Exploration of Opportunities to Reduce Lead Times for Engineered-to-Order Products

by

Jan Alarik Elfving

GRAD (Helsinki University of Technology) 1999

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy
in

Engineering-Civil and Environmental Engineering

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA, BERKELEY

Committee in charge:

Professor Iris D. Tommelein, Chair
Professor Glenn Ballard
Professor Dorit S. Hochbaum

Fall 2003

Exploration of Opportunities to Reduce Lead Times

for Engineered-to-Order Products

by

Jan Alarik Elfving

Abstract

Exploration of Opportunities to Reduce Lead Times

for Engineered-To-Order Products

by

Jan Alarik Elfving

Doctor of Philosophy

in

Engineering-Civil and Environmental Engineering

University of California, Berkeley

Professor Iris D. Tommelein, Chair

Scholars and practitioners have long advocated the benefits of reduced lead times. Moreover, most, if not all members of a supply chain would gain from reduced lead times. However, the construction industry has been slow to radically reduce lead times, particularly for Engineered-To-Order (ETO) products. This research applies Transformation-Flow-Value (TFV) theory and lean methods in order to answer the following research question: How can the performance of ETO supply chains be improved?

Data were collected from supply chains of power distribution equipment (PDE). The supply chains were described with help of detailed process maps and performance measures. Simulation was applied to gain further understanding of

supply chain behavior. The data demonstrated that current design and procurement practices have a major impact on the delivery lead time of PDE.

This work discusses the role design batch sizes and standards may have on the delivery process. It argues that the disadvantages of competitive bidding are poorly understood from a supply chain perspective. Competitive bidding generates waste not only in the procurement phase but also in the design and manufacturing phases, e.g., by forcing people to use early commitment and large batch sizes, and by involving downstream players late in the process. As a result, the delivery process is long and changes are tedious to carry out.

Finally, this dissertation proposes alternative practices to improve the current process of ETO products that can lead to major improvements over the delivery process. These alternatives include involving downstream players early in the delivery process, reducing document batch sizes, making decisions at last responsible moment, changing procurement methods, and sharing configuration software. In cooperation with industry partners it was estimated that these changes could have reduced a 2.5 year lead time by nearly 1 year. This could have led to major cost savings, particularly with respect to saved labor hours. However, major process changes in the delivery of ETO products also require redefinition of organizational relations in the delivery process. These extend to requiring an industry-wide rethinking of roles and responsibilities, risks and rewards as well as, contractual structures used in the ETO delivery process.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

I am grateful and I have been privileged of having so many people with extraordinary mind and vision involved in this project. I thank my advisors Professors Iris D. Tommelein and Glenn Ballard for their professionalism, encouragement, and patience. You did not only guide a doctoral thesis but you also taught me a profession. I thank Professors Dorit S. Hochbaum and Arpad Horvath for your feedback you gave me during my research presentations and our one-on-one meetings. I am particularly grateful for Dr. Lauri Koskela for encouraging me in the first place with this project; and guiding, believing, and supporting me ever since. I do not think this project would have ever started without you.

During these four years I received generous research funding from Tekes-National Technology Agency of Finland, Academy of Finland, Association of Finnish Civil Engineers, Svenska tekniska vetenskapsakademien i Finland, Foundation of Technology in Finland, Electrical Contracting Foundation, Confederation of Finnish Construction Industries (RT), Skanska Oy, and SRV Viitoset Oy, who I thank.

I want to thank the numerous practitioners who contributed to this research, particularly I want to acknowledge Steve Waters, Scott Peck, Gene Lujan, Elmer Savage, Matti Kärnä, Eero Nuutinen, Alpo Mäkinen, Esa Kauppinen, Petri Kiikka, Rauno Laatikainen, Jorma Kuparinen, Ben Schwegler, Chris Holm, Curt Sturmlauf, Jack Coffey, Bill Brownell, Lynn Halliburton, and Dave Evans.

I am grateful for Dr. Ari Ahonen of affiliating me with the Finnish construction industry, and believing in my research and me. I thank Professor Jouko Kankainen for the resources he has provided through Helsinki University of Technology. I want to thank my colleagues Michael Whelton and Dr. Nuno Gil for all the long and constructive conversations we had during these years. Also, my colleagues Cynthia Tsao, Thais da Alves, Nadia Akel, Dr. Hyun Jeong Choo, Dr. Yong-Woo Kim, Colin Milberg, and Roberto Arbulu thank you for sharing your thoughts with me.

Finally, I want to thank my family for all the support and understanding they have provided me these years. Most of all I am grateful to my wife Nadja, your love, support, and courage are unlimited.

1 INTRODUCTION

1.1 BACKGROUND

1.1.1 Construction industry

The construction industry is well known for its fragmented structure with multiple stakeholders and its uniqueness in products. These reasons, among others, have significantly slowed research and development in the industry. Taking into consideration the extensive impact the industry has on national economies and society as a whole it is important to see the industry progress. The industry has been blamed for lagging behind other industries with respect to productivity improvement, cost reduction, and project duration. This may be because the construction industry has lacked fundamental research and understanding of the various construction processes and their interactions on construction projects (e.g., Tucker and Laufer 1987, Koskela 1992, 2000).

1.1.2 Construction projects

One way of looking at construction projects and their processes is to consider the Lean Project Delivery System (LPDS) in terms of phases, such as project definition, design, supply, assembly, and use (Figure 1). Traditionally, these phases have been treated as sequential and independent from each other. However, in reality the phases overlap and influence each other (Koskela et al. 2002). This creates a complex network of dependencies throughout the construction project, which is normally beyond the control of any single stakeholder. The following example illustrates the case: After a building has been designed the owner of a building wants to have larger windows in order to have as much daylight as possible inside the building. This may increase the original estimated cooling requirements and the initial space reserved for the cooling equipment. As a result, the cooling equipment may have to be moved to a less ideal space causing major difficulties in installation of the equipment or a hazard for the service people to maintaining the equipment. Alternatively, instead of using standard cooling equipment as was originally programmed into design specifications, the equipment may have to be customized to fit the initial space. This may significantly impact the equipment cost and the equipment delivery lead time, which may jeopardize timely project completions and increase the risk of project cost overruns.

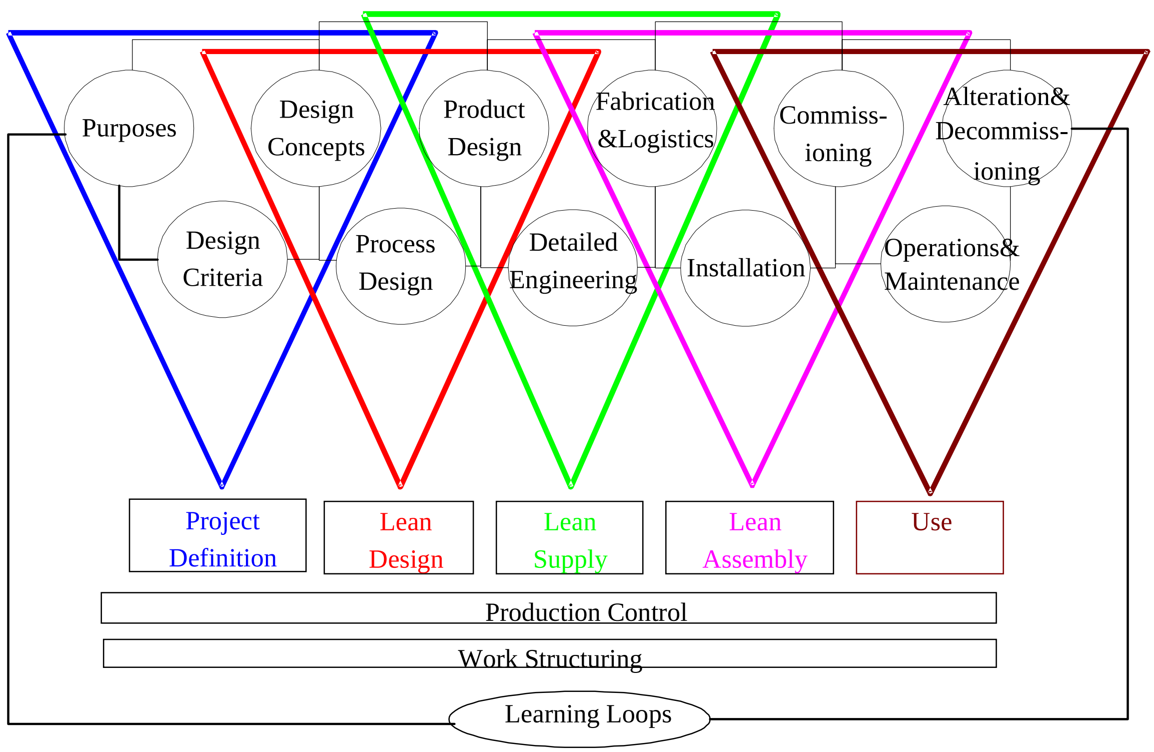


Figure 1: Lean Project Delivery System (Ballard 2000)

For some this may still sound manageable but when hundreds or thousands of similar decision patterns are added to the construction project, it is easy to understand the level of complexity stakeholders in a project have to face. In addition to this, construction projects also have become technically more complex during the last decades. There is more technology embedded in buildings, e.g., automation, lighting, security, cooling, heating, and information and communication technologies. Accordingly, there are more specialists involved in construction projects, e.g., application engineers, lighting, audiovisual, security, telecommunication, and environmental specialists. In summary, construction projects include all but simple and sequential transactions between independent processes; rather, they include complex and interacting processes requiring a significant amount of specialty knowledge, which tends to be spread among a large number of stakeholders. If the interactions between the various processes, such as product design, detailed engineering, fabrication, and installation, are not understood, it is hard to see how a construction project can be properly delivered or significantly improved.

1.1.3 Motivation for exploring construction delivery processes

Laufer and Tucker (1987) argued that uncertainty and complexity cannot be eliminated from construction projects and that there is an increasing demand of speed. Hence, construction projects and their underlying processes have to be designed to cope with uncertainty, complexity, and speed (Laufer 1997). Lean construction recognizes that most of today’s construction projects are too complex and dynamic to be managed as simple and sequential chains of activities. It proposes a new theory-based approach to construction projects that integrates both the product and process designs, where particular attention is paid to the interaction of the project phases and processes (Figure 1). The insights of lean construction and its underlying Transformation-Flow-Value (TFV) theory have opened new opportunities to analyze and to improve construction projects.

Lean construction is inspired by lean manufacturing (Toyota Production System), which fundamentally changed the traditional way of designing automobiles, supplying material for their production, and fabricating them. From automobiles the lean approach has expanded into other product types. Lean manufacturing has helped Toyota to deliver automobiles faster, at less cost, and better value to customers than its rivals. Similar advantages would certainly support the interests of customers in the construction industry. I elaborate on lean theory and concepts in chapter 2.

A central concept in lean construction is that downstream players are involved in upstream decisions. This includes contractors as well as suppliers. Studies have shown that managing material supply in construction projects is of major importance because, in general, around half of the project cost comes from material and equipment (Tanhuanpää et al. 1999), and most project delays are due to the lack of material (CII 1988 p. 1). Processing that adds value to materials and information amounts to only a small percent of total time (Jarnbring 1994, Arbulu and Tommelein 2002, Arbulu 2002). Most of the non-value-added tasks, (e.g., waiting), and problems, (e.g., poor information flow), are overlooked

(Vrijhoef and Koskela 1999). This is because often no single stakeholder is in the position to deal with the issues alone. In addition, material supply has traditionally been perceived from a solely transformation view rather than a simultaneous consideration of transformation, flow, and value views.

During the last decades the domain of material supply has dramatically expanded from materials management, in-house integration of functional views, such as procurement, operations management, and logistics, to Supply Chain Management (SCM), integration of interrelated processes between companies to better satisfy end-customer needs. A recent Construction Industry Institute study (Tommelein et al. 2003) calls SCM "the leading process improvement, cost saving, and revenue-enhancing business strategy practiced in today's business world". I elaborate on the TFV theory and SCM in chapter 2.

The emerging new theory in construction and the new business strategy for product delivery motivated me to explore the actual opportunities to improve construction supply chains.

1.2 RESEARCH HYPOTHESIS AND QUESTIONS

1.2.1 Working hypothesis

Understanding the current state of the construction industry and the emerging opportunities to improve construction delivery processes, I establish the following hypothesis for this dissertation:

"A significant opportunity exists to improve the delivery process of Engineered-to-Order (ETO) products with the application of the TFV theory and the help of shared knowledge among the process stakeholders".

The delivery process of ETO products includes the following phases: the engineering, detailing, procurement, fabrication, and shipping of the equipment. For simplicity in the rest of this dissertation I use design to encompass both engineering and detailing, and manufacturing to encompass both fabrication (shaping materials) and assembly (joining materials). With respect to the LPDS (Figure 1) I refer to product design and detailed engineering when I use the term design. Procurement is not shown in the LPDS because its place in any one of different phases depending, e.g., on product type and procurement method. Generally, procurement takes place in the Lean Supply triad.

1.2.2 Research questions

Based on my hypothesis I developed the following general research question:

"How can the performance of the supply chain of ETO products be improved?"

This question can be broken down into three sub-questions:

(1) What are the design, procurement, and manufacturing processes for an ETO product? This question aims to broaden our understanding of the delivery process of ETO products by investigating the specific phases of the delivery process in detail. What kinds of tasks does the process consist of, who performs them, and what are the task interdependencies? Which performance measures would focus attention on enhancing the design, control, and improvement of the delivery process? Are the tasks and their dependencies similar in different projects that involve like ETO products?

(2) What problems exist and why do they exist in the delivery process of an ETO product? The question aims to address the range and complexity of the problems in the delivery process. The primary focus is on lead time reduction. Some problems are rooted within one organization whereas others stretch over several. Who is in what role to address these problems? How should procurement be conducted in order to shorten lead times? How does design practice impact on the delivery lead time and robustness against changes? What opportunities do manufacturers have to reduce the lead times in the delivery process? What factors contribute to the manufacturing lead time and cycle time ratio? What kind of information is needed to reduce lead times?

(3) What changes in lead time reduction would yield what type of benefits and at what cost? The question focuses on the opportunities and limitations of reducing delivery lead times. If improvement opportunities were identified, what kind of improvements would they bring? What kind of obstacles may one encounter in the implementation of improvements?

1.3 RESEARCH SCOPE AND FOCUS

This study is approached as an engineering and social science problem. I decided to focus on ETO products, because they often have both a significant cost impact on construction projects and long delivery lead times. The distinction between ETO products and other types of products, such as Make-to-Order (MTO), Assemble-to-Order, (ATO) and Make-to-Stock (MTS) is the different intersection of customer orders with the entire production process or the Customer Order Decoupling Point (CODP) (Wortmann et al. 1997 p. 61). I elaborate on ETO products and other types of products in chapter 2.

Some examples of ETO products are prefabricated concrete elements, HVAC equipment, steel structures, elevators, turbines, nuclear reactors, semi-conductor tools, and power distribution equipment. After consulting with industry practitioners and reviewing existing work that had been conducted on various ETO products, I chose the delivery process of power distribution equipment (PDE) and the reduction of its lead time as the unit of analysis. PDE is the general name of equipment that is used to distribute and control electrical power in buildings. It is a critical procurement item, since the ability to deliver it on time and within a predetermined cost may determine whether or not an electrical contractor gets awarded a contract. As an ETO product it is particularly prone to changes because the electrical trade, workers who install the equipment, is one of the last trades on the site. As a result, problems from predecessor trades tend to accumulate on top of electrical trade's inherent perplexity, which leads to unreliable product and process plans.

This research focuses on three different types of PDE (1) low voltage switchboards, (2) panelboards, and (3) motor control centers. The research focuses on process structure and design. Organizational structure and design are beyond its scope, albeit that the need to re-design the organizational structure is recognized.

1.4 RESEARCH METHODOLOGY

This study is based on an inductive research method that relies on the interpretive research approach and a case study-experiment enquiry strategy. The study is inductive because I reasoned from individual cases to general conclusions. The study is interpretive because the data collection and analysis were not rigidly separated but rather interwoven and repeated several times as the research progressed, contrary to the positivists' approach. Because of the nature of this research, contemporary events–no control over behavior of the research environment (here: within the industry)–and form of research question (how), a case based research strategy was employed. Case studies are preferred when investigating a structure of a given industry (Campbell and Stanley 1963, Robson 2002, Yin 2003). Experiments were also applied on a small scale through simulation to complement the case findings.

I started the empirical study by conducting a pilot study on a switchboard delivery process. Then, I pursued three in-depth case studies on the delivery process of PDE, two in the United States and one in Finland. The case studies were conducted independently of each other and with close industry cooperation. First, I mapped the current state of the delivery processes of PDE, and calculated several performance measures with respect to the delivery process. I applied simulation to better understand procurement behavior and the potential causes for underestimating procurement lead times. Then, in cooperation with industry partners, I developed future state maps for the delivery processes. The TFV theory and lean principles were applied to map and to investigate the opportunities and restrictions of compressing the delivery process in time. Subsequently, the empirical findings were compared to findings in the literature. I describe the research methodology in chapter 3.

1.5 CONTENTS

The dissertation consists of five main parts: (1) a literature review, (2) a presentation of the research methodology, (3) case studies, (4) a simulation experiment, and (5) a discussion of the findings. Chapter 2, the literature review, explains key terms, and highlights earlier research work. It covers areas in the TFV theory and lean principles, SCM, and lead time reduction. I present SCM from the point of view of procurement, ETO products, and industrial organizations. Then, chapter 3 describes the research methodology.

Chapter 4 describes and analyzes three cases. I present the results and analysis of the cases with help of process maps, descriptions, performance measures, figures, and examples. I conclude the case studies with a cross-case comparison. Chapter 5, simulation experiment, demonstrates how procurement lead time rapidly increases even when only minor changes are introduced. This further supports the case findings.

Finally, chapter 6 presents conclusions, including a summary of research findings, contributions to knowledge, and future research questions.

2 LITERATURE REVIEW

This chapter defines key terms and provides insight into earlier work in the TFV theory, SCM, and lead time reduction to better understand the underlying theories, practical methods, and main opportunities and challenges related to improving the delivery process of ETO products.

2.1 TRANSFORMATION-FLOW-VALUE THEORY

Koskela et al. (2002) define the TFV theory as a theory-based methodology for construction that strives to enhance understanding and practice in the industry. However, the scope of the TFV-theory is not limited to the construction industry: it embraces the domain of project-based production management, which concerns with the delivery of "one-off" products.

2.1.1 Background

Two main motives sparked the emergence of the TFV theory, also called lean construction[1]. First, the construction industry had long been criticized for lacking a production theory, which by several scholars (e.g., Laufer and Tucker 1987, Koskela 1992) have been considered as the reason for poor performance of the industry. Second, the extraordinary achievements in "lean manufacturing"

---

[1] A number of scholars are conducting research and practicing within the "lean construction" framework; accordingly, there are slightly different interpretations of the term and its scope. In this dissertation, I use TFV instead of lean construction to explicitly cite the body of work developed by the International Group for Lean Construction (IGLC), http://cic.vtt.fi/lean/.

inspired scholars in the construction industry to rethink lean production methods and tools to project-based production, such as construction.

Lean manufacturing became widely known in the early 1990s after Womack et al. (1990) conducted a comprehensive study in the automobile industry. However, the concepts and techniques used in lean manufacturing can be partly traced back to the beginning of the 20th century. In fact, as early as 1913 Henry Ford invented a key concept, the flow of production, that later became a driving principle of lean manufacturing.

Toyota can be considered as the founder of “lean manufacturing” as we know it today. Two men, Shigeo Shingo and Taiichi Ohno created the so-called Toyota Production System (TPS) after WWII, which later became known as lean manufacturing in the Western World. They re-invented the way to produce automobiles and it sparked numerous process innovations throughout the next decades, which were intended not only to enhance manufacturing but also the design of automobiles (or product development) and the supply of materials. Ohno and Shingo each published several books on the TPS and on its fundamental concepts and techniques (e.g., Ohno 1988a, 1988b, Shingo 1988, 1992). Arguably, however, they did not fully reveal its theoretical foundations and implications; which is understandable given the fact that the TPS was a business-driven innovation. Also, the facts that Ohno and Shingo were not necessary theorists and the translation from Japanese, may explain why there was more focus on concepts and techniques rather than theoretical foundation.

The underlying theory of lean manufacturing was not explicitly explained until Koskela (2000) studied production theories in-depth. He identified at least three different conceptualizations of production that have been used, namely; transformation, flow, and value. Further, he argued that all three conceptualizations are necessary and should be used simultaneously. These concepts are at the core of TPS and they form the theoretical foundation of the TFV theory.

2.1.2 TFV concepts

According to the TFV theory, the design, control, and improvement of production should be conducted as an integration of transformation, flow, and value concepts and not as alternative concepts (Koskela 2000 p. 239).

The concept of transformation is based on the idea that production is conversion of inputs to outputs and the goal is to make the transformation as efficient as possible. Although this concept has dominated the construction industry, it has severe shortcomings. It does not aim to reduce wasted resources and does not focus explicitly on customer requirements (Koskela 1999).

The flow concept recognizes that production consists of inspection, waiting, transportation as well as transformation (Gilbreth and Gilbreth 1922, Koskela 1999). The first three factors are non-value-added; hence, they should be eliminated. Ohno (1988a) and Shingo (1988), who termed non-value-added tasks "waste", developed the flow view at Toyota. They identified seven main sources of waste, namely, (1) overproduction of goods, (2) inventories of goods awaiting further processing or consumption, (3) unnecessary production, (4) unnecessary movement of people, (5) unnecessary transport of goods, (6) waiting by employees for process equipment to finish its work or for an upstream activity to complete, and (7) defective products (Ohno 1988a, Shingo 1988). Later, as Womack and Jones (1996) described lean manufacturing concepts that added an eighth source of waste, that is, (8) production of goods and services that fail to meet user's needs.

Ohno (1988a p. 20) and Shingo (1988 p. 391) observed that by merely eliminating waste from the production system, significant productivity improvements were achieved. Womack et al. (1990) found that Toyota used less space, less material, less human effort and also less time and money, to assemble a better car than its Japanese, American, and European rivals. Santos (1999) conducted an empirical study about various production flow methods such as "reduction of cycle time", "reduction of variability", "increase of transparency", and "pursuing continuous improvement" in the construction industry. He found that the employment of the flow methods correlated positively with the performance of the companies. However, he observed a low level of systematic integration of practices.

The goal of the value concept is to generate best possible value to the customer, based on his requirements (Koskela 2000 p. 74). The quality movement (see, e.g., Deming 1986, Juran 1974) developed a significant body of work around the value concept and emphasized that the most important objective in any enterprise is to satisfy customer needs. However, value is not the same as quality. Quality is an assessment of how well customer needs are met, whereas value can be understood to also include the sacrifice to meet the needs (Thomson et al. 2003).

Although value inherently has nothing to do with cost, cost is relevant to choice because our resources are finite. Hence we tend to prefer one value to another if it costs less. And we may choose one purpose over another based on their relative costs (Ballard 2003). Value can be perceived from an “objective” and “subjective” view (Thomson et al. 2003), and based on the view a number of definitions have been introduced (e.g., Miles 1961, British Standards Institution 1997). The UK-based Institute of Value Management (IVM) (2003) defines value as the ratio of satisfaction of needs and use of resources, where “needs” refers to what is necessary for a desired user and “resources” refers to “everything that is required to satisfy needs”. Based on this definition value can be improved by increasing the satisfaction of need even if the resources used in doing so increase, provided that the satisfaction of need increases more than use of resources.

In order to quantify value, the needs and resources have to be measured. Based on this, various quantification methodologies have been developed, e.g., the Society of American Value Engineers (1998) has developed a standard to quantifying value based on needs and resource functions. This standard includes a pre-study, a value study, and a post study. In the pre-study, the main objective is to collect data about needs and evaluation factors. In the value study, the main objective is to develop “value functions”, assign costs or other measurement criteria for the functions, and to compare them. In the post study, the objective is to make sure that recommendations from the value study are implemented. For a comprehensive description of the Value Methodology Standard see http://www.value-eng.org/about_vmstandard.php#1.

The TFV theory and its concepts, transformation, flow, and value, are summarized in Table 1.

Table 1: Summary of TFV theory (Koskela et al. 2002)

	Transformation concept	**Flow concept**	**Value concept**
Conceptualization of production	As a transformation of inputs to outputs	As a flow of material composed of transformation, inspection, moving, and waiting	As a process where value for customer is created through fulfillment of his requirements
Main principle	Getting production realized efficiently	Elimination of non-value-added activities	Elimination of value loss
Methods and practices	Work-breakdown structure, MRP, organizational responsibility chart	Continues flow, pull, production control, continues improvement	Methods for requirement capture, quality function deployment
Practical contribution	Taking care of what has to be done	Making sure that unnecessary things are done as little as possible	Taking care that customer requirements are met in best possible manner

2.1.3 Tools and techniques

The objectives of the TFV production theory are to minimize waste, to maximize value, and to deliver the project (Ballard et al. 2002). Several authors have proposed a list of lean techniques and practical methods to achieve these goals, e.g., Ballard et al. 2002; however, as the theory evolves and is tested these lists are continuously updated. Therefore, I present in Table 2 only those techniques and practical methods that are of particular interest with respect to lead time reduction of ETO products.

