have lead time of 5 working days. However, now, because of Corona and the war in Ukraine, their lead time is around 10 working days, as there are problems in the supply of raw materials. In the future, we want to do the cutting ourselves here, so that we have less of variability in that part as well. I suppose that other companies do not work as we do, so others doing the cutting for them.

7. And then what is their batch size that you order from them for the whole project?

I think five batches, so five floors so that's let's say half a house. But I don't know for sure.

8. Is there a specific or an average price per batch or it depends on the pieces that are going into a specific house?

It depends on the type of house. I can check it.

9. What happens with inventory? Suppose that you have your final products, five batches that are waiting in order to be delivered. Is this loss of space translated into money loss for you? Do you put an extra charge because of this delay? Or it is negligible?

I think it's negligible. The costs are there, but you don't know exactly where. If it takes longer to deliver them, then of course, the loss is noticeable. But again, because here the air ducts are only mounted together, we cannot say that we end up with inventory often.