Table 2: Summary of TFV techniques applied in this research

Technique	Description
Make material and information flow	The flow concept pays special attention to how the work moves from one worker to another or from one operation to the next (Gilbreth and Gilbreth 1922, Ford 1926, Ohno 1988a, Shingo 1988, Womack et al. 1990, Tommelein and Ballard 1997), which was highly ignored in the traditional transformation view of production. Therefore, both stagnation and starvation of resources must be minimized.
Pull material and information	The pull principle means that 'no one upstream should produce a good or a service until the customer downstream asks for it. Pull is based on the system status (Womack and Jones 1996). In Kanban, an example of a pull system, parts are replenished when parts are withdrawn from so called "supermarkets". The opposite production technique is called push where the release of the work is scheduled. The advantage of a pull system over a push system is that the pull system controls overproduction (Shingo 1988), and it also shortens cycle times (Hopp and Spearman 2000).
Reduce variability	Variability impacts a production system in various ways, e.g., increases inventories and cycle times, and wastes capacity; consequently, almost all kinds of improvement efforts involve at least some reduction of variability (Hopp and Spearman 1996 p. 331). Managing variability must be the "intrinsic goal" (Koskela 2000) and is the first improvement action in the TFV theory.
Reduce lead times	Lead time can be reduced by reducing non-value-added activities, waste, or by improving the processing of value added activities. Most of the lead time consists of non-value-added activities (Hopp and Spearman 2000); hence significant potential for reducing lead times exists by reducing non-value-added times.
Challenge employees	Lean encourages employees to solve problems and suggest improvements to the production system. Ohno (1988a) and Shingo (1988) repeatedly emphasized the importance of employees in improving production systems. Among other things, this requires an organizational structure that is transparent and open for information exchanges.
Reduce defective products and poor information	These mean that production should be set-up so that defects cannot occur; and production should be shielded from uncertainty and not allow to start before reliable input information is available. Ballard and Howell (1994, 1998a), and Howell et al. (1993) have argued that the prime concerns of production improvements in the construction projects are the poor reliability of planning and the improper control tools

Along with the techniques, whole project delivery system, such as the Lean Project Delivery System (Ballard 2000b), and particular tools, such as Last Planner (Ballard 2000c), have evolved hand-in-hand with the TFV theory.

Next I describe the following practical methods derived from lean manufacturing: set-based design, synchronization, Single Minute Exchange of Die, Five Whys, One-Piece-Flow, and Standard Worksheets. Their adaptation and application to product delivery processes are essential for realizing performance improvements, and are central to this research.

2.1.3.1 Set based design

Set-based design means that design is performed while keeping track of sets of alternatives, which are gradually narrowed to one solution as the design evolves (e.g., Ward et al. 1995). This is a product development method that gave a serious advantage to Toyota over other automobile manufacturers. Each party in the design process submits its range of values and the intersection of these values define the solution space. The traditional design process follows the point-based solution, where one alternative is chosen for further development and the other alternatives are disregarded. If the initial choice proves to be wrong rework is needed, and, in the extreme, the process starts over.

The advantage of set-based design is that it enables reliable and efficient communication, which allows the earlier communication to remain valid while complementing further information, and reduces the incentive to delay work because the information might change. Further, set-based design bases the critical early decisions on data rather than assumptions. Also, set-based design promotes institutional learning, since the design process is documented and used in other sets of alternatives. Finally, set-based design searches for global optimum, since the best solution of all the alternatives is chosen, rather than the best solution of one alternative, which would lead to local optimum (Ward et al. 1995, Sobek 1996). For example, in case of sizing technical rooms in a building, local optimum would be the ideal measures of the rooms from the individual perspectives of the architect, structural, mechanical, and electrical engineer. A global optimum could be determined by request from the minimum and maximum measures of the room. Then, gradually, at last responsible moments reduce the solution space as the project evolves. Last responsible moment is the latest moment to which information and action can be postponement without delaying the process (see, e.g., Ballard et al. 2002).

2.1.3.2 Synchronization and takt-time

Several authors (Hopp and Spearman 1996, Shingo 1988, Toikkanen 1995, Harris and Ioannou 1998, Tommelein 1998, Tommelein et al. 1999, Rother and Harris 2001) have demonstrated how **synchronization** of tasks or workstations can dramatically reduce lead times. According to Shingo (1988) synchronization requires leveling the excess capacity and coordinating starting and ending times. Further he argued that synchronization is the only way to eliminate process delays, which are delays of an entire batch between processes. Synchronization is achieved by having all the tasks or operations involved in a process follow the same takt time. **Takt time** sets the pace of operations to match the rate of customer demand. Synchronization also reduces inventory and increases resource utilization and throughput (Hopp and Spearman 2000). **Inventory** can be in the form of raw material, work-in-process (WIP), finished goods, or spare parts. The function of inventory varies depending on the type of inventory and it includes: providing input for processing, providing customer responsiveness, allowing production in batches, and buffering variability. A **batch** is one or more units of material or information. Transfer and process batches are differentiated.

A transfer batch refers to the number of units that are accumulated before being moved to the next workstation. A process batch refers to the number of units that are processed simultaneously or the number of units that are processed before the workstation is changed over to another setting (Hopp and Spearman 2000). In the construction industry, few scholars, e.g., Tommelein (1998), Arbulu and Tommelein (2002), Alves and Tommelein (2003), have discussed the relevance of batching strategies. They all found that batching have a major impact on lead times. However, batching and buffering rules are often poorly understood among industry practitioners.

2.1.3.3 One-Piece-Flow

One-Piece Flow means that the batch size equals one. One-Piece-Flow is used to avoid process delays and to reduce cycle times (Ohno 1988a, Shingo 1988, Womack et al. 1990). Numerous studies have shown the dramatic impact one-piece-flow can have on cycle time and throughput. Probably one of the most prominent is Little's (1961) "Proof of the Queuing Formula", where he demonstrated the relation of throughput, cycle time, and WIP. **Throughput** is the output rate of a production system. Little demonstrated that as WIP increases also cycle time increases provided throughput remains constant.

2.1.3.4 Single Minute Exchange of Die

Single Minute Exchange of Die (SMED) is a set of methods to dramatically reduce set-up times (Ohno 1988a, Shingo 1988) and thereby impact the whole production system. In his book 'Non-Stock Production,' Shingo (1988) states that without the SMED method Toyota would not have been able to employ the production system we know today as the TPS, nor would concepts such as Non-Stock Production (NSP) or Just-in-Time (JIT) have been developed.

2.1.3.5 Five Why's

Five Why's is a technique used to analyze the root causes of problems. Often the immediate predecessor is not the real cause for the problem. Therefore, the solution to the problem should be sought from a larger set. The Five Whys asks at least five times why "the problem occurred" and after each why an explanation is provided which is questioned in the next round of asking "Why" (Tsao and Tommelein 2002). The goal is to eliminate the original cause of the problem (Ohno 1988a).

2.1.3.6 Standard worksheet

Standard worksheet contains the cycle time, work sequence, and standard inventory for a single workstation. The goal is to create a standardized work procedure that helps operations to stay in the planned takt-time, and also increases production efficiency by preventing the recurrence of defective products, operational mistakes, and accidents, and by incorporating workers' ideas (Ohno 1988a).

The engaging and inevitable expansion of the TFV theory and its underlying techniques and practical methods seem to be their implementation beyond the "factory" environment to include larger systems, such as supply chains, and to improve systems as a whole.

2.2 SUPPLY CHAIN MANAGEMENT

Though supply chain management (SCM) is regarded as a new management discipline, many of the concepts are based on well-known management concepts[2] (Ganeshan et al. 1999). However, it was the rapid development of information technology (IT) during the 1990s[3], which revolutionized the information exchange between companies (Gunasekaran and Nath 1997), and thus have made these concepts feasible on a larger scale. The emergence of the Internet and e-Commerce have given SCM a new meaning, since the problem with managing supply chains used to be the lack of timely and appropriate information. Today this constraint is diminishing due to the World Wide Web and wireless communication capabilities. Information does not need to traverse the traditional sequential path; rather, information can be made available for all parties simultaneously (Figure 2).

---

[2] These concepts include those from marketing (e.g., postponement), economics/ organizational theory (e.g., Outsourcing, Bullwhip Effect), operations research (e.g., multi-echelon inventory models, plant and distribution center location models), operations management (e.g., hierarchical production planning, Quick Response, Vendor Managed Inventory, JIT), and logistics (e.g., integrated logistics).

[3]Information technology was used already during 1960s to exchange information between organizations, but in much smaller scale than today, in only few industries, and it was relatively expensive (e.g., Durham, M.J. (1995)).

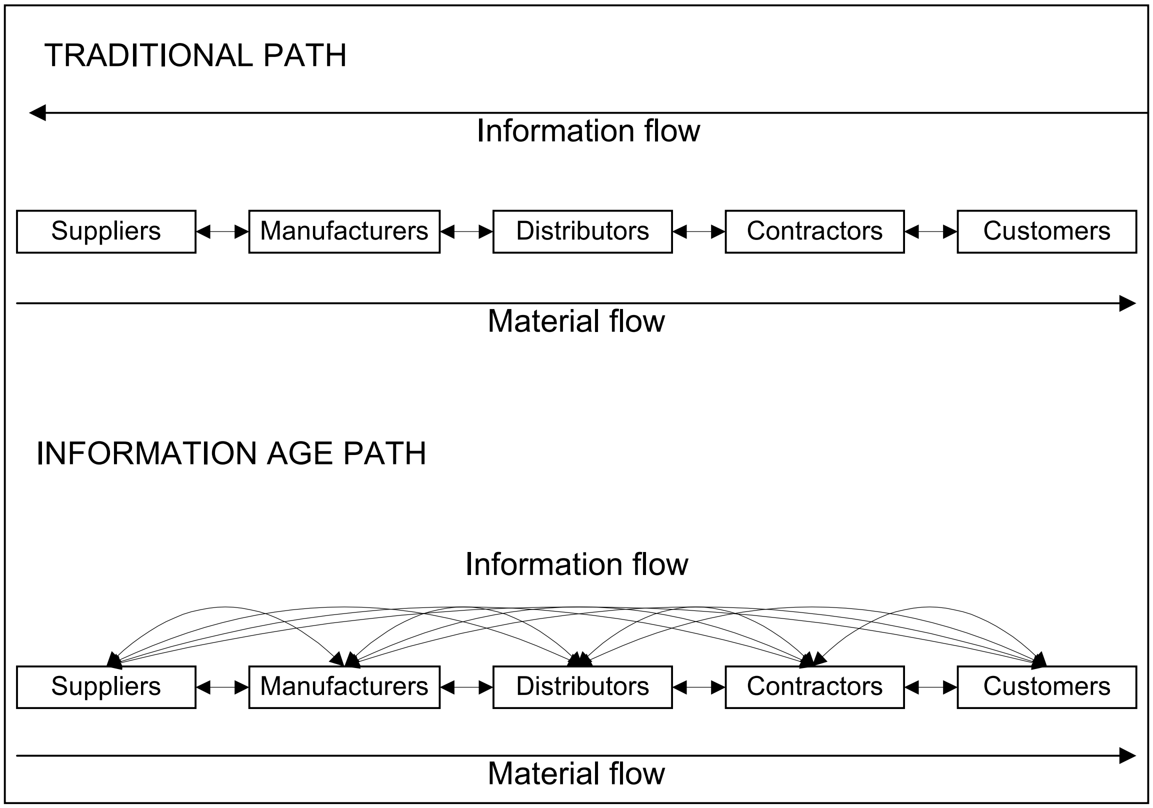


Figure 2: Traditional versus modern IT-enabled information flow

The cross-organizational integration of functional units with the help of advanced IT has also opened diverse research opportunities. Various studies have been conducted ranging from SCM frameworks (i.e., Chopra 2004, Grover and Malhotra 2003, Johnson and Whang 2002, Lambert and Cooper 2000, Riggs and Robbins 1998, Stadler and Kilger 2000, Ballou 1999, Lamming 1993), to SCM algorithms and simulation models (i.e., Vaidyanathan 2003, Hong-Minh 2002, Chen et al. 1988, Towill 1996). In the construction industry, the opportunities in SCM have been recognized (O'Brien and Fisher 1993, Egan 1998, Tommelein et al. 2003) but the industry has been short of basic research to realize the opportunities (London and Kenley 2001, Vrijhoef et al. 2003).

2.2.1 Background and definition of SCM

In the 1980s, it was still common to view SCM as logistics outside the firm involving customers and suppliers (Oliver and Webber 1982). Some considered the terms logistics, channel management, physical distribution, and material management as predecessors of SCM (Ballou et al. 2000). However, several authors criticized these concepts for being too restricted saying that local optimization could impact negatively the system as a whole and cause sub-optimal utilization of resources. Houlihan (1985) argued that the concept of materials management is obsolete because it considers the various functional units, such as purchasing, manufacturing, distribution, and sales, in isolation. He suggested a systems view or integration of the functional units and called it supply chain management.

Stevens (1989) and LaLonde (1998) conceived that the objective of SCM is to synchronize the requirements of the customer with the flow of materials from the suppliers. Lambert and Cooper (2000) proposed eight main processes for SCM, namely: (1) customer relationships management, (2) customer service management, (3) demand management, (4) order fulfillment, (5) manufacturing flow management, (6) procurement, (7) product development and commercialization, and (8) returns management.

In construction industry, SCM concepts have been less developed than in manufacturing although various proposals for a theoretical foundation have been recently presented (e.g., Vrijhoef and Koskela 2000, London and Kenley 2001, Daganzo 2003, Vrijhoef et al. 2003, Tommelein et al. 2003). Vrijhoef and Koskela

(2000) pointed out the importance of SCM focus in construction and found four distinctive roles of SCM[4]: (1) to focus on the interface between the supply chain and the construction site, (2) to focus on the supply chain itself, (3) to focus on transferring activities from the construction site to the supply chain, and (4) to focus on the integrated management of the supply chain and the construction site.

Tommelein et al. (2003) argued that there is not one single view to describe construction SCM. They present nine different views of construction SCM ranging from operations to market structures. In this dissertation, SCM is broadly defined as:

"Supply chain management is the management of all the processes that are required to deliver a service or a product for a customer through a network of organizations with minimum waste and maximum value".

In relation to the LPDS presented in chapter 1 (Figure 1) SCM can be seen as the vertical dimension of the Lean Supply triad, where each vertical triad refers to the delivery (supply chain) of a specific product. The goal of construction SCM is to manage each of the vertical triads so that a project can be efficiently delivered regardless of design criteria. The relations and interactions among the core processes; product design, detailed engineering, and fabrication and logistics,

---

[4] In fact, they include even a fifth potential focus on construction supply chains, which is to manage the construction supply chain by a facility or real estate owners.

are strongly shaped by the procurement method, product type, and industrial organization.

2.2.2 Procurement methods

In construction, procurement is a broadly used term and it is closely related to purchasing, materials management and SCM. Procurement is a process that defines what, when and how much to purchase and ensures that what is required is received timely according to the specifications (Burt 1984). Purchasing is the most important function of procurement; it is “the act of procuring materials, supplies, and services” (Stuckhart 1995 p. 102). Materials management encompasses the planning, execution, and controlling of procurement on a construction project (Stuckhart 1995 p. 295), whereas SCM simultaneously considers multiple projects and multiple organizations (Tommelein et al. 2003). The relations of procurement to purchasing, materials management and SCM are illustrated in Figure 3.

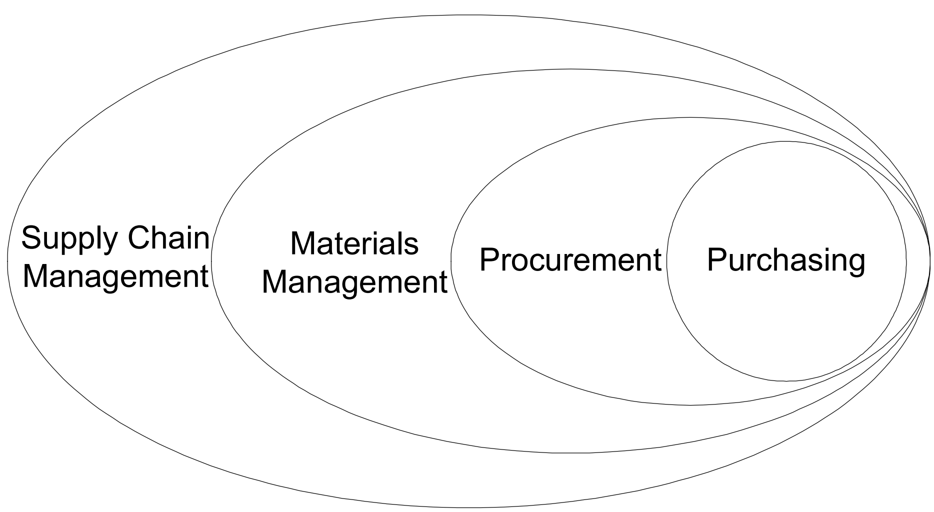


Figure 3: Procurement in relation to purchasing, materials management, and SCM

Although procurement is one of the core processes in a construction project it is not illustrated in the LPDS (Figure 1) because depending on the type of product that is procured procurement can take place before or after the product design and detailed engineering. This is soundly described in CII's (1998) RS-130 report with help of the PEpC (Procurement, Engineering, procurement, Construction) model. The big "P" stands for procurement of complex engineered equipment and systems essential for project performance. This type of procurement should take place prior to engineering so that suppliers who often have unique knowledge beyond owners and contractors about their products can influence and help to define the specifications of the product. The small "p" stands for non-strategic products, which are procured after the detailed engineering.

In construction, besides purchase of building components, systems, and services, procurement may also refer to the project delivery method. The most common project delivery method is Design-Bid-Build (DBB) (Ibbs et al. 2003), where the design and construction phases are separated and design is completed prior to construction (Hinze 2001 p. 14-5). However, in recent years the Design-Build (DB) delivery method, where the contractor has the design responsibility as well as the construction responsibility, and design and construction overlap, has increased in popularity (Songer and Molenaar 1996, ENR 2003a). The main advantage and disadvantages between DBB and DB are summarized in Table 3.

Table 3: Main advantages and disadvantages between DBB and DB (Hinze 2001 pp. 14-23)

Project delivery	**Advantages**	**Disadvantages**
DBB	- Owner has an idea of total project cost prior to construction. - Clearly defined roles of each of the contracting parties. - Owner minimizes the contractual liability for cost overruns and late project delivery	- Often extends project duration. - The nature of contract creates inherent adversarial relationship between parties. - The inflexibility of the DBB approach exposes the owner for greater probability of claims
DB	- Should have a higher constructability due to construction firm's involvement in design. - Allows overlapping of design and construction, which may reduce project duration. - Fewer changes because design evolves with construction. - Owner is less likely being embroiled in disputes between engineering and construction firm.	-Fewer checks and balances built into the process. - Owner has less control - Public works have laws and regulations that may place serious restrictions on DB. - Construction firm may cut corners in design quality.

"Lean" advocates favor integrated product and process design, which can be facilitated in DB but not in DBB (Ballard et al. 2002 p. 237). In DBB, contractors can only marginally impact on design, which may lead to poor constructability and expensive production methods. Accordingly, whether one refers to procurement of projects or its components procurement methods may have significant impact on both design and production. Some of the dependencies between procurement, and design and production are not always explicitly presented in the literature, e.g., choosing contract types and handling change orders. Although these may have important implication to design and production as discussed next.

2.2.2.1 CONTRACTS

Macneil (1974, pp. 712-3) defines a contract as "a promise of future exchange". He also distinguishes between two main types of contracts, namely, transactional and relational contracts, where both involve economic transactions but contractual relations also involve "whole person relations" and significant "non-economic personal satisfaction" (Macneil 1974, pp. 720-5). The transactional contract is short and limited, and past or future relations between the parties are not considered, whereas the relational contract does not have the same degree of measured transaction and the relation between the parties ranges from past to future (ibid.).

In construction projects, the most common methods are fixed-price, cost-reimbursed, and guaranteed maximum price contracts. Several factors, such as identity and relationship of owner and contractor, completeness of design and its complexity, and the type of work being done, may impact on the type of pricing methods that is applied in procurement. (Fisk 2003, pp. 424-6). In fixed-priced the buyer offers a fixed price for the contractor, whereas in cost-plus the buyer reimburses the direct costs of the contractor and pays a fee for his services.

Examples of fixed price contracts are lump sum, and unit price contracts. In lump sum contracts the contractor agrees to a specified construction for a fixed price. In lump sum contracts, bids are requested based on complete plans and specifications, which allow easy comparison of bid prices. Unit price sets the price for each unit of work constructed and is used when quantities are difficult to calculate in advance.

In cost-reimbursed contracts contractor is paid its actual cost of construction plus a specific mark-up for overhead and profit. The mark-up can be a percentage of total cost, a fixed fee or a cost plus incentive fee. In latter the contractor is paid a fixed fee if he meets time and quality criteria and if he exceeds the criteria he is paid an additional fee.

In guaranteed maximum price the contractor agrees that the project will not cost over a set price. Contractor is paid based on cost reimbursed contract but only until a set price. Sometimes if the project cost less than the guaranteed maximum price the owner and contractor share the savings (Fisk 2003 pp. 424-6).

The fixed price contract is normally awarded through competitive bidding and the cost-reimburse contract through negotiations (Bajari and Tadelis 2000). According to Bajari and Tadelis (2000) the fixed-price provides the greatest incentive for cost reduction whereas cost-reimburse is far smoother if the original contract needs to be changed. In cost-reimburse contracts the cost reduction incentive disappears because it is difficult to establish fair cost targets (Ashley and Workman 1986).

The disadvantage of fixed-price contracts is when the original contract must be adjusted. This leads to a tedious reimbursement process that is handled with the help of change orders and change order directives[5].

---

[5] For further comparison of fixed-price and cost-reimburse contracting see e.g., Ibbs et al. (1986).

2.2.2.2 COST OF CHANGE ORDERS

A change order is a formal document that alters some conditions of the contract documents agreement. It may alter the contract price, schedule of payment, completion date, or plans and specifications (Fisk 2003 p. 503). In construction projects changes are the rule rather than the exception (Hester et al. 1991, Nunnally 2002 p. 499). The main causes of change orders are unforeseen field conditions; correction of design discrepancies, errors, or omission in contract documents; owner requested changes in scope; change in building code interpretation; and changes in availability of materials and products (R.S. Mean 2001 p. 575).

The cost of changes in work may be higher than the immediate change[6] (Fisk 2003 p. 502), because changes often require significant administrative effort, they may lead to scheduling problems, and even legal disputes between contract participants (Bajari and Tadelis 2000). In addition, the cost of change orders is difficult to measure. Studies have reported that change orders average between 5% and 8% of contract value (Zeitoun and Oberlander 1993, Cox et al. 1999). However, these numbers do not reveal the whole truth, because they only consider the direct costs associated with the change and not e.g., effects on project schedule and other activities. Some scholars have argued that the direct cost is only a minor part of the total cost (Burati et al. 1992, Love 2002). Hanna et al. (1999) studied how change orders impact electrical and mechanical

[6] The immediate change refers to direct labor, material, and equipment cost. These may be challenging to estimate, particularly changes in labor productivity (RS Means 2001 pp. 576-578)

contractors. They found that contractors are not making more money as the amount of change order hours increase. Love (2002) reported that re-documentation caused by changes may have a significant impact on design fees but it has become a common practice that designers do not get reimbursed for the service. The indirect cost of change orders to various supply chain members has been little documented, one reason may be that part of the cost is absorbed by the members of the supply chains as “cost of doing business”. Thus, the cost is not necessary questioned. In conclusion, the cost of change orders seems to be considerable and most of them are hard to trace; therefore, concentrating only on the changes in contract value may significantly underestimate the actual cost of changes.

2.2.3 Industrial organizations

According to Coase (1972 p. 60) the organization of industry “describes the way in which the activities undertaken within the economic system are divided up between firms”.

2.2.3.1 THEORY

Two dominating schools of thought have emerged to explain the structure and behavior of industrial organizations[7]. One is the so called “economics of organizations”, the second is the “knowledge-based view”. Economics of organization is grounded on Coase’s (1937 p. 390) argument that there is on top

---

[7] Some may argue that there are three competing schools of thought, because Foss (1999) proposes an integration of this two rival theories naming it “intergrationism”.

of the production cost an administrative cost, “the transaction cost”, of coordinating resources within and between firms. Consequently, this determines how firms are organized in an industry. When the transaction cost is low, the firm acquires the product from the market using the pricing system (Stigler 1946) and when the transaction cost is high the firm integrates vertically and produces the product internally. This is a significant simplification of the real world. Hence, Williamson expanded Coase’s “transaction cost economy” (TCE) to include the concepts of “opportunism”, “bounded rationality”[8] (1975), “asset specificity”, “uncertainty”, and “frequency” (1985). These concepts have frequently been used to analyze industry structures and firm boundaries (Hobbs 1996, Brockmann 2001, Grover and Malhotra 2003).

However, scholars (e.g., Richardson 1996) have also been critical of Williamson’s transaction cost economy and identified numerous instances where the theory is not conforming, particularly because both Coase and Williamson assume that the production cost for the same type of products are the same for all firms[9].

The other major school, the knowledge-based view, argues that firms will not confront the same production and transaction cost for the same type of product because they possess different levels of tacit knowledge. Therefore, the boundaries of a firm are influenced by the need to gather, to coordinate, and to

---

[8] Bounded rationality was not originally introduced by Williamson but rather by Herbert Simon (1961) a decade earlier.

[9] This is just one example of disagreement in the TCE, others exist as well see e.g., Foss (1999).

communicate knowledge (Foss 1999 pp. 735-6). Penrose (1959) can be considered the founder of the knowledge-based view, though Hayek (1945) discussed, as early as 1936, the role of knowledge in economic activity.

Central concepts in the knowledge-based view include the "coordination of complementary investments (activities)" (Richardson 1960), capabilities[10] (Richardson 1972), complementary assets, and appropriability (Teece 1996). However, the knowledge-based view has not passed without criticism. It has been criticized for lacking a clear micro-foundation and predictive power (Foss 1999).

To sum it up, as Williamson (2000) puts it, "the field [industrial organization] is still far away from a unified theory and there is a vast amount of unfinished business". Nevertheless, the concepts underlying both TCE and the knowledge-based view provide valuable insights into inter-firm relations and can be considered as a starting point for analyzing different structures in the construction industry. Until now, industrial organization has not been systematically studied in construction (London and Kenley 2001) though sporadic studies have taken place (e.g., Winch 1989, Akel et al. 2001, Arbulu 2002, Tommelein et al. 2003).

2.2.3.2 INTER-ORGANIZATION RELATIONS

In practice, products and services between firms are acquired through a wide range of inter-organizational settings. On one end, there is the market, where

---

[10] Prahalad and Hammel (1990) used the term core competences instead of capabilities in their distinguished Harvard Business Review article.

products are acquired through a single transaction in the marketplace; and, on the other end, there is merger, where business units merge to form a corporation and units report to one headquarter (Williamson 1975). In between, various cooperative activities between firms exist, both at the business level (for example joint ventures), and at the firm level (for example alliances and partnerships), and between groups of firms (for example networks and clubs) (Kay 1998 p. 222). A cooperative agreement is a long term, explicit agreement between two or more firms (Mariti and Smiley 1996 p. 276). It is used for both allocating resources and organizing the firms' activities (ibid. p. 291).

When products and services are well standardized, characteristics are clearly specified, and there are many sellers and buyers, the (spot) market tends to be an efficient way of allocating resources. However, as products and services are less standardized and specified, more coordination between firms are required (Williamson 1975).

In the construction industry, all the above inter-organizational relations can be identified. However, little research has been conducted, and limited understanding exists about the structure and behavior of construction supply chains, as well as strategic management of inter-organizational relationships (London and Kenley 2001, Walsh et al. 2003). Particularly, the temporary nature of the construction industry is considered challenging with respect to cooperative activities. Dubois and Gadde (2000) suggest that a supply system in construction should actually consist of two network layers, one temporary for joint learning and one permanent for long-term benefits.

The concept of Vendor Managed Inventory (VMI) is an example of the "permanent" or cooperative agreement. Mahaffie (1998) reported a successful VMI arrangement between an electrical contractor and a distributor, where the distributor took ownership of the contractor's inventory and automatically replenished the inventory based on real consumption. Whereas the VMI is meant for standardized products, shared information technology allows less standardized products to be managed to varying degrees as if they were standardized products. Cooperation through shared information technology has become more common in the construction industry (e.g., Koo and Fisher 2000, Sacks et al. 2003, Frutos and Borenstein 2003, ENR 2003b).

2.2.4 Product types and costs

2.2.4.1 Product taxonomy

Besides procurement methods and industrial organization, also the types of products that flow in the supply chains play a key role in supply chain configuration. Generally, production management separates products into four main categories, namely, (1) make-to-stock (MTS), (2) assemble-to-order (ATO), (3) make-to-order (MTO), and (4) engineered-to-order (ETO) (Wortmann et al. 1997, Handfield 1995). The taxonomy is driven by the different intersection of customer orders with the entire production process (Figure 4), also called the Customer Order Decoupling Point (CODP) (Wortmann et al. 1997 p. 59).

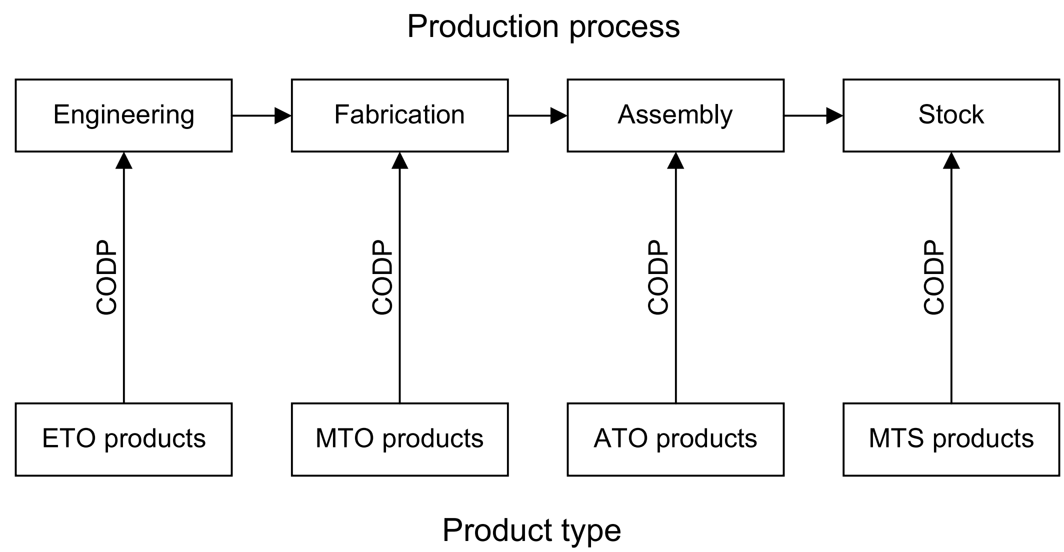


Figure 4: Intersection of customer orders with production process based on product type (After Wortmann et al. 1997)

In MTS products, the customer order is filled from a finished goods inventory and products are made to stock based on forecasts. Therefore, the customer order lead time is very short, though the manufacturing cycle time may be very long. In ATO products, options or other subassemblies are stocked prior to customer order and the customer dictates when they are assembled. Consequently, compared to MTO, lead time can be reduced, though at the cost of increased inventory. In MTO products, the inventory is held at the raw material stage, and products are fabricated after receiving customer orders (Handfield 1995 pp. 5-7). In the ETO products, customer orders are processed through engineering, fabrication, and delivery.

Table 4 provides an overview of production characteristic of the products. Wortmann et al. (1997) provide an in-depth discussion of the above taxonomy.

Table 4: Characteristics of production management in the product taxonomy (Wortmann et al. 1997 p. 65)

Orientation	Product	Workflow	Resource	Product	Product
Product	**ETO**	**MTO**	**MTO**	**ATO**	**MTS**
Example	Power distribution equipment	Prefabricated electrical receptacle	Cast-in-place concrete	Doors, windows	Bricks, bolts
Top management's focus is on	Customer order contracts	Process innovation	Capacities	Product innovation	Marketing/ Distribution
Uncertainty of operations is concentrated in	Product specifications	Volume of production	Work preparation	Mix of orders	Product Life-Cycle
Complexity of operations is concentrated in	Engineering	Final production stages	Component manufacturing	Assembly	Physical distribution
Middle management's focus is on	Project management	Quality control	Subcontracting, Shop floor control	Master Production Schedule, customer order contracts	Stock control
Information systems for PM are focused on	Support for product engineering	Progress control	Support for manufacturing engineering	Support of material supply and order entry	Support of forecasting and stock control
Nature of IS oriented towards	Generative solutions	Workflow management	Reference solutions	Rules	Decision support

Each of these products can be further broken down, based on investment in the product and process development, to resource-oriented, product-oriented, and work-flow-oriented. A resource-oriented company has invested substantially in resources but not in specific process or products (e.g., ship building, repair shops, construction company). A product-oriented company has made significant investment in product development independent from customer orders (e.g., packing machines, machine tools, medical systems). A workflow-oriented company has made substantial investments in production process development (e.g., printing, fine paper, service industries) (ibid. pp. 60-1).

In ETO products, the main manufacturing uncertainty is in the content of customer specification, where a small deviation from standard products may require significant investment in product development or design. The product engineering is the most complex and largely determines the cost, lead time, and quality of the product. Hence the focus should be on defining and maintaining a standard engineering process and standard solutions (ibid. pp. 67-8).

2.2.4.2 MEASUREMENT OF PRODUCT COST

The cost of the same product may vary significantly depending on how cost is perceived (Figure 5). This is an important issue with respect to ETO-products, because various stakeholders may have different and adverse cost interests. In the narrowest definition the cost includes only the purchase price of the product. However, there is also a “transaction cost” on top of the purchase price. The transaction consists of the cost of specifying the details of procurement contract, the cost of discovering what prices should be, the cost of negotiating the procurement contract, and the cost of monitoring the fulfillment of contract (Arrow 1959 p. 48). The transaction costs tend to be significant for ETO-products particularly if the product is acquired through competitive bidding (Nishiguchi 1994 pp. 124-126)[11]. Wortmann et al. (1997 pp. 310-311) argue that as

[11] Transaction cost is not only related to transactional contracts, there are also transaction costs in relational contracts, although these are often considered lower than in transactional contracts (Nishiguchi 1994 pp. 124-126).

competition stiffens the cost reduction and quality improvement of ETO products require minimization of transaction costs.

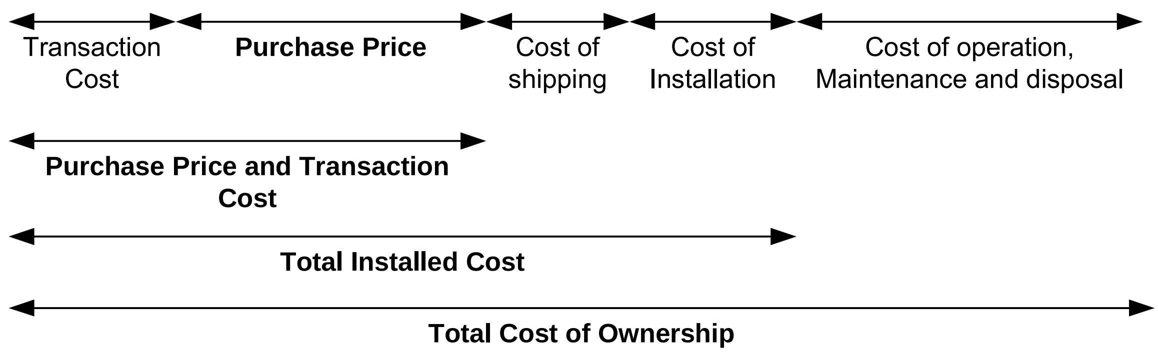


Figure 5: Various scopes of product cost

In construction, nowadays, some buyers consider the Total Installed Cost (TIC) and the Total Cost of Ownership (TCO) as they procure capital intensive products (Tommelein et al. 2003 p. 78). In TIC, the cost of installing the equipment to its final location in the building is considered along with purchase price and transaction cost. TCO is the broadest definition of cost. It includes transaction costs (e.g., the time and effort needed to exchange data between the buyer and the supplier during design, engineering, detailing, on-site assembly, and startup), product purchase price, shipping cost, operation and maintenance cost, and disposal costs. These costs are also referred to as life cycle cost (Society of American Value Engineers 1998).

2.3 LEAD TIME REDUCTION

Lead time reduction has long been considered a fundamental objective for overall business improvement (Forrester 1961) and a cornerstone for lean thinking (Ohno 1988a, Shingo 1988). Lead time can be understood as an anticipated time to complete a process. Lead time is sometimes confused with cycle time. Cycle time is the time it actually takes for a job to go from the start to the end of the process. It is the “real” time it takes for a job to go through a process; thus, it may vary from job to job. In manufacturing, there are two main types of lead time, (1) customer and (2) manufacturing lead time. Customer lead time is the time between order placement and fulfillment. Manufacturing lead time is the longest “allowable” cycle time (Hopp and Spearman 2000 pp. 321-3).

In construction projects, long lead times of product delivery often dictate the pace of the construction project. Figure 6 illustrates the relationship of the delivery lead time of a subsystem or a product and project lead time. The delivery lead times have often considerable “slack time”, because there is a tendency to separate design, procurement, manufacturing, and installation lead times, and then to separately allocate significant “slack time” to each of the “functional” lead times. Design lead time is the time that is reserved for defining and specifying product characteristics. Procurement lead time is the time that is reserved for product acquisition. Manufacturing lead time refers to Hopp and Spearman’s customer lead time (discussed above), and installation lead time is the time reserved for installing the equipment in the building.

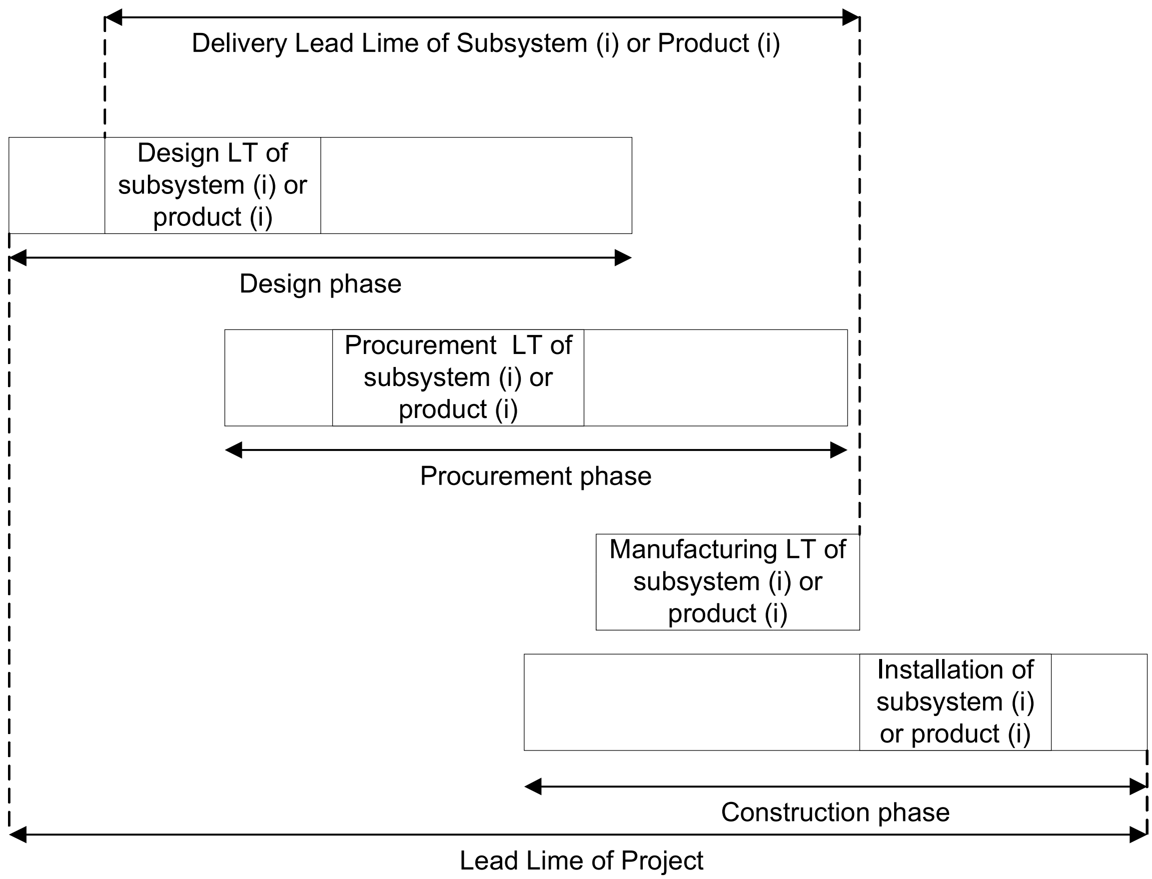


Figure 6: Product delivery lead time pacing project schedule (LT=Lead time)

2.3.1 Significance of lead time reduction

The advantages of reducing lead times are considerable. According to Karmarkar (1983) long lead times in manufacturing:

- increase work-in-progress.
- force schedules to be frozen over long periods, thus increasing the chance of schedule changes.
- increase safety stocks due to the protection against longer lead times and forecast errors that tend to increase with the forecast horizon.

- suboptimize improvement efforts, because increased delay between fabrication and use means a loss of information about quality and satisfaction.
- increase variability, since the task of coordination becomes more difficult due to long delays.
- erodes competitiveness of a company because of long response times to changing customer needs.

In some cases, these issues are even more significant in the construction industry because of its characteristically high uncertainty and variability (Tavistock Institute 1966, Koskela 1999). Further, due to long lead times, too many design decisions have to be made early and based on vague assumptions, which often leads to suboptimal solutions, quality defects, and rework. In many cases, the feedback loops from the field to the supplier are so long and inefficient that some quality defects continue to repeat throughout production even after problems have been identified.

2.3.2 Lead time reduction in design

Strategies to reduce design lead time include overlapping design tasks[12] (Clark and Fujimoto 1991), reduction of process waste, and standardization of components and detailing. Overlapping tasks mean that multiple tasks are worked simultaneously (Smith and Reinertsen 1998). The main idea is that the upstream task can be performed in chunks; i.e., information can be released in

[12] Concurrent engineering (Winner et al. 1988) is based on the idea of overlapping tasks.

smaller batch sizes to the downstream task so that the downstream task can start before the upstream task is completed (Takeuchi and Nonaka 1986).

Iansiti (1995) noted that overlapping product development tasks (concept development and implementation) also reduced uncertainty and improved the flexibility to react to market and technology changes. Overlapping requires good communication between the team members (Yazdani and Holmes 1999); therefore, organizational matters must be carefully addressed. Several analytical methods have been developed to analyze the degree and benefits of overlapping (Krishnan et al. 1997, Smith and Eppinger 1997, Steward 1981).

Parallel execution of tasks is the extreme form of overlapping. It requires decoupling of the tasks (Krishnan et al. 1997). In many cases, the decoupling may be difficult to realize, and it may require fundamental rethinking of processes. Nevertheless, the literature recognizes examples of successful parallel execution of design (Ulrich and Eppinger 1999, Sobek et al. 1999, Shingo 1988). In construction, it is common to divide larger buildings into “building blocks” that are developed and constructed relatively independently of and in parallel with each other.

Studies in construction have shown that more than 50% of design is non-value-added time (Freire and Alarcon 2000). Hence, reducing waste, such as waiting and redesign, from the design process may significantly cut the design time. Ballard (2000a) lists a number of techniques to reduce design waste including set-based design and reduced batch size.

The design process may also be simplified by standardizing the system design and detailed engineering processes (Wortmann et al. 1997 p. 68, Ulrich and Eppinger 1999). This will significantly cut uncertainty and reduce the number of design iterations and/or speed up the iteration process (Loch and Terwiesch 1998), since the set of solutions is reduced and predefined before the process starts.

2.3.3 Lead time reduction in manufacturing

In production management, the "Lean" doctrine can be considered as one of the philosophies of reducing lead times (e.g., Womack et al. 1990, Schonberger 1996). Lead time reduction is also one of the main principles to reduce waste, such as waiting and rework (Shingo 1988). According to Hopp and Spearman (2000 p. 282) most of the time in a production process is spent on waiting. Waiting may be caused by lot delays, in which one product has to wait until the whole lot is processed; or process delays, in which poor synchronization makes a whole lot wait (Shingo 1988 p. 313). Variability, which exists in every production environment, can also have a significant impact on production systems (Zipkin 1986). 100% utilization of capacity is infeasible in the presence of variability. If variability is tolerated, one will pay for it in a combination of lost throughput, wasted capacity, long cycle times, and high WIP levels (Hopp and Spearman 2000 p. 297).

2.3.4 Improving ETO supply chains

Several authors have studied time compression in supply chains (e.g., Forrester 1961, Burbidge 1989, Stalk and Hout 1990). Handfield (1995) described two types of lead time reduction in supply chains: (1) reducing the mean lead time and (2) reducing lead time variation. He also identified several means to compress time for make-to-order products, such as system simplifications and component standardization. Clark and Fujimoto (1991) found the overlapping of activities an effective time compression strategy for new product development, which is a form of ETO process. Many opportunities to reduce project duration rely on understanding the interface of engineering and fabrication (Sobek et al. 1999). Consequently, various forms of cooperation between firms have been suggested (e.g., Lamming 1993, Nishiguchi 1994, Wortmann 1997, Tommelein et al. 2003).

Luhtala et al. (1994) and van der Vaart et al. (1996) among others have studied the complexity and prevailing uncertainty in MTO supply chains, which they consider as a major challenge in improving MTO supply chains. According to Wegelius-Lehtonen and Pahkala (1998), poor information flow is the main problem in MTO construction products and typically the problems are located at the boundaries of different organizations. Gil et al. (2000) identified how early involvement of specialty contractors would improve the MTO process, but noted restrictions as well.

Tommelein and Weissenberger (1999) studied the supply of structural steel and found that buffer sizes and locations are not rationally planned throughout the supply chain and that lean practices are poorly understood across organizational boundaries. Sacks et al. (2003) applied advanced information technology to reduce precast concrete inventories and to improve delivery reliability. Also, many other ETO products, such as HVAC ductwork (Holzemer et al. 2000), concrete elements and facades (Vrijhoef and Koskela 2000), transformers (Tommelein et al. 2003), and switchgear (Barker 1994), have been studied from a supply chain perspective. Many studies have identified possible improvements, but with few exceptions, those improvements have not actually been implemented and achieved.

The reasons are many. Ballou et al. (2000) regard as the most challenging in supply chain management the structure of the supply chains so that the optimizing of activities should not happen at the expense of other members of the supply chain. Lambert and Cooper (2000) also emphasize that several issues need to be solved before greater gains can be achieved. They provide a list of research topics in SCM, which among others include: the relationship between various processes, measures and guides for supply chain maps, SCM metrics, barriers of SCM implementation, and type and level of inter-organizational integration. Hershauer et al. (2000) argue that contractual and organizational changes are needed to improve construction supply chains and that the owner is the key driver.

2.4 CONCLUSIONS

Undoubtedly, the construction industry would benefit in multiple ways from reduced lead times. Today, it seems that there are better opportunities than ever before to reduce lead times. First, a production theory, the TFV, has emerged in the construction industry. This permits new understanding about process behavior and resource optimization. Traditional project delivery in construction has merely focused on the transformation concept of production or converting specifications to products, without the consideration of flow, and value concepts. The TFV theory argues for the simultaneous use of transformation, flow and value concepts. It strives to design the product and process in an integrated manner as opposed to separately and sequentially.

Second, scholars in SCM have demonstrated that significant gains can be achieved if "traditional functional units" such as design, procurement, and manufacturing are viewed from a systems approach rather than as isolated units. In construction, the gains include reduced project schedules, costs, better customer satisfaction, and increased profit margins for the members of the supply chains.

However, the literature review also revealed that there are major gaps in our understanding on construction SCM. This may be one reason why, although major opportunities have been identified, the industry has not been able to gain at large from SCM. We do not know enough e.g., how procurement of ETO products is related to design and production, how contracting methods and industrial organization impact product delivery, how changes impact various supply chain members. Moreover, with respect to ETO products, lead time reduction appears to benefit all members of the supply chain, but yet, why are we not able to radically reduce it?

It seems evident that more data are needed to understand in detail what an ETO supply chain consists of, and what are the dependencies between various processes within the supply chain, to other supply chains, and to the construction project. Then, it would be of interest to investigate how the TFV theory and lean techniques can be applied to improve the delivery process.

Finally, as Hammond (1990) argued: “processes have to be regularly reengineered because they simply get obsolete”.

3 RESEARCH METHODOLOGY

3.1 OVERVIEW OF AVAILABLE RESEARCH METHODS

The classical distinction of research methods is to inductive and to deductive reasoning. The former is based on reasoning from particular facts or individual cases to a general conclusion, the latter is based on reasoning from general to specific or from premises to a logically valid conclusion (Ladyman 2002).

Another major distinction is between the positivist and interpretive approaches. The positivist approach refers to the scientific approach also labeled as hypothetico-deductive, quantitative, and natural science based approach (Robson 2002). Here, a theory is regarded as a starting point, and then hypotheses are deduced and tested, which then confirm or falsify the theory[13]. The world is considered external and objective, and the observer independent. In the interpretive approach, also called hermeneutic, ethnographic, and qualitative approach, theories and concepts tend to arise from the enquiry (ibid.). Hence data collection and analysis are not rigidly separated rather interweaved and repeated several times as the research progresses. In the interpretive approach the world is considered socially constructed and subjective and the observer may be part of the system.

With respect to the research enquiry the research strategies are experimentation, surveys, archival analysis, history, and case studies (Table 5)

---

[13] The actual scientific methods are less evident among researchers than the approach in itself and have been widely debated for a long time (see e.g., Kuhn 1962, Ladyman 2002).

(Yin 2003 p. 5). In an experiment, one or more variables are manipulated and its/their effects on other variables are measured, in other words, the testing is conducted in a controlled environment. Simulation is an example of an experiment. In a survey, information is collected in a standardized form from people. The information is then mainly analyzed through statistical methods. In archival analysis past records are analyzed, e.g., to describe the incidence of a phenomenon or to predict a certain outcome. In history, the investigator relies on past facts, documents and artifacts, and has no access to interviews and observations. Case study is "an empirical inquiry that investigates contemporary phenomena in a real-life context" (Yin 2003 p. 12-4). Typically it has more variables than data points, and it relies on multiple sources of data.

Table 5: Use of different research strategies (Yin 2003 p. 5)

Strategy	**Form of research question**	**Requires control of behavioral events**	**Focuses on contemporary events**
Experiment	How, what?	Yes	Yes
Survey	Who, what, where, how many, how much	No	Yes
Archival analysis	Who, what, where, how many, how much	No	Yes/No
History	How, why	No	No
Case study	How, why	No	Yes

3.2 APPLIED RESEARCH METHOD

I chose an inductive approach, which relies on the interpretive method and a case study-experiment strategy. The inductive approach was chosen because I had limited number of data points; and thus, I generalize the characteristics and behavior of the investigated process from specific case findings. The interpretive method was chosen because in the beginning of this study it was not clear what specifically would be looked for and as data became available, the scope and the focus of the research was revised and new enquiries were launched. The positivist method was not applied because the strict requirement of separating data collection and analysis. Also, the consideration of the world as external and objective would not have been possible.

Due to the nature of this research: contemporary events, no control over behavior (here: the industry), and form of research question (how), a case based research strategy was employed. Case studies are preferred when investigating a structure of a given industry (Campbell and Stanley 1963, Robson 2002, Yin 2003). Experiments were also applied on a small scale through simulation to support the case findings. However, experimentation as a sole strategy was not considered feasible in this research context, since the control over the behavior of the whole power distribution equipment (PDE) delivery process could not be established.

According to Yin (2003 p. 6) a survey-based research is not considered appropriate, when dealing with "operational links" that needs to be traced over a time period (ibid.). Therefore, I rejected survey-based enquiries.

Finally, because it was possible to conduct a wide range of interviews as well as observations, there was no need to limit the enquiry strategy to archival analysis and history.

3.3 CASE STUDY DESIGN

I chose a multiple-case design, which has a hybrid exploratory-explanatory approach. The objective of exploration was to gain insight into the current process being studied and to identify improvement opportunities. In addition, the intent was to explain why the process lead times were so long and why certain improvements would make sense. The case studies were launched in February 2002 and completed in October 2003. The case studies were preceded by an internship, a pilot study, and a literature review on cross-industry supply chains. During the internship I mapped material management practices by a major electrical contractor in the US, including some of its suppliers. The pilot study focused on the delivery process of switchboards.

3.3.1 Delivery process of PDE as a unit of analysis

The case studies focused on the delivery process of switchboards, panelboards, and motor control centers (MCC), which are types of PDE. PDE is used to manage and to control the electrical power flow in capital facilities. PDE is a critical procurement item, since the ability to deliver it on time and within a predetermined cost may determine whether or not an electrical contractor gets awarded a contract. In 2000, the value of switchboard shipments alone was $8.1 billion in US (US Census Bureau 2001). As an engineered-to-order (ETO) product it is particularly prone to changes because the electrical trade, who installs the equipment, is one of the last trades on the site. As a result, problems from prior trades tend to cumulate on top of electrical trade's "inherent quandary", which lead to unreliable product and process plans. Also, there is a gap in the current literature regarding the delivery process of PDE, which also encouraged me to choose it as a unit of analysis. Barker (1994) has been studying means to reduce the switchboard manufacturer's lead time but the delivery process as a whole and its organizational structures had not been studied to the extent of this study.

3.3.2 Data collection

In case based research, data from multiple sources is desirable for the trustworthiness of the research (Robson 2002 p. 179, Yin 2003 p. 97). Data was collected from workshops and interviews including owners, users/operators, architects, electrical engineers, project management firms/general contractors, electrical contractors, and equipment manufacturers; and through observations; and records analysis.

3.3.2.1 Workshops

The workshops had three main functions: (1) to collect information about the delivery process, (2) to disseminate information about current practice and potential future practices to the process participants, and (3) to validate findings. The workshops were applied in two, Novo and Paradise Pier, of the three cases. In each case, there were three half-day workshops. A key criterion in the workshop setting was that all the main process stakeholders were represented. It was recognized straight from the beginning that this potentially could lead to some confrontation, because there were adverse goals and interests among the stakeholders. However, these were regarded as strengths in evaluating and validating the process.

In Novo, the project management firm hosted the workshops, and invited the owner, the architect, the electrical engineer[14], the electrical contractor, and the manufacturer. The project management firm was represented by their head electrical engineer, head mechanical engineer, and R&D director. In Paradise Pier, the owner hosted the workshops, and invited user and owner representatives, the architect-of-record, electrical engineers (including the electrical engineer-of-record), the electrical contractor, and the manufacturer representative. Figure 7 demonstrates the workshop sequence and approximate duration of each phase.

The preparation of the workshop took a long time because; even though, the hosts were interested in the topic of the study, they were hesitant to commit to the case study. They were cautious about making sources available to conduct the case study. Also, the consequences of the study and a suitable project as a case raised some concern. In addition, the tied up schedule of key persons made the information exchange and decision making regarding the participation and its arrangement very slow, and even tantalizing.

---

[14] The electrical engineer was not directly involved with the case project. He was the electrical engineer of the project for which the future state process was designed. The project management company's head electrical engineer developed the electrical design together with the outside electrical engineering firm.

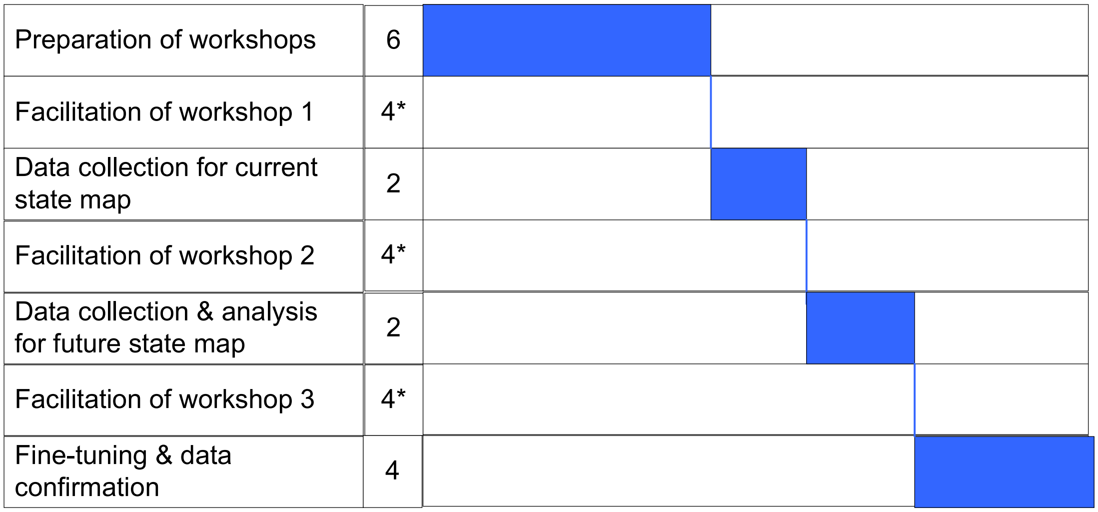


Figure 7: Workshop sequence and approximate duration of the phases (numbers refers to months[15], except those with an aster refer to hours)

The first workshop was an introductory gathering, where the background of the study was presented, and the purpose and scope of the study was specified. As the workshop participants introduced themselves to each other, they were given an opportunity to disclose “burning issues” in the current delivery process. This led to lively and fruitful discussions. Then, in a group effort the participants wrote their tasks with respect to the delivery process on stickers that were arranged on the wall according to the sequence of work (Figure 8). Before ending the workshop, missing data and their source were identified, and “homework assignments” based on remaining data needs were given to the participants.

---

[15] In Paradise Pier most of the current state mapping took place after the second workshop, because in the first workshop only in-house participants; owner representative, architect, electrical engineers, and R&D people were involved.

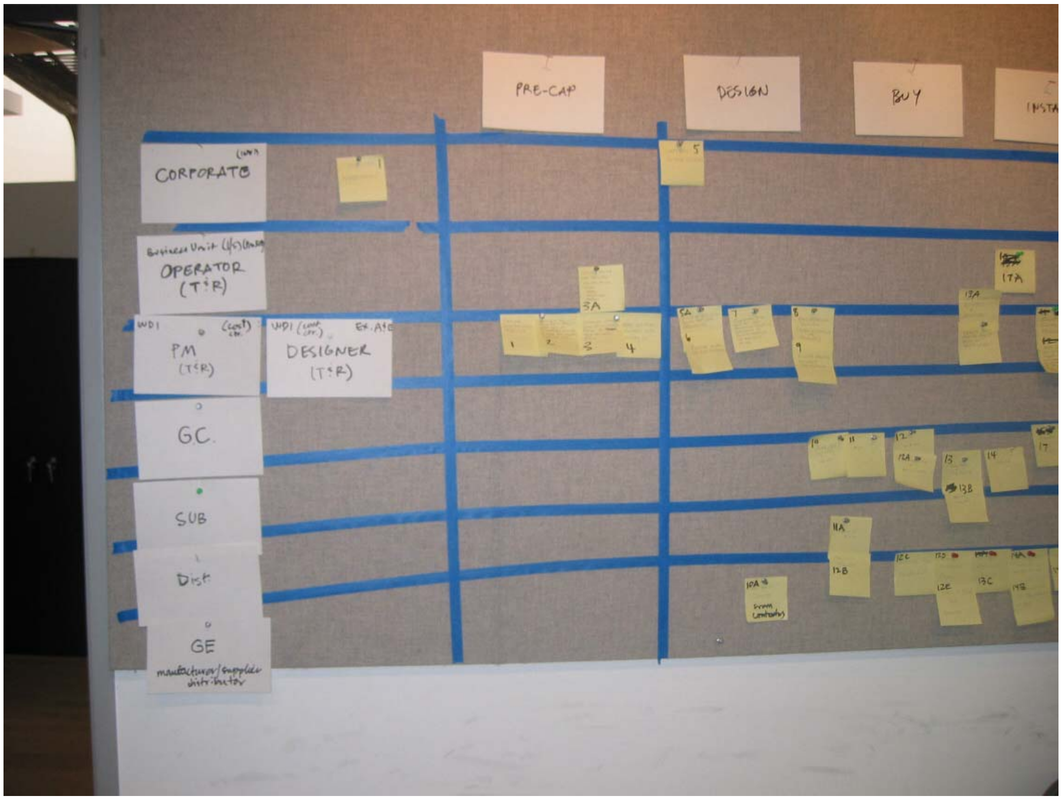


Figure 8: Result of initial process mapping in the workshop

In the second workshop, the current state delivery process was validated, performance measures were presented, and problems were identified. Then, I facilitated with help of “The Airplane Game” (Santech Industries 2003) the participants to rethink the process. The game visualizes some of the ideas underlying the TFV theory making them easier to perceive. This generated a number of improvement suggestions, which were recorded and applied as starting point in the third workshop.

In the third workshop, a future state process map based on workshop participants’ suggestions and the TFV-concept was presented. The future state map was compared to the current state map, as it was debated and fine-tuned. The workshop ended by an analysis of potential methods to implement the future state map. Finally, the remaining details were collected with the help of one-on-one interviews.

In conclusion, the first workshop was tedious to launch, but the workshops became a critical "backbone" in the case studies. They were informative and provided instant triangulation of the data points. The participants found them to be an "efficient" and "stimulating" method to understand their current practices and to explore opportunities. Nevertheless, the applied research strategy took twice as much time as originally scheduled. One of the main reasons was that so many people had to be involved and sometimes it was hard to match the individual schedules.

3.3.2.2 INTERVIEWS

The interviews were semi-structured. A set of questions was prepared for each interview session but depending on interviewee's responses some, were emphasized more, elaborated on or eliminated. Together 104 telephone and face-to face interviews were conducted (Table 6).

Table 6: Distribution of interviews

Stakeholder	**Bay Street**	**Novo**	**Paradise Pier**	**Total**
Owner/ user representatives	3[16]	3	10	16
Architect	2	4	6	12
Project management/ General contractor	4	13	-	17
Electrical engineer	5	6	8	19
Electrical contractor	6	6	5	17
Manufacturer's sales representative	2	-	6	8
Manufacturer	4	7	4	15

[16] In case 1, I did not manage to interview owner or tenant representatives directly, but I interviewed city and utility company representatives.

3.3.2.3 *OBSERVATIONS*

The observations[17] took place on construction sites, manufacturers' shop floors, and workshops (Table 7). I made 22 observations and took a "Participant-as-Observer" role (Robson 2002 p. 317), where my role as an observer was made clear to all in the focus group, and I was allowed to interact with the members and to pose questions to them, if I wanted further explanation about what is going on.

Table 7: Distribution of observations

Observation	**Bay Street**	**Novo**	**Paradise Pier**	**Total**
Construction site	6	5	2	13
Manufacturing shop floor	1	1	1	3
Workshop	-	3	3	6

3.3.2.4 *RECORDS ANALYSIS*

Record analysis included following documents: schedules, Request-for-Quotes, (RFQ), Bill-of-Materials (BOM), Purchase Orders (P.O.), design drawings, approvals, and data sheets from configuration and pricing software.

3.3.3 Data analysis

A theoretical proposition (the TFV theory) and case description were applied as strategies for data analysis (Yin 2003 p. 111-6). Then, with the help of mapping, simulation, and metrics, I employed the following data analyzing techniques (ibid. p. 120-37): explanation building, time series, logic models, cross-case synthesis.

---

[17] Generally, observation is watching and recording what happens (Robson 2002 p.309).

3.3.3.1 *MAPPING*

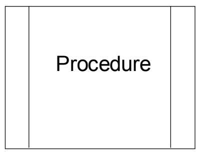
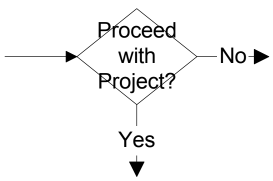
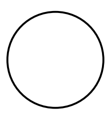
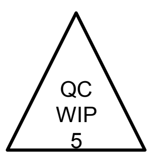
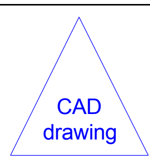
Mapping is a technique that gives an overview of the operating structure, which helps to capture and frame knowledge, share concepts, focus discussion, and reach consensus (Senge and Sterman 1994). Mapping has been widely employed in applications in diverse areas, such as systems dynamics (e.g., Forrester 1961, Sterman 2000), in analyzing business strategies (e.g., Porter 1985), and in lean manufacturing (e.g., Ohno 1988a, Shingo 1988, Rother and Shook 1998). In recent years[18], there have been some efforts to map the delivery processes in the construction industry as well (e.g., Fisher and Yin 1992, Tommelein 1998, Tommelein and Li 1998, Tommelein and Weissenberger 1999, Arbulu 2002, Wegelius-Lehtonen and Pahkala 1998, Vrijhoef and Koskela 2000, Walsh et al. 2003). These process maps have been helpful to understand relationships and dependencies between various tasks and organizations.

In this research, I applied a type of value stream mapping (Rother and Shook 1998) that has been modified by Tommelein (e.g., Tommelein 1998, Arbulu and Tommelein 2002) to suit supply chain mapping. In this type of mapping important characteristics are the visualization of hand-offs between organizations by clearly separating organizations from each other and the use of a minimal amount of symbols for clarity (Table 8).

---

[18] However, simulation process models, which are a type of mapping, have existed since 1960s.

Table 8: Supply chain mapping symbols

Symbol	Name and Meaning
	Connector [Universal connector, Line connector, or Line-curve connector]: thin arrow represents a flow relationship.
	**Procedure** [Procedure]: represents a relatively high-level activity or work to be done. Depending on the level of detail at which the supply chain map is being developed, one may distinguish a procedure from an operation. Operations are detailed steps or tasks in a procedure. An operation requires a specific type of resources throughout its execution, whereas a procedure is more aggregated and may require different resources at different times in the course of its execution.
	**Decision node**: represents a decision-making event that can result in one out of two (yes arrow [Result] or no arrow [No result]) alternative paths being followed.
	**Relationship with other specialties**: related to the participation of specialists to perform tasks or activities.
	**Material inventory**: represents material that is between procedures. The number indicates the number of units that are in inventory and is a variable.
	**Document**: represents the information input or outcome of a procedure, which in most cases is a document or manual.

3.3.3.2 SIMULATION

Simulation is a technique where computers are used to imitate a real world process (Law and Kelton 2000 p. 1). The main advantage of using simulation is that it allows "experimenting" with various system set-ups without interfering with the actual process. Accordingly, it is a very cost-effective operations research technique particularly for complex systems, e.g., sizing production facilities. It has also been widely used in business process reengineering (Forrester 1961, Sterman 2000), which represent another school of thought. Though, numerous simulation engines or packages are available, discrete event simulation is based on just three simulation logics: (1) event scheduling, (2) activity scanning, and (3) process interaction (Schruben and Schruben 1999).

In this research, I used discrete event simulation engines based on both event scanning (Stroboscope (Martinez 1996)) and event scheduling (Sigma (Schruben and Schruben 1999)), the reason being that I had easy access and first hand tutorial to both of them. I elaborate on the simulation in chapter 5.

3.3.3.3 METRICS

Metrics or performance measures are needed to monitor and evaluate the fundamental objectives of a system or business strategies. The set of performance measures may vary depending on the system (Hopp and Spearman 2000 p. 289-290). The "quality school" (e.g., Shewhart 1939, Deming 1994) developed measures particularly for quality monitoring and evaluation. The "Lean school" (e.g., Ohno 1998, Shingo, 1988, Womack et al. 1990) developed measures particularly for production monitoring and evaluation. The Supply-Chain Council (2003) has developed an extensive set of supply chain metrics within their Supply Chain Operation Research (SCOR) model to evaluate and benchmark supply chain performance. However, SCOR; although it is probably the best known model for supply chain measurement is not the only one. Other groups and scholars have been developing metrics and measuring supply chain performance as well, e.g., Housing Forum 2000, Beamon 1996, Choi and Rungtusanatham 1999, Vonderembse and Tracey 1999, and Weber 2000.

Based on the TFV theory and the feasibility of data collection from the case studies I developed 26 performance measures, which I present in chapter 4 along with the cases.

3.4 SUMMARY

An inductive and interpretive research methodology was employed, where data were enquired by case studies and experiments. The challenge with case based approach is that there are no comprehensive templates for the case design as may be the case in other enquiry forms. Also, the treatment of evidence is difficult and demanding in case studies as compared to other enquiry forms. I cope with these challenges by employing a wide array of data collection and analysis techniques.

4 EMPIRICAL CASE STUDIES

Three cases studies were developed, one in Finland and two in the US. They were conducted between February 2002 and September 2003. The data collection took from six to ten months per case study. The case studies are described in detail in three separate reports (Elfving 2003, Elfving et al. 2003a, Elfving et al. 2003b). In this dissertation, I provide an overview of each of the case projects and maps for the current state delivery processes. I also highlight issues that contribute to the lead time, and suggest improvements for future state maps.

4.1 DEFINITION OF THE EQUIPMENT

In my studies I focused on the delivery process of switchboards, panelboards, and Motor Control Centers (MCC). Other major power distribution equipment (PDE) includes switchgear and transformers, but these are not included in the scope. Switchgear is only used when high power flow reliability is required, e.g., for hospitals and certain types of process industry facilities. None of the cases had switchgear. In addition, both switchgears and transformers are large product groups and would demand their own studies. Also, significant work about transformer supply chains has been already conducted within Construction Industry Institute (Tommelein et al. 2003).

4.1.1 Switchboard

A switchboard is "a type of switchgear assembly that consists of one or more panels with electrical devices mounted thereon and associated framework"

(ANSI/IEEE 1985). The switchboard is the main PDE in a building that does not require extreme high power reliability, unlike hospitals and some process industry facilities. The incoming power to the building gets transformed in the transformers to the main switchboard from which the power is further distributed with feeders e.g., to motor control centers, which supply mechanical equipment (chilled water systems, pumps, fans, etc.), and local panelboards. Besides switches, the switchboard may include instruments such as voltmeters, ammeters, wattmeters, and varmeters.

4.1.2 Panelboard

Panelboards are used to distribute power to local areas within a building. For example, each floor may have its own panelboard that handles all the power needs on that floor, from lighting to equipment. They are generally categorized as power distribution, lighting and appliance, and multisection panelboards (Chen 1990). The main difference between switchboards and panelboards is that a switchboard is floor-mounted and a panelboard is wall-mounted. Figure 9 demonstrates a schematic layout and relation of switchboards and panelboards.

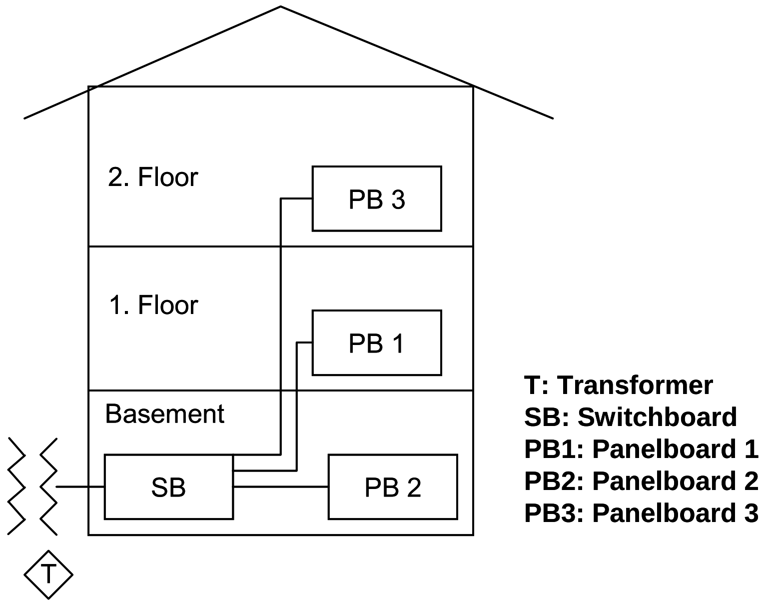


Figure 9: Schematic layout and relation of switchboard and panelboard

4.1.3 Motor control center

A motor control center (MCC) is "a floor-mounted assembly of one or more enclosed vertical sections typically having a horizontal common power bus and principally containing combination motor control units" (NEMA 2001). The main functions of an electrical motor control are starting, accelerating, stopping, reversing, and protecting electrical motors (Smeaton 1987). From the three product groups studied the MCC is the most customized equipment because of the numerous motor sizes, types and controlling logics.

4.2 CASE 1: BAY STREET

Bay Street is a 1 million-square-foot urban development project in Emeryville, California including retail and entertainment offerings in 5 separate buildings (A, B, C, D, E). The project included 400,000 square feet of retail, with 65 shops, 9 restaurants and an AMC Theatre (with 16-screens and over 3,300 seats), over 2,000 parking spaces in multi-level structured facilities and surface lots. The retail developer and owner launched the project as a Design-Bid-Build and hired an Architect/Engineering (A/E) firm to handle architectural, electrical and mechanical design, in August 2000. The electrical design started in November 2000. In May 2001, the electrical contractor was selected; a PM company had been hired a few months earlier. The construction started in Summer 2001 and the first phase, retail and parking, was completed in November 2002. The second phase, which includes the residential spaces, was scheduled to be completed by the end of 2003, but was not part of the case study.

4.2.1 Overview of the delivery process

The project has 6 electrical rooms and each of them has a Siemens' low-voltage switchboard. All buildings have one electrical room, except Building E, which has two electrical rooms. Besides switchboards the buildings have 8 MCC and 150 panelboards. Every switchboard and MCC is different due to different tenant needs. The electrical load for Building A is 4000A (retail 2000A and the movie theater 2000); for Building B, 1600A; Building C, 1200A; Building D 1200A, and for Building E, 2300A. The local utility company allows a maximum load of

4000A/building without a special permit. The specification of the switchboard (load calculation) started in November 2000, the drawings for quotation were finished in April 2001, and the electrical contactor was awarded the job in May 2001. All the switchboards were ordered and delivered at the same time and for the most part engineered simultaneously. The electrical contractor released the switchboard purchase order in February 2002, and the switchboards were delivered to the site in May 2002. The installation of the first switchboard (Building A) started in mid-June and the installation of the last switchboard (Building D) started in mid-October. The MCC and panelboards were ordered at the same time as the switchboards; however, they were not released and delivered simultaneously.

4.2.2 Description of current state

The delivery process of the PDE had three main phases or collections of tasks: design and engineering, procurement, and manufacturing and shipping. The outcome of the first phase was equipment specifications, also referred to as contract documents. The outcome of the second phase was purchase order release, which also included approval of shop drawings. The outcome of the third phase was equipment-on-site (Figure 10). The complete current state process map is presented in Appendix 1.

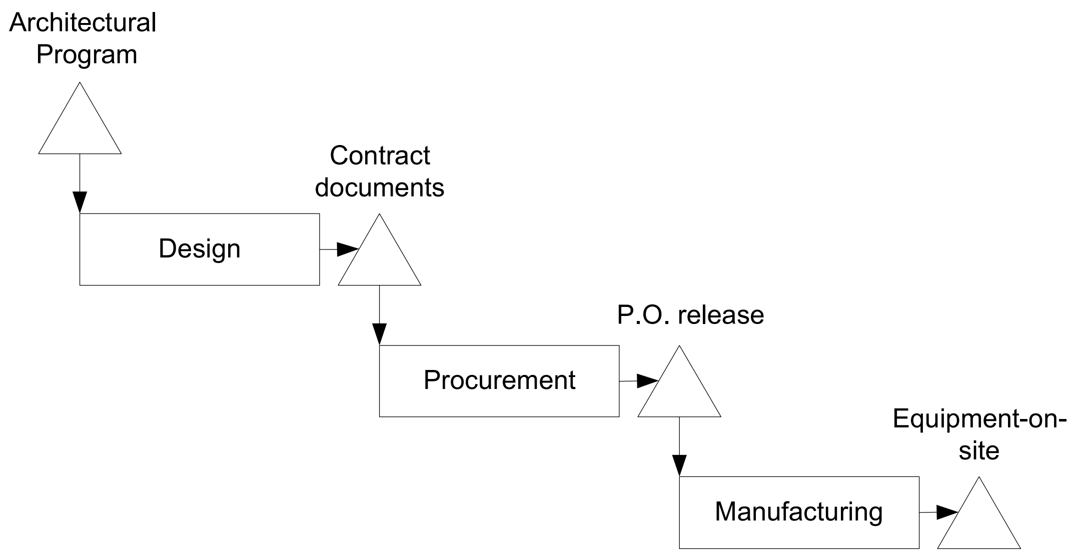


Figure 10: Main phases in the delivery process in Bay Street

4.2.2.1 DESIGN

The design of the pieces of equipment did not require anything unusual. The major challenge was to keep the design up-to-date, because the owner continuously modified the design specifications and the many tenants, many of whom signed the lease agreement after the construction phase had started.

Because the architect, electrical and mechanical engineer represented the same company, there was little formal information exchange. Therefore, it was difficult to verify the time it took to coordinate the design. My sense is that the numbers about design updates presented later are underestimated.

Because the electrical engineer did not have prior experience in dealing with the local requirements, lacked definitive user requirements, and for some other reasons, the design information was not always complete and error free. This particularly frustrated the electrical contractor and the utility company: their work got delayed and consumed more resources than was planned.

The specific activities in design the equipment were (1) calculate the electrical loads, (2) design the electrical power distribution system (define type of equipment and fit to space), (3) consult the local utility company, (4) design one-line diagram, (5) design MCC, and (6) fine-tune equipment documents for bidding (Figure 11). The electrical engineer-of-record (A/E firm) executed all the above activities, except the connection design to the utility grid, which the local utility company executed.

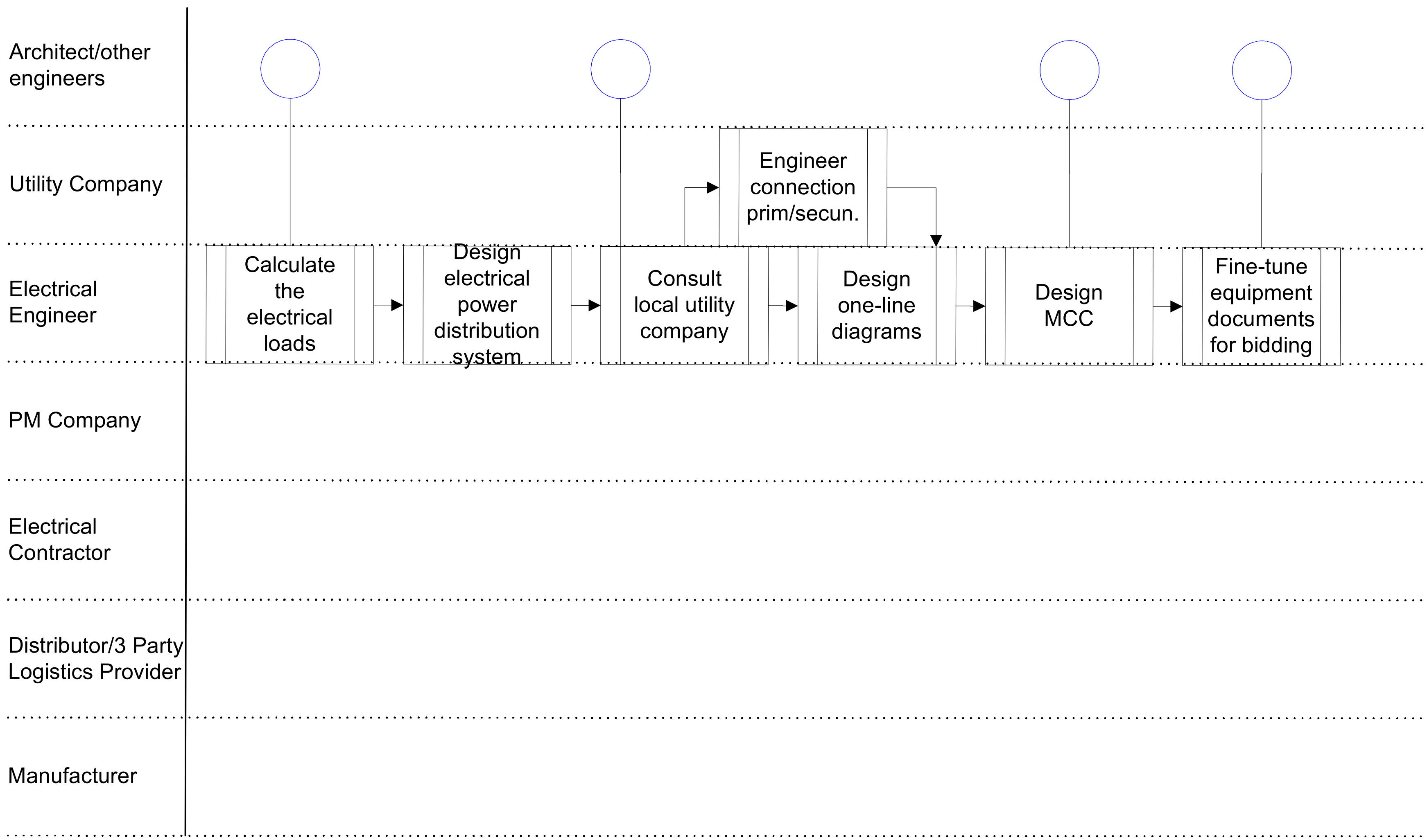


Figure 11: Design activities in Bay Street (Symbols are explained in chapter 3)

4.2.2.1.1 Calculate electrical load

The architect provided the electrical engineer the architectural program, which defines the basic spaces in the buildings including size and intended use of the space. The mechanical engineer provided the electrical loads for mechanical equipment. The electrical engineer estimated loads per square foot for each particular space based on its intended use. The electrical loads had to be separately calculated for over 30 spaces.

4.2.2.1.2 Design electrical power distribution system

Electrical engineer defined the dimensions of the equipment and arranged the pieces of equipment in the spaces predefined by the architect. The dimensions were estimated because the manufacturer had not been chosen at this stage, thus precise equipment dimensions could not be determined. At this stage significant coordination between the electrical engineer and the architect, who got input from the owner, took place.

4.2.2.1.3 Consult local utility company

The electrical engineer met with the utility company in order to decide how and where the buildings were to be connected to the local utility grid. Then the utility company designed the connections.

4.2.2.1.4 Design one-line diagrams

The electrical engineer generated a conceptual design with a one-line diagram of power distribution and a 3D layout drawing based on his estimation of electrical loads. The electrical engineer defined the switchboards' components, including the type and number of circuit-breakers or fuses, the metering and meter requirements, motor control centrals, etc.

4.2.2.1.5 *Design MCC*

The electrical engineer designed the MCCs based on the architect and the mechanical engineer's equipment list. Of all the PDE the MCCs had the most changes and add-ons because of their high level of customization.

4.2.2.1.6 Fine-tune equipment documents for bidding

All the necessary design documents and remarks from the utility company were reviewed before they were submitted to the construction PM company, who prepared the Request-for-Quotation (RFQ). This included not only switchboard related documents but also other power (e.g., lighting) and non-power systems (e.g., voice/data systems).

4.2.2.2 Procurement

The procurement of the PDE went through three levels of competitive bidding. First, the PM company bid to the owner-developer for the whole site work of the construction project, including power distribution equipment. Second, the electrical contractor bid to the PM company for the electrical work including the power distribution equipment. Third, the manufacturer's sales representative and distributor bid to the electrical contractor for the equipment. The four manufacturers, who were pre-selected by the owner, have trade agreements that require their equipment to be bought through a distributor and not directly from them. Therefore, even if the manufacturer's sales representative placed the quote, one of its distributors would actually execute the sales transaction. Hence, provide the necessary customer service after the placement of P.O., during the site installation.

Besides the bidding process, another major process in the procurement phase was the approval of shop drawings. The manufacturer generated the shop drawings, and passed them through to the distributor, the electrical contractor, and the PM company, to the electrical engineer-of-record. This is a tedious process due to the embedded hierarchy and bureaucracy (Figure 12).

The specific activities in the procurement phase were: (1) Request-for-Quotation (RFQ) of electrical work, (2) Request-for-Quotation (RFQ) of equipment, (3) prepare equipment quote, (4) prepare electrical work quote, (5) select electrical contractor, (6) select equipment supplier, (7) place purchase order, (8) prepare and send shop drawings, (9) review and approve shop drawings, and (10) release order (Figure 12).

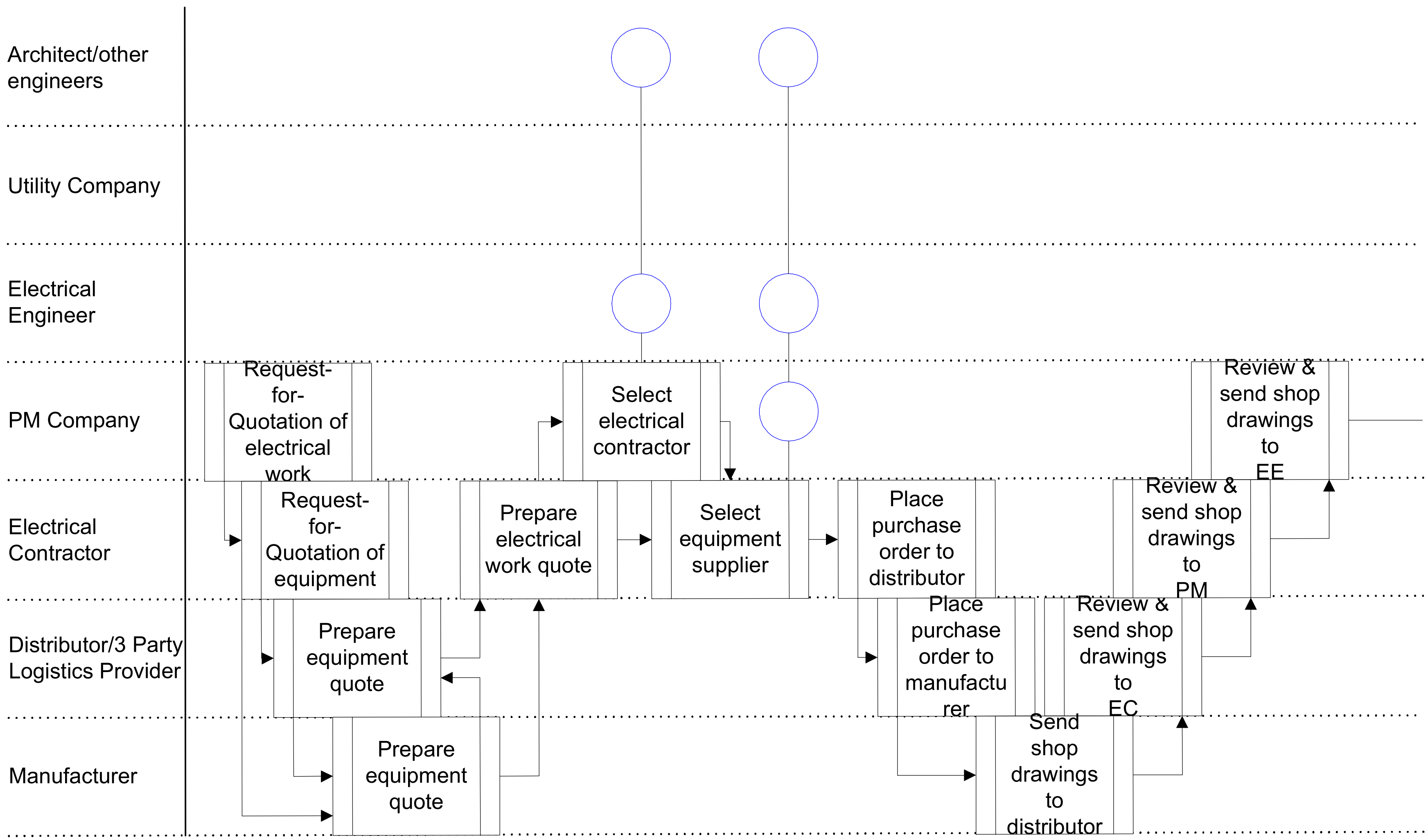
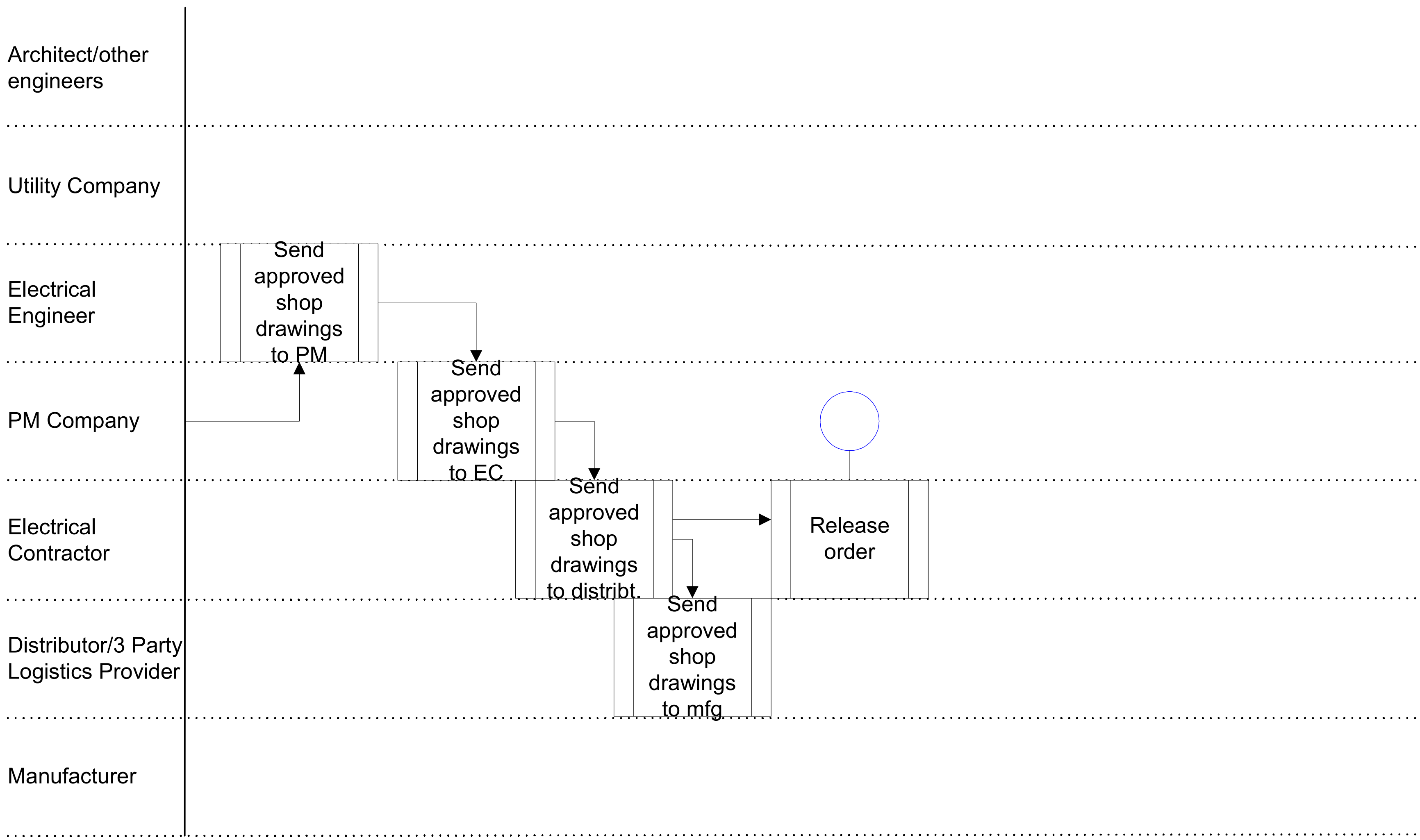


Figure 12: Procurement activities in Bay Street



Procurement activities in Bay Street (Figure continues)

4.2.2.2.1 Request-for-Quotation of electrical work

The PM company requested quotes from three electrical contractors. It took about 20 hours to prepare all the bid documents but only 0.5h (2.5% of this time) to address switchboard related issues.

4.2.2.2.2 Request-for-Quotation of equipment

The contractor placed five Requests-For-Quotations (RFQs), one to a manufacturer's sales representative and four to various distributors. The distributors then further passed the RFQs to the manufacturer's sales representatives. This practice is elaborated in chapter 4.2.5.2.

4.2.2.2.3 Prepare equipment quote

The sales representative did a take-off from the one-line diagram. The data from the one-line diagram, which specifies the details of the switchboard, was fed to the pricing software in order to produce the price and submittal drawings, which provided the dimensions and the general configuration of the equipment.

4.2.2.2.4 Prepare electrical work quote

After the electrical contractor had received the prices from its suppliers, he submitted a quote to the PM company. From the issuing of the RFQ for electrical work, it took three weeks for the PM company to receive quotes. The quotation of the PDE consumed only a fraction of the bid time; other electrical work such as lighting and wiring had to be estimated as well.

4.2.2.2.5 Select electrical contractor

The quotes included all electrical work. The PDE was only a part of it and consumed a small part of the total evaluation time. The PM company chose the electrical contractor based on the lowest bid.

4.2.2.2.6 Select equipment supplier

The electrical contractor chose the equipment supplier based on the lowest bid.

4.2.2.2.7 Place purchase order

Six months after the electrical contractor was awarded the job, he placed the Purchase Order (P.O.) with the distributor. Even though the contractor got the quote from the manufacturer’s sales representative, he placed the P.O. with the distributor. This is due to trade agreements between manufacturers and distributors in the supply chains being studied. The distributor is required to take the P.O. with the manufacturer’s price. The distributor’s margin, which is a percentage of the equipment price, is included in the manufacturer’s price.

4.2.2.2.8 Prepare and send shop drawings

The shop drawing documents include the bill-of-material (BOM), layout drawings, and 3-line diagram drawings. The BOM and layout drawings are generated automatically during the quotation process with the help of the manufacturer’s pricing and configuration software; but the 3-line diagram, precise wiring and component drawings of the equipment require manual drawing and were done by the manufacturer’s electrical engineer. The shop drawings were then passed through to the distributor, electrical contractor, and PM company to the electrical engineer-of-record.

4.2.2.2.9 Review and approve shop drawings

The electrical engineer approved the shop drawings, but the electrical contractor and the PM company also reviewed them. There were no major remarks regarding equipment. The approved drawings were then passed back to the manufacturing plant via the PM company, the electrical contractor, and the distributor.

4.2.2.2.10 Release order

After the architect and the electrical engineer at the A/E firm had approved the shop drawings of the equipment, the electrical contractor released the order for fabrication. Only after the release of the order did the manufacturer schedule the order for his production.

4.2.2.3 Manufacturing and shipping

The pieces of the PDE were fabricated in several facilities in the US. The manufacturer had standardized and documented all the operations from procurement to shipping within the plant. However, there was a significant exchange of information between the manufacturing plant and the sales representative in order to clarify the customer requirements. Information was exchanged 3 to 4 times a week during a 6-week period.

The specific activities in manufacturing were: (1) plan production, (2) procure components, and (3) fabricate parts and assemble (Figure 13).

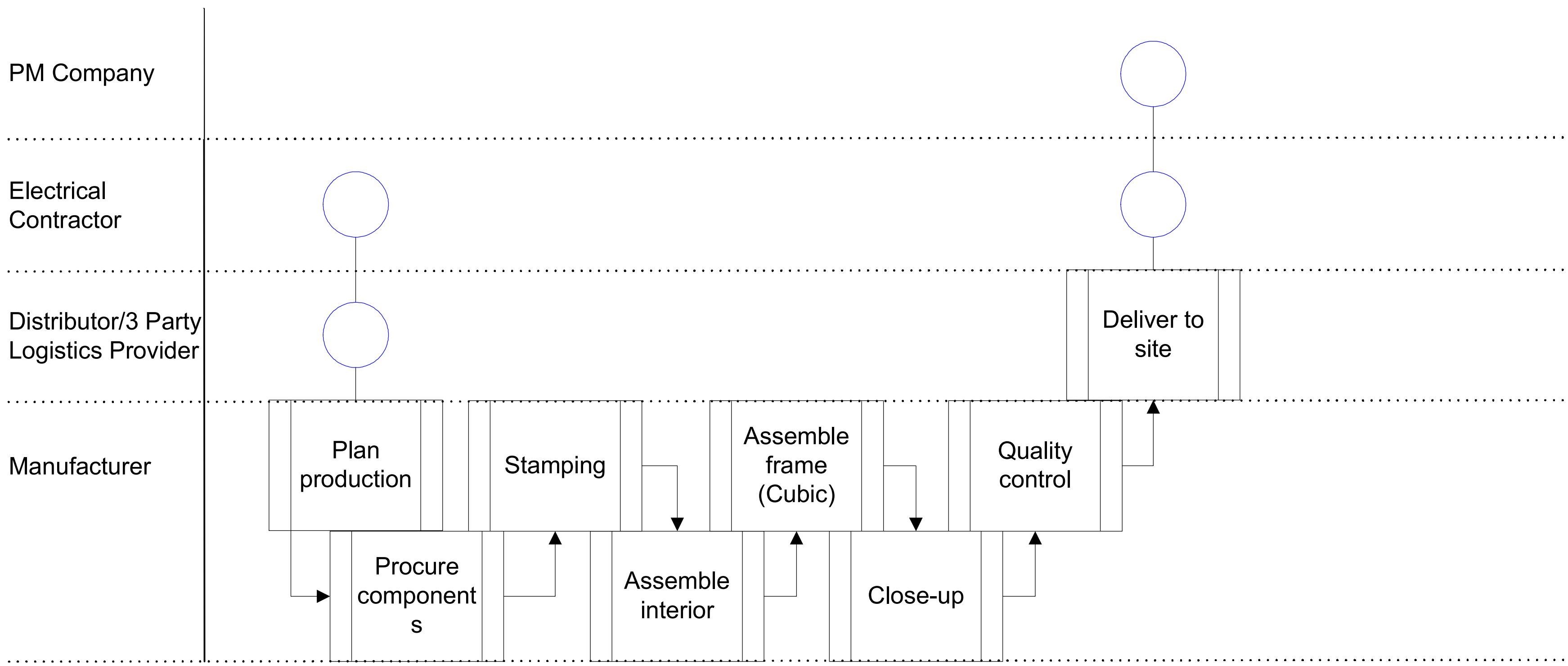


Figure 13: Manufacturing activities in Bay Street

4.2.2.3.1 *Plan production*

A scheduling program automatically scheduled the jobs based on required shipment days, component delivery lead times, workload/section, and on six weeks lead time. If the demanded lead time had been less than six weeks, the customer would have needed to pay extra.

4.2.2.3.2 *Procure components*

From the components that went to the Bay Street pieces of equipment the maximum manufacturer's supplier lead time was two weeks. The manufacturer preferred to have one week of material in inventory at all times. Therefore, material had to be ordered three weeks prior to production. Orders were placed every week, based on a forecast of the next three weeks of production. The assembly of the equipment started after all required components were in inventory.

4.2.2.3.3 *Fabricate parts and assemble*

The switchboard factory had five workstations: stamping, assemble interior, assemble frame, close-up, and perform quality control. In stamping, the cover sheets and busway parts were shaped. In interior, the components were installed and wired. In cubic, the frames of the switchboard sections were assembled. In close-up, the cover sheets, and partition boards on and inside the section were installed. In quality control, the controller went through a check list and fixed small errors, but larger ones were sent back to the workstations. The ready sections were shipped the same day as they passed quality control.

4.2.3 Process performance measures

26 performance measures were measured and calculated (Table 12).

4.2.3.1 LEAD TIME OF THE DELIVERY PROCESS

The lead time of the PDE delivery process includes the design, procurement, and manufacturing lead times. The design started November 1st 2000 and the last switchboard was received May 3rd 2002, thus the time between is 79 weeks or 395 days (5 days in a week).

4.2.3.2 DESIGN LEAD TIME

The design started when the electrical engineer received the design task November 1st 2000, and ended when the electrical contract documents were completed April 1st 2001. This results in a design lead time of 22 weeks or 110 days[19]. However, even if the contract documents should have been complete, in reality, they were still relatively uncompleted and the fine-tuning of the PDE continued still during the procurement phase. Therefore, the engineering lead time is probably underestimated. Note that manufacturer's CAD drawings were approved February 19th 2002. If this had been included in the design lead time, it would have been 68 weeks or 340 days. The dates were captured from design documents.

---

[19] Significant design rework took place still in February 2002, which means that the design and engineering lead time could be interpreted to be as long as 65 weeks.

4.2.3.3 PROCUREMENT LEAD TIME

The procurement lead time is measured as the time between preparation of electrical RFQ and release of the P.O. This includes the generation and approval of shop drawings. The preparation for electrical RFQ began April 1st, 2001, when electrical design was completed. The P.O. was released in March 6th, 2002. Thus, the procurement lead time is 49 weeks.

4.2.3.4 MANUFACTURING LEAD TIME[20]

Manufacturing lead time started when the P.O. was released from the electrical contractor and ended when the equipment was received at the site. The contractor released the P.O. in March 6th, 2002, and the last equipment arrived in May 3rd, 2002. This results in a lead time of 8 weeks or 40 days. Note that if the manufacturing lead time would have been measured from P.O. (November 30th, 2001) the lead time would have been 21 weeks or 110 days.

4.2.3.5 MANUFACTURING CYCLE TIME

The manufacturer did not have data available about the pieces of equipment in Bay Street, but the plant manager estimated the cycle time to 16 hours. The cycle time did not include production planning or inventory management. I validated the order of magnitude of the cycle time by observing activity durations and waiting times of "equivalent" equipment. The average value added time was

[20] Only switchboards were considered in manufacturing phase, so that data with the three cases would be better comparable. The switchboards are relatively similar in all cases, whereas MCCs and panelboards vary largely.

about 163 hours per switchboard, because up to 8 workers were working simultaneously with a piece of equipment and some activities overlapped, the 16 hours cycle time was considered sound.

4.2.3.6 Manufacturing lead time-cycle-time ratio

The manufacturing lead time-cycle time ratio calculated from the contractor's order release is 20 (8 weeks*5days*8h/16h). The manufacturing lead time-cycle time ratio would be 52.5 (21weeks*5days*8h/16h), if it were calculated from the P.O.

4.2.3.7 Manufacturer's bottleneck procurement lead time

The longest component lead time for the manufacturer with respect to the switchboards was 12 days (5 days a week, weekends not included). This was a special switch from an outside supplier. The manufacturer's plant manager provided the data. All bulked items including some high volume breakers were stocked at the manufacturing facility.

4.2.3.8 Number of change orders

The project had 5 switchboard, 32 MCC, and 300 panelboard changes. The panelboard changes are based on an estimate of 2 changes per board. The numbers were captured from interviews with the electrical engineer.

4.2.3.9 Number of design iterations

The project had 22 documented Mechanical-Engineering-Plumbing (MEP) design iterations. All design iterations included some kind of update in PDE as well. The data was captured from design documents and interviews with the electrical engineer.

4.2.3.10 Value-added time

This measure compares the ratio between the actual hours spent for the activities and the total lead time required for the delivery process. Site installation, utility company's design and third party approvals are not included in the calculation, because comparable data could not be captured in all three cases. All the value added times are captured from interviews. I measured the ratio of the whole delivery process by adding the proportional value-added shares from design, procurement, and manufacturing together. The sum of all value added hours is 1352. For the three main phases, I used the below equation (i) to calculate the value-added time (VAT):

(i) VAT = LH/(W*LT), where

LH = sum of labor hours spent on each activity within a phase

W = number of workers that were simultaneously occupied with an activity during the phase, e.g., number of electrical engineers that were working on systems design.

LT = lead time of the phase

For design LH is 916 hours, the average W is 3, and LT is 880 hours (22 weeks), thus VAT is 35% (916h/(3 workers*880h)) or 12% when the re-designing during the procurement is considered. The VATs per facility are 7% and 2% respectively. For procurement LH is 217 hours, the average W is 2, and LT is

1960 hours (49 weeks), thus procurement VAT is 6%. Because it was not possible to verify how many workers were involved during the fabrication a slightly different method was applied to measure the manufacturing VAT[21]: Here the cycle time was divided with the manufacturing lead time. The cycle time is 16 hours and manufacturing lead time is 320 hours (8 weeks); thus, manufacturing VAT is 5%. The VAT for the whole delivery process (ii) is then calculated as the sum of the proportional shares of the tree phases:

(ii) VAT (delivery process) = [(VAT(design) * LH(design))/LH(delivery process] + [VAT(procurement) * LH(procurement)) / LH(delivery process] + [VAT(manufacturing) * LH(manufacturing)) / LH(delivery process]

=> [12%*916 hours / 1352hours] + [6%*217 hours / 1352hours] + [5% * 219 hours / 1352hours] = 10% (Figure 21). The ratio per facility is much lower, 2%.

4.2.3.11 Number of different components within one product

The total number line items were between 10-36 items per switchboard section. The numbers were taken from manufacturer's BOM.

[21] With respect to switchboards 414h were spent on the manufacturing activities.

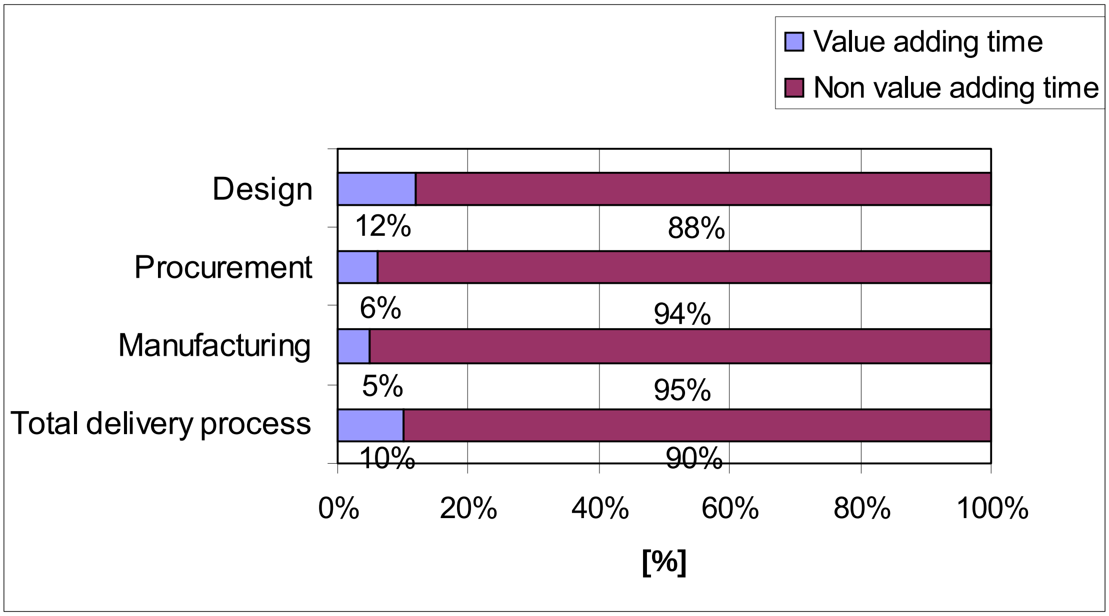


Figure 14: Value-added times in Bay Street

4.2.3.12 Percentage of Standard Components

Those components that were not manufactured by the manufacturer were considered as non-standard components. On average only 2 components per switchboard were from an outside supplier; thus, the percentage of standard components is as high as 99.5%.

4.2.3.13 Number of Batches and Batch Sizes

The unit of the batch is one job (equipment). There are 5 facilities which have 6 switchboards, 8 MCCs, and 150 panelboards, thus a total of 164 jobs The number of batches and the batch size varied throughout the project. In the design phase, the drawings were generated as one batch (with 164 jobs). Also, all the equipment was procured, and shop drawings were generated and approved as one batch (batch size 164 jobs). In the manufacturer's production planning, the process was broken down to 164 batches (each job/ equipment was one batch). Also, all the switchboards and MCCs were fabricated and shipped as a separate batch (19 batches, batch size 1) though within a week from each other. The panelboards were shipped as 2-25 jobs per batch. The sequence of the batches did not remain the same throughout the delivery process.

Table 9 Summary of performance measures in Bay Street

Performance measure	Unit	Value
Lead time of the delivery process	Week	79
Design lead time	Week	22 (65)
Procurement lead time	Week	49
Manufacturing lead time	Week	8 (21)
Manufacturing cycle time,	Hour	16
Manufacturing lead time-cycle time ratio	N/A	20 (52.5)
Manufacturer's bottleneck procurement lead time	Days	12
Number of change orders/ add-ons	N/A	337
Number of design iterations	N/A	22
Value-Added Time, total	%	10
Value-Added Time, design	%	12 (35)
Value-Added Time, procurement	%	6
Value-Added Time, manufacturing	%	5
Hours consumed in design	Hour	916
Hours consumed in procurement	Hour	217
Hours consumed in manufacturing	Hour	229
Hours consumed in the whole delivery process	Hour	1352
Number of different components in equipment	N/A	10-36
Percentage of standard components	%	99.5
Batch size in engineering	Job	164
Batch size in procurement	Job	164
Batch size in manufacturing	Job	1-25

4.2.4 Elements contributing to lead time of delivery process of PDE

The delivery lead time was 79 weeks; of this, design took 22 weeks, procurement including shop drawing approvals 49 weeks, and manufacturing including shipping 8 weeks.

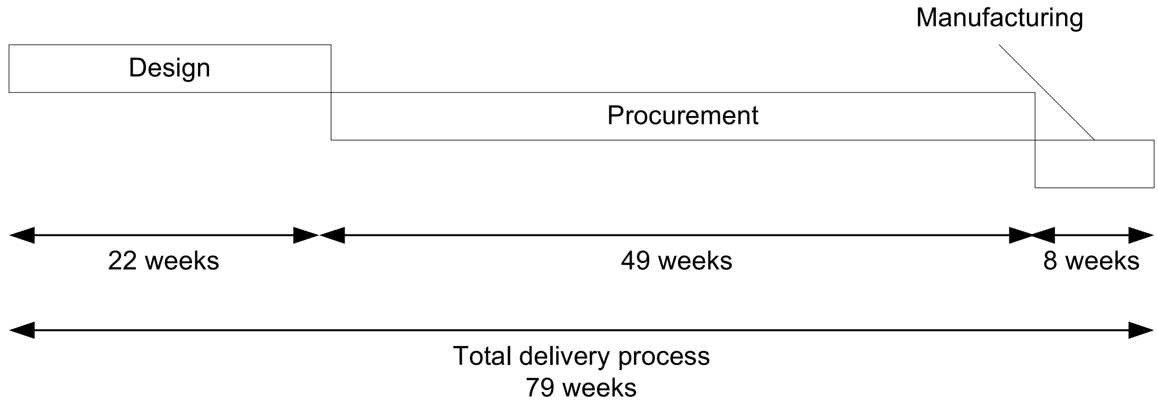


Figure 15: Design, procurement, and manufacturing lead time proportions of total delivery time in Bay Street

4.2.4.1 DESIGN

The value-added time with respect to PDE was not more than 12% during the design[22]. The design lead time was 22 weeks. In theory, the electrical design should have been 100% completed at this stage. However, after the design was put out for bid and before manufacturing, some changes took place that caused additional design and detailed engineering work. The shop drawings and the connection to the utility grid were also engineered after the RFQ. The manufacturer developed the shop drawings and the local utility company developed the connection design. The shop drawings were developed in less

[22] There was not enough data available to measure the precise VAT. Therefore, 12% is the highest possible VAT that could have been achieved. The true value is lower because I assumed that always when the activity performer had his hands on the activity it generated value, in reality, part of this time was waste (e.g., rework, data transformation). Also, all the other VAT calculations in this dissertation provide the “no more than” value.

than a week but their approval took nearly four months. If measured to the completed shop drawings, design took 65 weeks.

The connection design took almost one year. The pieces of equipment were already on site, and the site installation had started before the final connection design was ready. If measured to the completed connection design, the design for the PDE took 86 weeks.

4.2.4.2 Procurement

The value-added time with respect to PDE was 6% during procurement. The procurement lead time was 49 weeks.

From the 49 weeks procurement lead time the preparation of RFQ documents took one week. Then electrical contractor quoted three weeks. This includes the manufacturer's sales representative's and distributors' one week equipment quotation. The evaluation and negotiation of electrical work took five weeks; the generation of shop drawings took one week; and the approval of shop drawings took five weeks. The electrical contractor placed the purchase order to the distributor six months after the electrical contract was sealed, and released the order two weeks after the approval of shop drawings. Thirty-four weeks of the procurement lead time was pure waiting (Table 10).

Table 10: Relative time shares of procurement activities in Bay Street (unit: week)

Preparation of RFQ	1
RFQ electrical work	3
RFQ equipment	1
Evaluation & negotiation	5
Waiting of P.O.	24
Waiting of shop drawings	7
Shop drawing generation	1
Shop drawing approval	5
Waiting of P.O. release	2

4.2.4.3 MANUFACTURING

The value-added time with respect to PDE was 5% during manufacturing. Manufacturing lead time was 8 weeks. Because the manufacturer's sales representative had to clarify some details with the electrical contractor with respect to the P.O. and with the manufacturing plant with respect to production capacity, the manufacturer's sales representative hold the P.O. three weeks prior to releasing to the manufacturing plant. The manufacturer's cycle time was only 2 days, but the plant wanted to reserve up to five weeks of buffer time. Three weeks buffer time guaranteed that all components could be purchased before fabrication of the equipment. One to two weeks buffer time was used as an emergency buffer in case of an urgent order or problems in manufacturing, and to level production load on the factory. After the equipment was fabricated, 24 hours was needed for shipment of one switchboard or MCC. Each switchboard and MCC was shipped separately, but several panelboards were batched into one shipment. Therefore, panelboards sometimes waited in the manufacturing plant few days before the entire batch was ready for shipment.

4.2.5 Causes of long lead time

The value-added time of the whole delivery process was 10%. If one puts all activities head-to-tail with no waiting time in between, the whole delivery process would have taken only 8 weeks. Why then did it actually take 79 weeks for the delivery process? Explanations can be traced to all the various phases from design to manufacturing. Generally, it can be said that there were significant gaps in the stakeholders' comprehension of the delivery process and even their own task. A case in point is the design value-added time with respect to switchboards, where the electrical engineer gave three different values ranging from 92h to 564h based on the request technique.

First, the electrical engineer was asked to provide the total number of labor hours that was spent on the design of switchboards the response was 564 hours. Second, the electrical engineer was asked to provide labor hours for each design activity separately, which added up to 370 hours. Third, the design hours of switchboards was requested from the electrical engineering firm's accounting department, which was only 92 hours for switchboard[23]. A similar example was identified regarding the value-added time that the electrical contractor needed for quoting the job. The electrical contractor repeatedly insisted that it took him 40

---

[23] After several interviews, document reviews, and adding the redesign hours it was agreed that the design hours for the PDE is 916.

hours but according to the PM company, this time was exaggerated. Accordingly, there were differences in the perception between the interviewees, although it was not clear if the difference was due to lack of understanding or misrepresentation.

4.2.5.1 DESIGN

Design did not appear to be considered as part of the delivery process. For example, design batch sizes were not structured to speed handoffs and downstream processing. Nor were design synchronized with site installation. Further, in this phase the lead time was extended by changes due to early commitment, lack of knowledge, coupling of PDE design with other systems, and outdated practice of auxiliary design[24].

4.2.5.1.1 CHANGES DUE TO EARLY COMMITMENT

The electrical design had to be completed prior to the RFQ of electrical work, which was placed 18 months before the completion of the construction project. At this stage, only a few of the nearly 80 tenants were known; evidently the electrical engineer had to make assumptions regarding some input values, e.g., breaker sizes, which he had to corrected later when the information became

---

[24] By auxiliary design I mean the supporting design that is not directly linked to the delivery process of the power distribution equipment but has to do with the facility. It must be completed before the equipment can be put to use. Example of auxiliary design is the utility company's connection design. Similarly, auxiliary approvals are, for example, city approvals of electrical drawings and third party equipment inspections.

available. However, because of the sequential process it took a long time before a single change got handled and implemented. The information had to be passed to the PM company, the electrical contractor, the distributor, and the manufacturer. At every organizational interface some negotiations regarding the implications had to take place. In conclusion, the information was both processed multiple times and had to wait to be processed multiple times. As a result, transmitting information and information waiting time consumed a major part of the total delivery time.

4.2.5.1.2 CHANGES DUE TO LACK OF KNOWLEDGE

The electrical engineer was based in Kansas and was familiar with the utility company application process there, but lacked experience and knowledge about the requirements and the application process of the utility company in the San Francisco Bay Area. Therefore, a consultant was hired by the A/E firm to deal with all the utilities. Unfortunately he also was not familiar with the local requirements or the local utility company's application process. This delayed the connection application and design by more than six months and also caused additional work for the electrical engineer, the PM company, the electrical contractor, and the utility company. In fact, the PM company took over coordination with the utility company, to avoid delaying of the whole construction project.

4.2.5.1.3 Coupling of PDE design with other systems

In many phases of the process, numerous closely related tasks were coupled to the PDE, which significantly increased the complexity and lead time of the process; and vice versa, the longer lead time made the process more complex. In the design phase, the electrical engineer generated all electrical drawings, including floor plans and lighting schedules before the next phase, procurement of the PDE, commenced. Work related to the PDE was only about 5% of the electrical engineers' overall task. Also, any delay of input values or problems in any of the electrical systems delayed not only that particular system but also the whole electrical design including the PDE.

The utility company has also coupled several other utilities, such as gas, high-speed cable, and telephone cables, with the power connection. These couplings and dependencies were even more time consuming and complex than the ones by the electrical engineer because several different organizations participated in the design, and the coordination between the organizations was hierarchic and sequential. Accordingly, the more the PDE is integrated to other systems, such as automation, the more dependencies there will be making the design coordination more complex, which then tend to extend the design lead time of the PDE.

4.2.5.1.4 Outdated practice of auxiliary design and approval

Several interviewee's pointed out that the process to design PDE has been stagnant for commercial buildings for a long time, even as construction projects have become more complex, faster, and more cost sensitive. Many of the auxiliary designs and approvals, such as the utility company's connection application and connection installation, and city approvals of electrical drawings, have adapted to and are organized according to the sequential delivery process, where design has to be completed prior to the start of construction. As a result, there has been no flexibility for design changes without incurring a time penalty. Hence, every time the design was updated, it extended the lead time of auxiliary design and approvals.

The utility company's lead time for the connection application is normally 25 to 30 weeks. The utility company was not able to compromise on this due to its own lengthy and sequential internal procedures. Two other issues made the process even more tedious and prone to changes. First, the utility company had coupled several other systems (gas, telephone, cable). Second, all input data was required when the application was placed. There was a very high probability that some of the input data would change during the six months period. In a hierarchical and sequential process, as a change occurs, the job is returned to the beginning of the process and the original six months lead time increases rapidly. On Bay Street, it went up to over a year. Similar characteristics were identified in the city approvals of electrical drawings, which took 3 months.

4.2.5.2 PROCUREMENT

Design-bid-build (DBB) where the procurement method is based on competitive bidding was applied as the project delivery method. The competitive bidding forced the electrical engineer to commit early to the design and to use a large document batch size; namely, the set of bid documents. Also, lack of sequencing, and the way the industry was organized extend the lead time. As a result the procurement of the equipment consumed most of the delivery lead time and generated much of the process waste.

4.2.5.2.1 Competitive bidding

In comparison to design-build, DB, DBB increased the lead time of the delivery process in three ways. First, in DBB there are two bidding rounds compared to one in DB; one for electrical design and one for installation. In DB, the electrical design and installation are bid or negotiated simultaneously. The extra bidding (electrical work) took about one month on the Bay Street project. Second, if the electrical contractor designs and builds, he can design the electrical work so that it optimally supports his production methods. This will improve site productivity, e.g., for the installation of the switchboard by reducing the need of wiring and cabling on site, and so the shipment of the equipment is not required so early allowing more time for design completion[25]. Third, DBB requires that the design be completed in a very early phase, before the second round of bidding. This leads to a longer forecast window and increases the probability of changes.

4.2.5.2.2 Exclusion of flexibility

In competitive bidding, every step of the delivery process is tightly competed for (project management, electrical work, equipment, etc.). As a result, the equipment is customized just for the requirements that prevail during the bid

---

[25] When less time is need to for the installation the equipment does not need to be so early on site, also the P.O. and the P.O. release can be placed later with more up to data information.

period and not for needs that may occur later, e.g., if additional capacity is needed due increased use of the building. As a result, the owner loses his flexibility for changes, and probably ends up spending the savings achieved in competitive bidding on change orders. On Bay Street, the change order cost of electrical work was about 40% of the contract price; the changes in PDE about 8% of contract price.

4.2.5.2.3 DOCUMENT BATCH SIZES

Lumping not only all the PDE into one document batch but also all electrical work into the same batch increased the waiting time for the PDE, and hence helped reduce the value added time of design and procurement. In the procurement phase, the project manager firm used less than 5% of their time on the switchboard and the rest of the procurement time went to other electrical services. The RFQs included all electrical work, not only the PDE. Similarly, when the electrical contractor quoted and the PM company evaluated the quotes and negotiated the electrical contract, only a small part of the total time went to PDE. Finally, the approval of the shop drawings was conducted simultaneously for all five buildings. Handling multiple pieces of equipment and systems simultaneously increased dramatically the waiting time of single equipment during the procurement phase.

4.2.5.2.4 LACK OF SEQUENCE

Even though the original schedule had several months' difference between the installations of the switchboards, they were all procured and delivered at the same time.

4.2.5.2.5 INDUSTRIAL ORGANIZATION

The commercial relationship between the electrical contractor and the PDE manufacturer was complex. The manufacturer had trade agreements with distributors, who were allowed to represent the manufacturer's products. The electrical contractor had to purchase equipment through the distributor. The distributor purchased the switchboard from the switchboard manufacturer's sales representative, who then placed the order to the manufacturer. This meant that there was a very long path from the buyer (owner) to the seller (manufacturer), and even a longer path from the end-user (tenant) to the equipment manufacturer. A sequential process like this did not have much flexibility to cope with changes or postpone inputs. Moreover, it delayed decision making causing significant uncertainty during the site installation. The electrical contractor's description is a case in point: *"We do not have a week schedule on this project because we can't keep up with changes"*.

4.2.5.3 MANUFACTURING

Besides the manufacturer's supplier lead times, the rigid organizational structure and bureaucracy, where information had to pass through several people before it reached the shop floor, was one of the main causes of the eight week manufacturing lead time. However, there are also some erroneous beliefs about the demand and capabilities among the players. One erroneous belief is that the more upstream one goes the PDE supply chain, the less the players are willing to reduce lead time. The manufacturer stated that they would be ready to further reduce their lead time but the market has not made that demand.

Finally, the switchboards arrived much earlier than they were actually needed (2 weeks-6 months). This triggered a chain reaction in all electrical work, which got out of sequence and the electrical contractor was not able to maintain an efficient workflow. The electrical rooms also had to be rebuilt several times due to changes in the owner's requirements, adding another complicating factor.

4.2.6 Opportunities to improve the process: Future state

Based on interviewees' suggestions and applying the TFV theory, considerable improvement could be achieved, especially in the design and in the procurement phases.

4.2.6.1 Design

Some of the improvement suggestions of the design phase will require a change in the procurement phase as well. Some of the improvement suggestions will require organizational restructuring.

4.2.6.1.1 Postponement of detailed engineering

The changes regarding PDE did not occur in system design but rather in detailed engineering. Hence, in anticipation of design changes it seems to make sense to postpone the detailed engineering as close as possible to the installation. On Bay

Street, a postponement of up to 44 months could have been possible with a different procurement strategy, smaller design batches, and a redesign of the auxiliary design and approval process (see chapter 4.2.6.2 Procurement).

4.2.6.1.2 Reduced batch size

Because none of the switchboards or MCCs was installed simultaneously, there was no need to have the detailed engineering of them ready simultaneously. Alternatively, by reducing the design batch to one electrical room or switchboard instead of six, the design cycle time of one switchboard could have reduced from 22 weeks to less than four weeks.

4.2.6.1.3 Redesign of auxiliary design and approval process

In the future, the city and the utility company may need to reconfigure their process in a way that satisfies various project demands, especially those that require rapid project execution. Standardized connection design and/or Internet based application processes are potential future directions. E.g., the city of Sunnyvale, California uses on-line permission of drawings. Also, there may be cases where the city does not need to approve the electrical design at all. E.g., the city of Helsinki, in Finland, does not anymore approve the electrical design but requires a third party inspection when the installation is completed. Streamlining the city approval may also save the city resources. In the production theory terms, the three first design improvement suggestions would address the flow view of the process.

4.2.6.1.4 Recognition and inclusion of local knowledge in the design phase

The PM company, the electrical contractor, and the manufacturer's sales representative had extensive knowledge about local requirements and practice. Had any one of these organizations been actively involved in the design phase, their local knowledge could have avoided change orders and also saved months from the utility and city approval process.

4.2.6.1.5 Design coordination across disciplines

It is advantageous to have an integrated design organization, like the A/E firm where architectural, mechanical, and electrical engineering performed within the same organization. It seems to be effective in design coordination. Particularly, because formal approvals and hierarchical document flows can be reduced among the design disciplines.

4.2.6.1.6 Application of pricing and configuration software

It would be beneficial if the A/E firm would be given access to the manufacturer's pricing and configuration software. It could already during the system design evaluate options, and check dimensions, configurations and even the price of investigated solutions. Then they could keep open as many options as possible to absorb future changes. In the production theory terms, these last three design improvement suggestions would address the value view of the process.

4.2.6.2 *PROCUREMENT*

There seem to be a significant opportunity to improve the current practice of procurement and approval of shop drawings. Probably, a redesign of the organizational relations has to take place to streamline the document flow so that the information flow between the electrical engineer and the manufacturing plant is significantly shorter. This could be achieved for example by reducing the number of players that need to be involved in the process and reducing the document batch size.

4.2.6.2.1 *ALTERNATIVE PROCUREMENT METHODS*

Some considerable disadvantages were identified when the PDE was procured through several competitive bids. Alternative procurement strategies, e.g., electrical contractor has a design-build responsibility, are proposed. This would allow early involvement of contractor and manufacturer, and allow a fixed price for the electrical system without the penalty of premature design decision.

Another alternative could have been that the PM company, which actually had in-house design capabilities, would have had a design-build role. This could have reduced the need to pass documents via electrical contractor and distributor to the manufacturer. Alternative procurement methods could have theoretically[26]

---

[26] In reality, it is difficult to predict precisely how much time is needed for the procurement and approval of shop drawings; therefore, at least a few weeks of buffer time would probably always be left for procurement. Thus, to completely eliminate the 35 weeks waiting between purchase order and order release may not be feasible.

eliminated the whole 34 weeks waiting between the purchase order and order release.

4.2.6.2.2 REDESIGN OF ORGANIZATIONAL RELATIONS

The pattern from the manufacturer's shop floor to the electrical engineer-of-record is slow and wasteful. E.g., if the manufacturer's plant needed clarification of something regarding the equipment, up to 10 handoffs were required before the information was passed to the electrical engineer and back (Figure 9). This supports for further exploration of alternative relationships and structures. For example, could the distributor be cut off, because the relation with the electrical contractor and the manufacturer's sales representative were well established and they were able to shift matters among themselves. Another possibility to explore is if the manufacturer's representative could deal directly with the electrical engineer-of-record or the electrical engineer could deal directly with the manufacturer's plant. In these cases, six activities from the current approval process could be eliminated, and reduce the procurement lead time by up to three weeks[27].

4.2.6.2.3 STREAMLINING THE DOCUMENT FLOW

The rearrangement of the organizational structure would also help to streamline the document flow. Particularly, if the electrical engineer-of-record

---

[27] The time between the shop drawing's release from the manufacturer and the electrical engineer's approval stamp was five weeks. I assume that the electrical engineer had the shop drawings only two weeks and rest of the time the shop drawings were in transit or waiting.

approves the shop drawings, there is little need to pass the drawings first to the distributor, then to the electrical contractor, then to the PM company, and then finally, to the electrical engineer. The manufacturer could send the shop drawings directly to the electrical engineer, and he could send the approved shop drawings directly to the manufacturer's plant. This would eliminate five activities from the current procurement task, and reduce the procurement lead time by up to six weeks. An alternative would be to send the documents electronically between the parties; however, this does not eliminate the delay caused by the "waiting of being processed". The procurement related improvement suggestions are based on a flow view of the process.

Table 11summarizes all the improvement suggestions in the procurement phase and their potential impact on the delivery lead time. Up to 44 weeks of the current 49 weeks procurement lead time, and 11 of the current 48 activities could be reduced by considering the flow and value concepts in addition to the transformation concept of production. The equipment price may be slightly higher[28] but net savings would come from a reduced process cost. The future process is illustrated in Figure 16.

---

[28] The reason why the equipment price may be slightly higher is that it is not fiercely competed through competitive bidding and some suppliers may use higher margins in negotiated contracts than competitive bidding.

Table 11: Summary of key improvement suggestions for Bay Street (The numbers in parenthesis are the original numbers from the currents state map)

Improvement suggestion	Number of reduced tasks	Reduced lead time [weeks]
Decoupling	N/A	35
Redesign of organizational relations	6	3
Document flow	5	6
Total	**11 (48)**	**44 (79)**

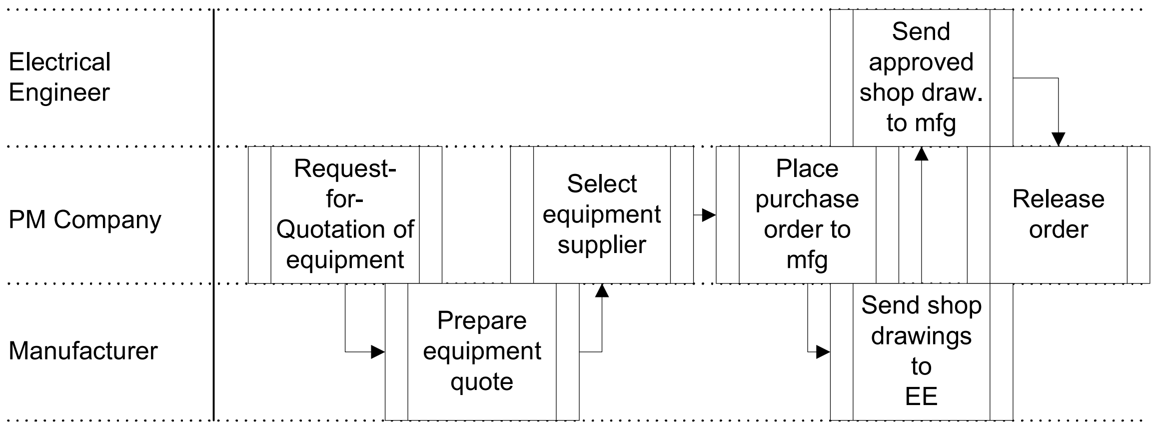


Figure 16: Streamlined procurement process in Bay Street.

4.2.6.3 *MANUFACTURING*

The manufacturing including shipping should be sequenced and released according to site production. Also, the manufacturer may need to consider following alternatives; try to cut in half its supplier lead time, order components based on real demand, and streamline the information flow from customer to shop floor, in order to further reduce the manufacturing lead time. The streamlining of information may be possible with the help of the pricing and configuration software, especially if it is web based. Finally, the manufacturer need to more aggressively market its capabilities for facilitating the delivery process, and make those capabilities criteria in the procurement decision alongside purchase price.

4.2.7 Summary

It appears to be the case that the delivery process of PDE could be better planned and executed. An indication of the potential and need for improvement is delivery process lead time or duration, which was 79 weeks, of which at most 10% was value-added, even if the competitive bidding[29] is considered as value added. The manufacturing methods and lead time were not seen as big contributors to the long delivery lead time compared to the current design and procurement practices. The main causes for the long lead time were:

- Coupling of the design and procurement of PDE with other systems.
- Large document batches.
- Failure to 'pull' detailed engineering to installation.
- Unsynchronized document and material flows.
- Bureaucratic and hierarchical organizational structures and relationships.
- Cumbersome and time consuming shop drawing approval process.
- Cumbersome and time consuming auxiliary design and approvals process.
- Use of competitive bidding as a procurement method.

[29] It is questionable if the competitive bidding is adding value at all.

4.3 CASE 2: NOVO

Novo is a 300,000 square feet office building for a large IT-company in Helsinki, Finland. The building has 10 floors of which 3 are subsurface. The office space is around 234,000 square feet and provides workspace for about 1,000 employees; the rest is subsurface parking structure. The PM company operated as a developer and launched the project as a Design-Bid-Build. In October 2001, it hired an architect and engineers to handle the design of the project. The owner and tenant got involved in January 2002, though the contract between them and the developer was signed in April 2002. After the owner got involved, the electrical engineering firm was changed, in January 2002. Construction started in July 2002 and will be completed in May 2004.

4.3.1 Overview of the delivery process

The project has one electrical room, on the first sub-surface floor, that houses two Kuopion Kojeisto low-voltage switchboards. The emergency generator and seven MCCs are housed in two mechanical rooms on the eighth floor. The two switchboards both have a capacity of 2500A but have different configurations. The schematic electrical design started in October 2001, but specifications for the electrical power system and equipment did not begin until January 2002. The contract drawings for PDE were finished in December 2002. The pieces of equipment were designed simultaneously for the most part. The electrical contractors were selected in March 2003. The electrical contractors signed the equipment purchase contracts in June 2003, and the switchboards were delivered to the site in the beginning of August 2003. Switchboards and MCC were ordered separately from the panelboards, and the pieces of equipment were delivered based on the sequence of the site installation. The installation of the first switchboards started in August, and the installation of the MCCs and panelboards started in September.

4.3.2 Description of current state

The delivery process of the PDE had three main phases: design, procurement, and manufacturing. The outcome from the first phase was equipment specifications or contract documents. The outcome from the procurement phase was approval of shop drawings; there was no separate release of the purchase order. The outcome of the third phase was equipment-on-site (Figure 17). The complete current state process map is presented in Appendix 2.

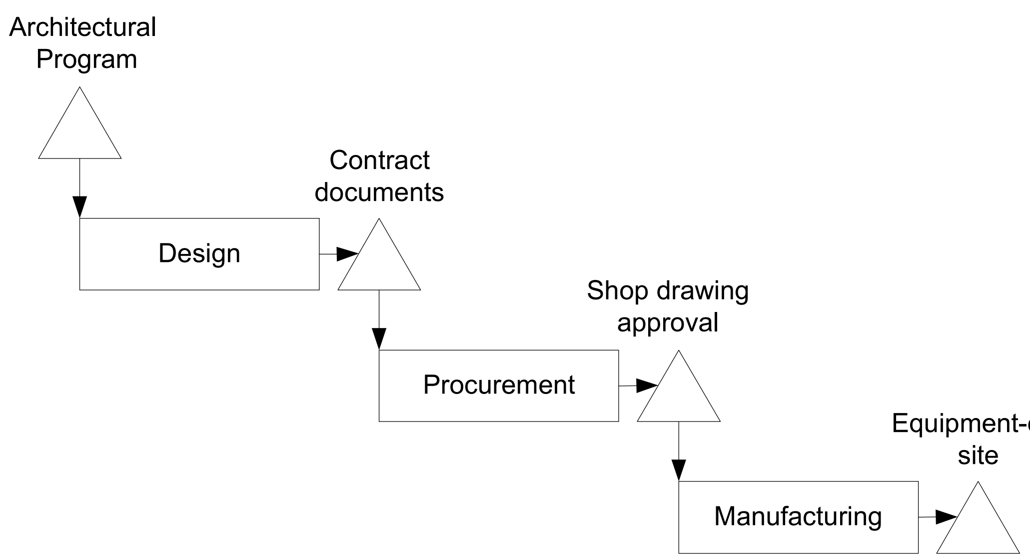


Figure 17: Main phases in the delivery process in Novo

4.3.2.1 *DESIGN*

For the Finnish construction market this office building development is considered to be large. However, because there was only one owner and one tenant, the design coordination was somewhat eased. As the owner got involved he required a “price check” of the design firms. Thus, based on the schematic design of the initial electrical engineering firm, competitive bids were requested on electrical design. The PM company favored the initial electrical engineering firm, because they had an established business relation and they were aware of each other’s work methods. Nevertheless, the initial electrical engineering firm did not place the lowest bid and was not selected to continue the work.

The owner and tenant did not have resources to provide timely input data for the PDE design, which led to waste in the process, and to a rush towards the end of the design. Also, because of lack of standardization and automation the detailed design, 3-line diagrams, were time consuming and tedious. Moreover, four companies, the initial electrical engineering firm, the actual electrical engineering firm, the electrical contractor, and the equipment manufacturer, performed the electrical design or detailing, which added steps to the design process.

The specific tasks within design the equipment were (1) develop preliminary system design, (2) evaluate preliminary system design, (3) calculate electrical loads, (4) design MCC, (5) define connections and tariff, (6) design equipment, and (7) fine-tune equipment documents for bidding.

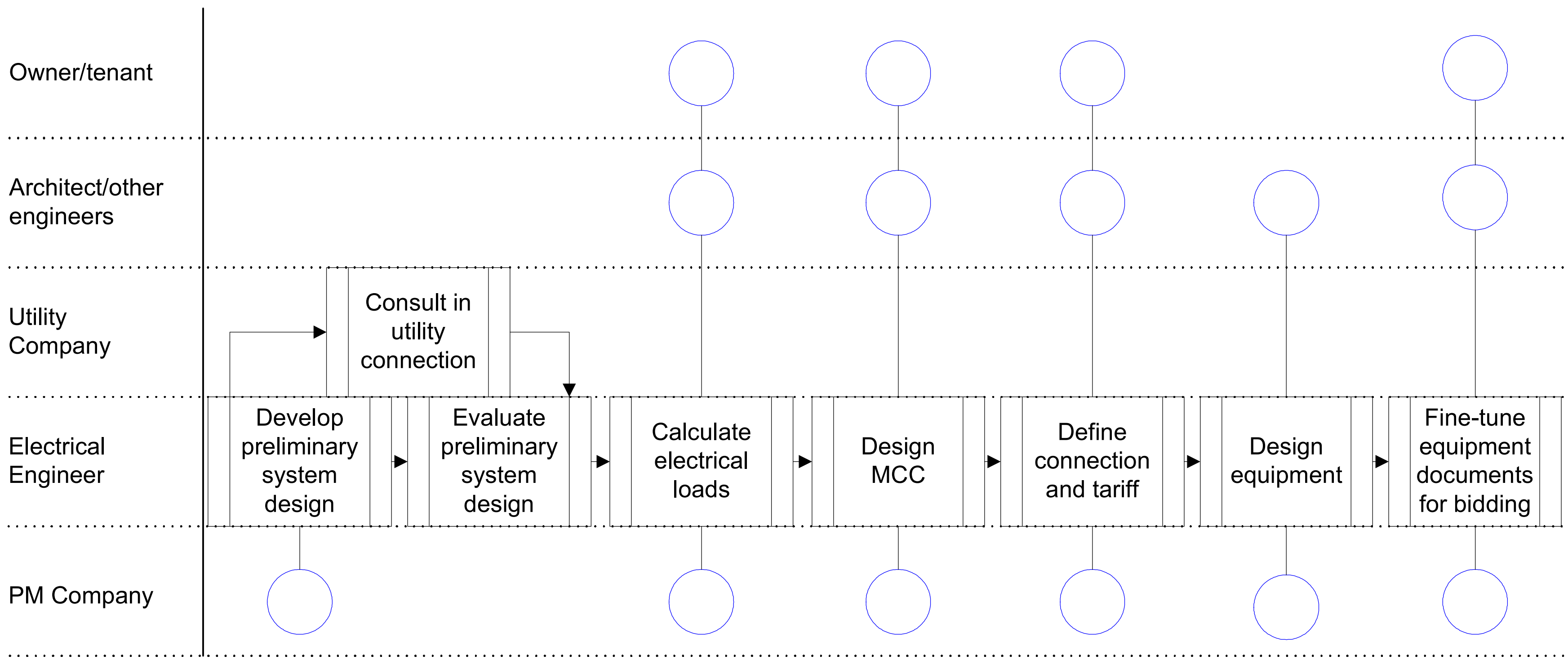


Figure 18: Design activities in Novo

4.3.2.1.1 Develop preliminary system design

The electrical engineer contacted the local utility company to clarify connection alternatives to the utility grid. Then based on the architectural program he specified the main requirements and the scope of electrical design. Then he preliminarily grouped the PDE and specified space requirements. Later the architect adjusted the space requirements. Until this point, the initial electrical engineering firm conducted the work.

4.3.2.1.2 Evaluate preliminary system design

The electrical engineering firm awarded the contract came on board and analyzed the existing electrical design and specifications. It analyzed each space separately and defined a more detailed electrical design, which took into account the type of air conditioning and elevators, etc.

4.3.2.1.3 Calculate electrical loads

The electrical load calculations were performed floor-by-floor. The electrical engineer got input from the owner, architect, mechanical engineer, audio-visual designer, fire control engineer, and lighting engineer.

4.3.2.1.4 Design MCC

The control logic of motors was defined. The main part of the design considered lighting and air-conditioning related motors, but also elevator, fire control, pumping, and automation related parameters were defined.

4.3.2.1.5 DEFINE CONNECTIONS AND TARIFF

The electrical engineer defined where and how (low/high voltage) the building would be connected to the utility grid and how many meters would be used, because it impacted the electrical power tariff. The owner wanted to have separate meters on every floor so as to have the flexibility to rent the floors separately. This had a cost and equipment configuration impact.

4.3.2.1.6 DESIGN EQUIPMENT

The electrical engineer developed the elevation drawings (one-line diagrams) and specified the configuration and component requirements for each piece of equipment. He also fixed the dimensions of the equipment. At this stage, the owner had to decide if he needed an emergency generator and UPS.

4.3.2.1.7 FINE-TUNE EQUIPMENT DOCUMENTS FOR BIDDING

Finally, before the quote request, the electrical engineer fine tuned all the documents, made sure that the equipment could be moved from outside to its final location, and developed detailed specifications such as labeling of cables and quality requirements.

4.3.2.2 PROCUREMENT

The procurement of the PDE went through four levels of competitive bidding. First the PM company requested a quote directly from the manufacturers. Then, the PM company requested from the electrical contractors a quote that included besides site installation the purchase of the PDE. The electrical contractor requested preliminary but binding quotes directly from the manufacturers. Finally, after the electrical contractor had been selected, the electrical contractor again requested quotes directly from the manufacturers. The procurement method was based on competitive bidding, and it consumed a large portion of the delivery time and a significant amount of resources.

The specific task in the procurement phase were: (1) Request-for-Quotation (RFQ) of PDE 1, (2) preparation of equipment quote 1, (3) RFQ of electrical work, (4) RFQ of PDE 2, (5) preparation of equipment quote 2, (6) preparation of electrical work quote, (7) selection of electrical contractor, (8) preparation of 3-line diagrams, (9) review of 3-line diagrams, (10) RFQ of PDE 3, (11) preparation of equipment quote 3, (12) selection of equipment supplier, (13) preparation of shop drawings, and (14) review of shop drawings (Figure 19).

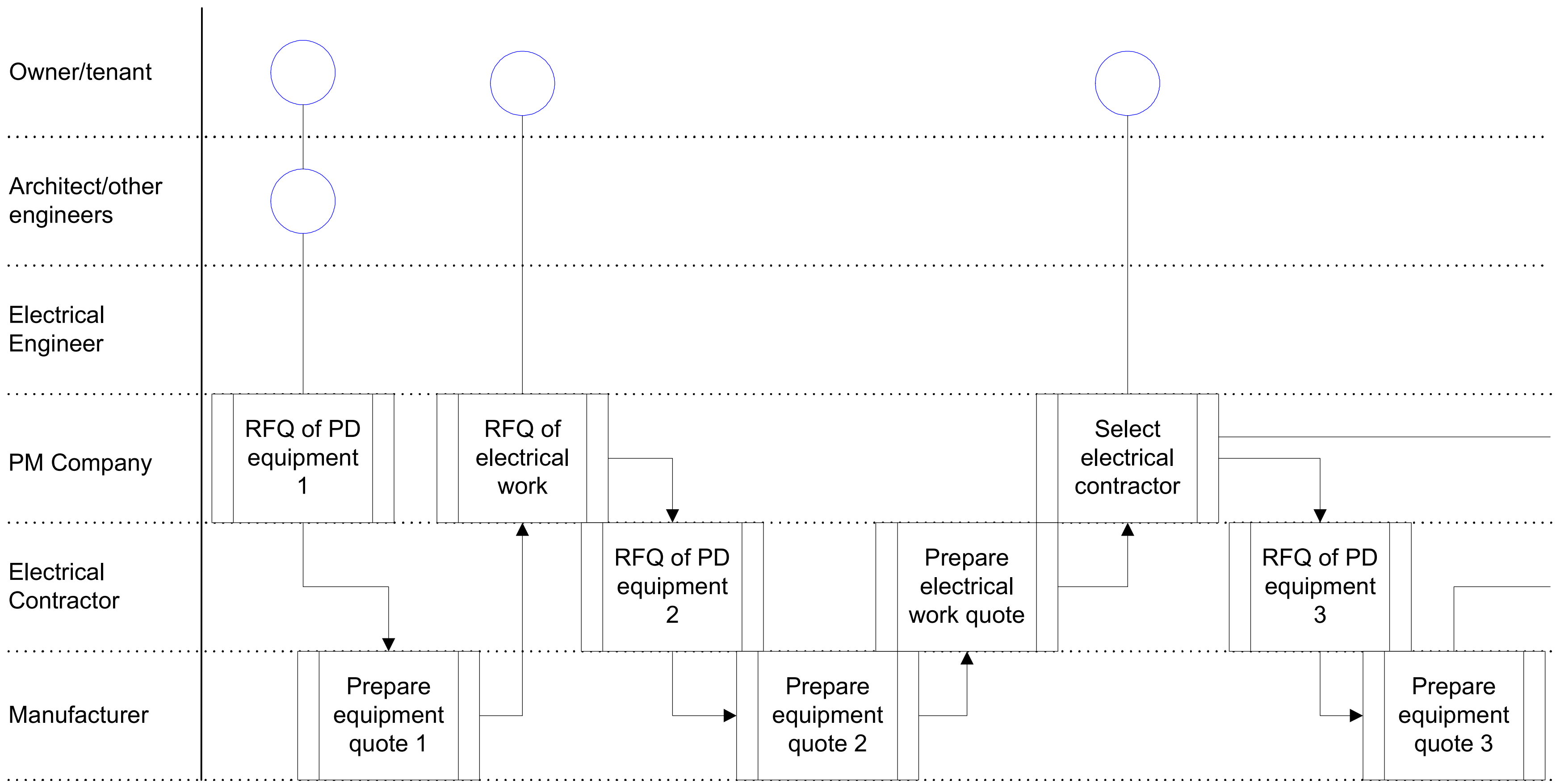
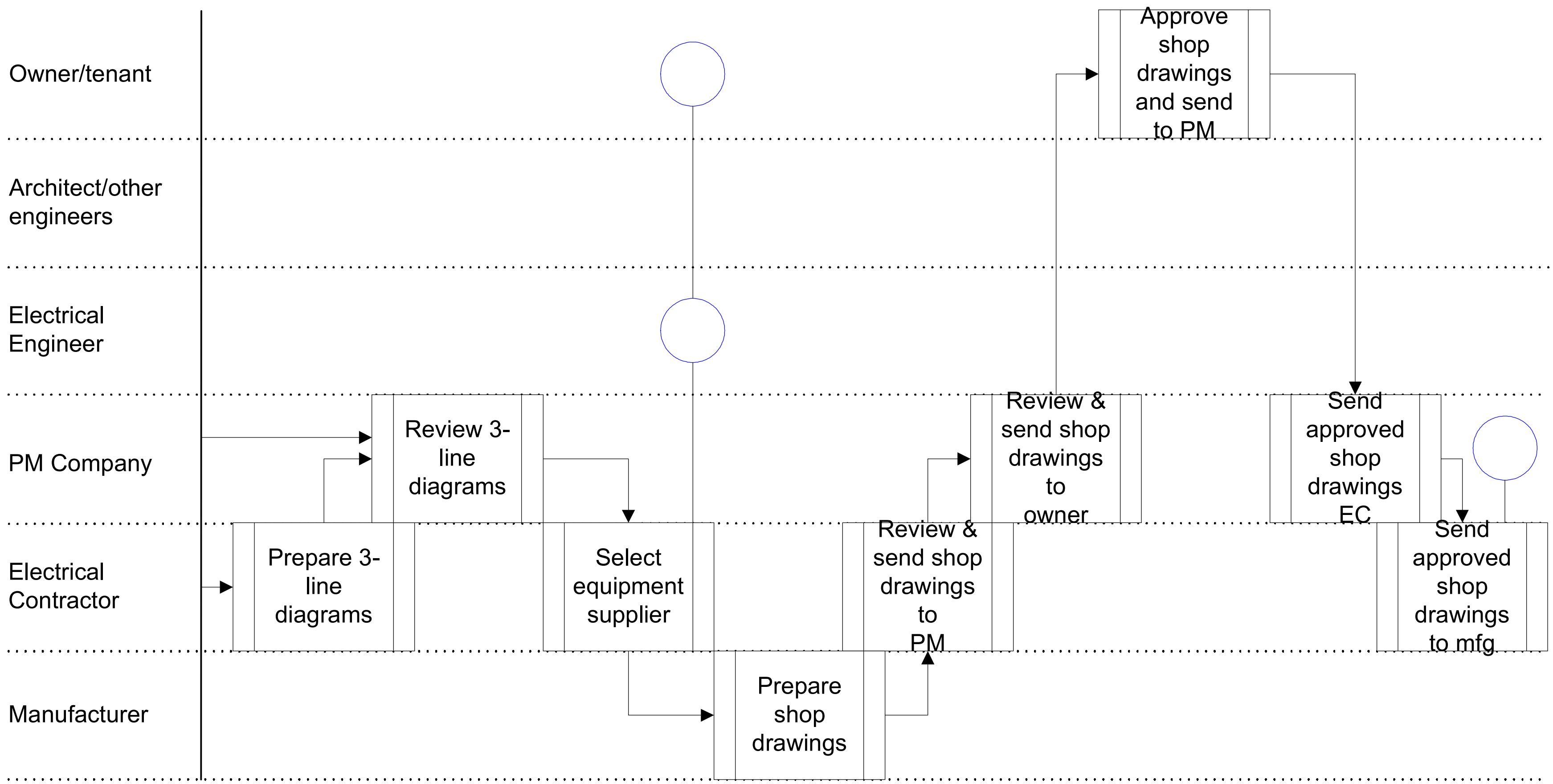


Figure 19: Procurement activities in Novo



Procurement activities in Novo (Figure continues)

4.3.2.2.1 *Request-for-Quotation of PDE 1*

The PM company prepared the bid packages. There were six packages for electrical work of which one was PDE. Quotes were requested from six manufacturers.

4.3.2.2.2 *Preparation of equipment quote 1*

In general, even if the symbols in the RFQ documents are mostly the same, the technical solutions vary depending on the electrical engineer's skills and habits. Although there were some possibilities to improve the design solution, the manufacturer did not propose any at this stage so that the quote was comparable with other manufacturers' quotes. Then CAD drafts were generated to provide dimensions of the equipment and a component list was developed. The quote separated labor and material cost.

4.3.2.2.3 *Request-for-Quotation of electrical work*

After the PM company received the manufacturers' quotes, he sent 10 RFQs for the electrical work, which included the PDE. The PM company requested the quote from the manufacturer prior to the electrical contractors' requests, because some of the larger electrical contractors may demand the manufacturer to quote solely for them if they purchase the equipment. Hence, the PM company may end up paying a higher price than by procuring directly from the manufacturer.

4.3.2.2.4 *Request-for-Quotation of PDE 2*

The electrical contractors called two manufacturers for a preliminary but binding quote[30]. The manufacturers had already received the RFQ documents from other electrical contractors.

4.3.2.2.5 *Prepare equipment quote 2*

The manufacturer gave the same quote for all electrical contractors; basically he used the quote he had placed for the PM company a month earlier.

4.3.2.2.6 *Prepare electrical work quote*

Only 10% of the electrical contractor's time went to power distribution related issues; most of the time went to the take-off of cable, wire, and other electrical equipment. Also, in the four-week bidding period, only 40h were used for actual work. The rest was waiting for inputs.

4.3.2.2.7 *Select electrical contractor*

Because the electrical contractors' PDE bids were lower than the manufacturers', the PM company decided to purchase the equipment through two electrical contractors. The PM company selected one electrical contractor to install the main power distribution including switchboards and another electrical contractor

[30] The quote was preliminary because the electrical contractor had not yet been awarded, but the manufacturer's unit prices were binding in case of the electrical contractor got awarded. The electrical contractor prepared his own quote then based on this.

to install the local power distribution including MCCs and panelboards. The lowest bids were selected.

4.3.2.2.8 Prepare 3-line diagrams

After the equipment manufacturers were chosen and their bill-of-materials were available, the electrical contractor prepared the 3-line diagrams. Even if the electrical contractors had old diagrams from which they could cut and paste part of the diagrams, they had to go through all the component labels because every manufacturer has different labels. This was a tedious process not only because it included a few thousand CAD drawings, but also because most of the changes occurred while the 3-line diagrams were generated.

4.3.2.2.9 Review 3-line diagrams

The PM company reviewed the 3-line diagrams. No detailed review took place. Only the most critical parts were reviewed.

4.3.2.2.10 Request-for-Quotation of PDE 3

After the electrical contractors were awarded the job, they again requested quotes from five manufacturers. At this stage, some of the PDE changes had already taken place.

4.3.2.2.11 Prepare equipment quote 3

Because of major changes took place after manufacturer's second quote, one week of work had to be spend to update the initial quote.

4.3.2.2.12 Select equipment supplier

After four months of evaluation and negotiations the lowest bids were selected and purchase orders were written. The two electrical contractors selected different manufacturers to deliver the equipment. The purchase orders also included precise shipping dates; hence no separate order release was required.

4.3.2.2.13 Prepare shop drawings

The shop drawings had been prepared already at the bidding stage, and they included BOM and front and side views of the boards. The original shop drawings were just updated after the equipment manufacturer was selected.

4.3.2.2.14 Review shop drawings

The owner reviewed only the BOMs and approved them. Also, the PM company reviewed the component lists and made sure they were within the project budget and scope.

4.3.2.3 Manufacturing

The switchboards were fabricated in the same facility but by a different manufacturer as the MCCs and panelboards. All the MCC and panelboards were fabricated in the same location. Due to the relatively small size of the manufacturers the information flow between sale and assembly was short. The sales representative visited the shop floor daily. Even if most of the key components came from abroad, their lead time was only 2-3 weeks. The manufacturers seasonally adjusted the manufacturing lead time. During the winter months, when demand is low, the lead time could drop to 3 weeks. During the summer months, when demand is high, the lead time could go up to 12 weeks.

The specific tasks in manufacturing were: (1) Procure components, (2) Plan production, and (3) Fabricate parts and assemble (Figure 20).

4.3.2.3.1 PROCURE COMPONENTS

Most of the key components are manufactured abroad, in France, Italy or Germany, and they are procured based on actual demand through an importer. The bulk items and high demand breakers are bought based on monthly forecasts. The manufacturer carried on average a two weeks inventory.

4.3.2.3.2 PLAN PRODUCTION

Production scheduling is based on First-In-First-Out (FIFO) methods; but sometimes, key customers take priority. The production is planned based on the average labor hour capacity per week, for example, if the manufacturer has 40 workers, who work 40 hours a week, on the shop floor, the manufacturer has 1600 shop floor hours available. Then the manufacturer can calculate how many equipment he is able to fabricate per week, because he has a database of required installation hours per equipment.

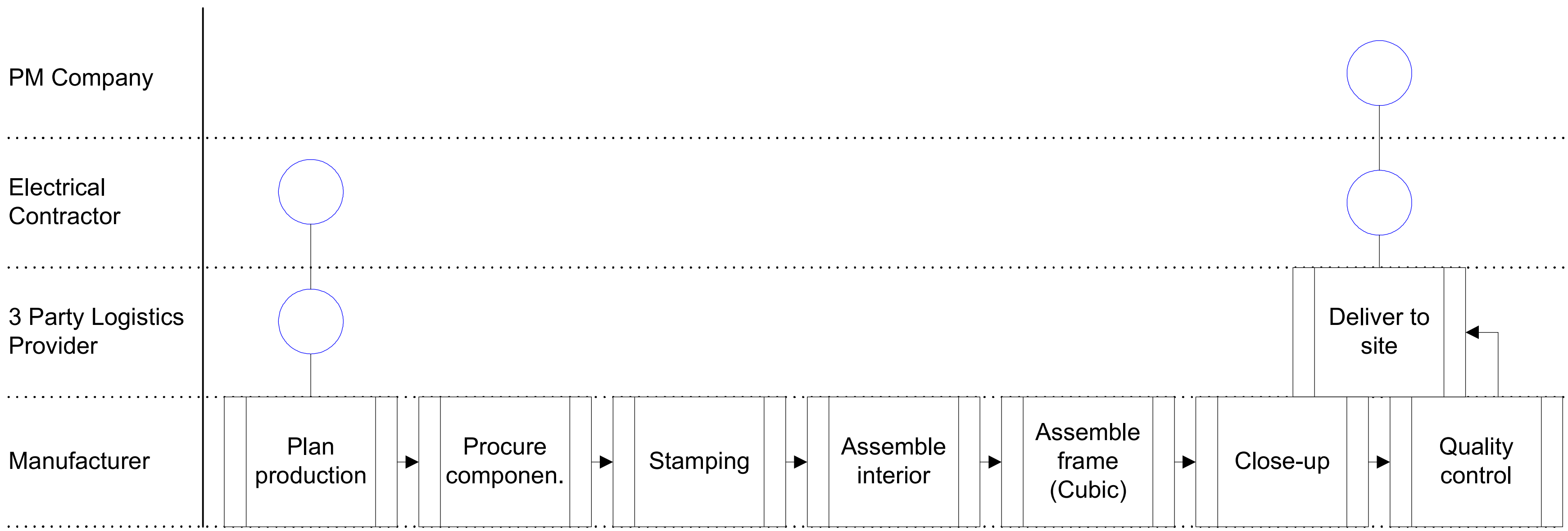


Figure 20: Manufacturing activities in Novo

4.3.2.3.3 Fabricate parts and assemble.

The switchboard factory had four workstations: stamping, framing, assembling and wiring, and quality control. In stamping, holes were punched in the cover sheet. The sheets were delivered cut and bent. In framing, the aluminum structure of the whole line-up was built and horizontal buses were installed. In assembling and wiring, one or two workers installed all the components and vertical buses, and wired the equipment. In quality control, the controller inspected the quality of the equipment with the help of a check list. The cycle time for the switchboards was 12 days. All the switchboards and MCCs were shipped separately the same day they passed inspection and were normally on the construction site within 12 hours. Panelboards were shipped as 4-10 pieces of equipment in the same batch.

4.3.3 Process performance measures

21 performance measures were measured and calculated (Table 12).

4.3.3.1 Lead time of the delivery process

The lead time of the PDE delivery process includes the design, procurement, and manufacturing lead time. The design started January 17th 2002 and the last equipment was received September 23rd 2003, thus the time between is 86 weeks or 430 days (5 days in a week).

4.3.3.2 DESIGN LEAD TIME

The design started when the electrical engineer received the design task January 1st 2002, and ended when electrical contract documents were completed December 13th 2002. This results in a design lead time of 47 weeks or 235 days.

4.3.3.3 PROCUREMENT LEAD TIME

The procurement lead time is measured as the time between preparation of electrical RFQ and placement of P.O. or approval of shop drawings[31]. The preparation for electrical RFQ began December 13th, 2001, when the electrical design was completed. The last switchboard and MCC shop drawings were approved June 1st, 2003. The last panelboard 3-line diagrams were approved September 10th, 2003. Thus, the procurement lead times are 25 and 40 weeks respectively.

4.3.3.4 MANUFACTURING LEAD TIME[32]

Manufacturing lead time started when the P.O.[33] was placed by the electrical contractors and ended when the last switchboard was received at the site. The

---

[31] In Novo, the electrical contractors only placed a P.O., no separate release of the P.O. was issued. One of the electrical contractors placed the P.O. with manufacturer before the approval of shop drawings and the other of the electrical contractors placed the P.O. after the approval of shop drawings. Nevertheless, the manufacturer did not start the fabrication before the P.O. was placed and shop drawings were approved; therefore, here, I used the value that had a later date.

[32] Only switchboards were considered in manufacturing phase, so that data with the three cases would be better comparable. The switchboards are relatively similar in all cases, whereas MCCs and panelboards vary largely.

contractors placed the POs in June 11th, 2003, and the last switchboard arrived August 19rd, 2003. This results in a lead time of 10 weeks or 50 days. The first switchboard arrived one week earlier.

4.3.3.5 MANUFACTURING CYCLE TIME

The cycle time did not include production planning or inventory management. The cycle time for Novo's two switchboards is about 108 hours per switchboard or 13 days. The source for the data is the manufacturer database.

4.3.3.6 MANUFACTURING LEAD TIME-CYCLE-TIME RATIO

The manufacturing lead time-cycle time ratio calculated from the contractor's P.O. is 3.7 (10 weeks*5days*8h/108h).

4.3.3.7 MANUFACTURER'S BOTTLENECK PROCUREMENT LEAD TIME

The longest component lead time for the manufacturer with respect to the switchboards was 12 days (5 days a week, weekends not included). This was a special (compact) switch from an outside supplier. The manufacturer's plant manager provided the number. All bulked items including some high volume breakers were stocked at the manufacturing facility.

4.3.3.8 NUMBER OF CHANGE ORDERS

The project had about 300 changes, most of them were changes in panelboards. The numbers were captured from interviews and workshops.

---

[33] In case of switchboards the P.O. was placed after the approval of shop drawings.

4.3.3.9 *VALUE-ADDED TIME*

This measure compares the ratio between the actual hours spent for the activities and the total lead time required for the delivery process. Site installation, utility company's design and third party approvals are not included in the calculation, because comparable data could not be captured in all three cases. All the value added times are captured from interviews. I measured the ratio of the whole delivery process by adding the proportional value-added shares from design, procurement, and manufacturing together (i). The sum of all value added hours is 1353. For the three main phases, I used the below equation (i) to calculate the value-added time (VAT):

(i) VAT = LH/(W*LT), where

LH = sum of labor hours spent on each activity within a phase

W = number of workers that were simultaneously occupied with an activity during the phase, e.g., number of electrical engineers that were working on systems design.

LT = lead time of the phase

For design LH is 583 hours, the average W is 3, and LT is 1880 hours (47 weeks), thus VAT is 10% (583h/(3 workers*1880h)). The VAT per facility is 10%. For procurement of switchboards and MCCs LH is 174 hours[34], the average W is 2, and LT is 1000 hours (25 weeks), thus procurement VAT(1) is 9%. For

---

[34] Two electrical contractors were awarded the job and the process map in Appendix 2 includes the value added hours of both of them.

procurement of panelboards LH is 370 hours, the average W is 2, and LT is 1560 hours (40 weeks), thus procurement VAT(2) is 12%. In manufacturing, the value-added time for one switchboard is 108 hours, W is one per switchboard, lead time is 400 hours (10 weeks); thus, manufacturing VAT is 27% (108 hours/(1 worker*400h)). The VAT for the whole delivery process (ii) is then calculated as the sum of the proportional shares of the tree phases:

(ii) VAT (delivery process) = [(VAT(design) * LH(design))/LH(delivery process] + [VAT(procurement) * LH(procurement)) / LH(delivery process] + [VAT(manufacturing) * LH(manufacturing)) / LH(delivery process]

=> [10%*583 hours / 1353hours] + [11%[35]*554 hours / 1353hours] + [27% * 216 hours / 1353hours] = 13% (Figure 21). The ratio per facility is also 13%.

4.3.3.10 Number of different components within one product

The total number line items were between 120 items per switchboard. The numbers were taken from manufacturer's BOM.

[35] I use the average value (11%) of the procurement VAT switchboards and panelboards (9%), and of the procurement VAT of panelboards (12%).

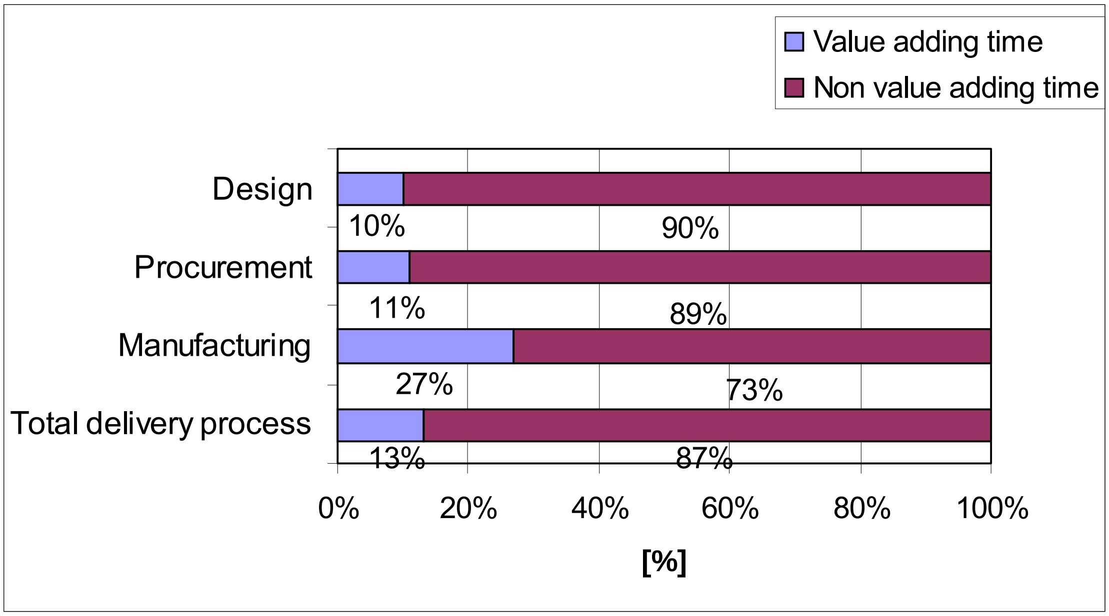


Figure 21: Value-added times in Novo

4.3.3.11 PERCENTAGE OF STANDARD COMPONENTS

The manufacturer did not fabricate any of the components. From the 120 switchboard components about 90 were ordered based on forecast and the manufacturer considers them as “standard components”. Thus, the percentage of standard components is 75%.

4.3.3.12 NUMBER OF BATCHES AND BATCH SIZES

The unit of the batch is one job (equipment). There is one building which has 2 switchboards, 4 MCCs, and 72 panelboards, thus a total of 78 jobs. The number of batches and the batch size varied throughout the project. In the design and engineering phase, the drawings were generated as one batch (with 78 jobs). The equipment was procured in two batches (batch sizes 6 and 72 jobs), and shop drawings were generated and approved as 4 batches (batch sizes 1-20 jobs). In the manufacturer's production planning, the process was broken down to 78 batches (each job/ equipment was one batch). Also, all the switchboards and MCCs were fabricated batches (6 batches, batch size 1), but shipped in two batches (batch sizes 2 and 4) within a week from each other. The panelboards were shipped as 4-10 jobs per batch. The sequence of the batches did not remain the same throughout the delivery process.

Table 12 Summary of performance measures in Novo

Performance measure	**Unit**	**Value**
Lead time of the delivery process	Week	86
Design lead time	Week	47
Procurement lead time	Week	40 and 25
Manufacturing lead time	Week	10
Manufacturing cycle time,	Hour	108
Manufacturing lead time-cycle time ratio	N/A	4
Manufacturer's bottleneck procurement lead time	Days	12
Number of change orders/ add-ons	N/A	300
Value-Added Time, total	%	13
Value-Added Time, design	%	10
Value-Added Time, procurement	%	9 and 12
Value-Added Time, manufacturing	%	27
Hours consumed in design	Hour	583
Hours consumed in procurement	Hour	554
Hours consumed in manufacturing	Hour	216
Hours consumed in the whole delivery process	Hour	1353
Number of different components in equipment	N/A	120
Percentage of standard components	%	75
Batch size in engineering	Job	78
Batch size in procurement	Job	6-72
Batch size in manufacturing	Job	1-10

4.3.4 Elements contributing to lead time of delivery process of PDE

Total delivery lead time was 86 weeks, of which design took 47 weeks, procurement including shop drawing approvals 25 and 39 weeks, and manufacturing including shipping 10 weeks (Figure 22).

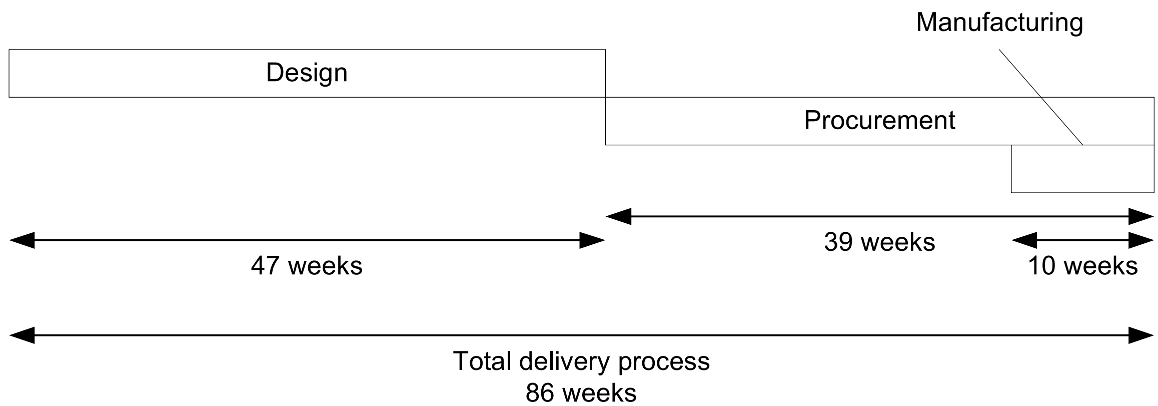


Figure 22: Design, procurement, and manufacturing lead time proportions of the total delivery time in Novo

4.3.4.1 DESIGN AND ENGINEERING

The value-added time with respect to PDE was 10% during design phase. The design lead time was 47 weeks. Most of the time in the design phase was spent waiting on input values from the owner and tenant; e.g., the electrical engineer had to wait six months for the owner's decision about the emergency generator. Another major time contributor was the numerous updates that the electrical engineer had to handle. There was an estimated 300 changes or add-ons to PDE.

Since the end of the 1990s the electrical drawings have not required approval by the city of Helsinki. The electrical engineer is responsible for his design. However, a third party certified inspector had to test the equipment before it was energized. Therefore, the only outside approval for the project was the connection application with the local utility company, which took a few months.

4.3.4.2 PROCUREMENT

The value-added times with respect to PDE were 9 and 12% during the procurement. The procurement lead times were 25 and 40 weeks. However, there were four rounds of competitive bidding, where the manufacturer got basically the same documents four times; hence, the value-added of all four rounds is questionable. However, in this research I still assume that all rounds of bidding added value. If only the first round of bidding was considered, where the quote price was already close to the final contract price, the value-added time would have been only 7%[36].

Within the procurement phase, the PM company prepared the RFQs in four weeks (Figure 23). Then, two weeks went to the first round of bidding where the PM company requested quotes directly from manufacturers. Then, four weeks went to the second round of bidding where the PM company requested quotes from the electrical contractors, including one week that the manufacturers quoted for the electrical contractors. Although the electrical contractors were selected already four weeks after they had placed the quotes, the contract negotiations between the PM company and the electrical contractors took still another eight weeks. After the electrical contractors were selected but before the contracts were signed, the electrical contractors requested second quotes from the manufacturers. The final round of bidding and equipment negotiations between electrical contractors and manufacturers took another 11 week. Then, then generation of the 3-line diagrams, which were considered as part of the shop

---

[36] The PM company's and manufacturer's value-added hours were in this case 104.

drawings, and thus belonged to the procurement phase, consumed 12 weeks. Lastly, 11 weeks went to preparing and approving shop drawings.

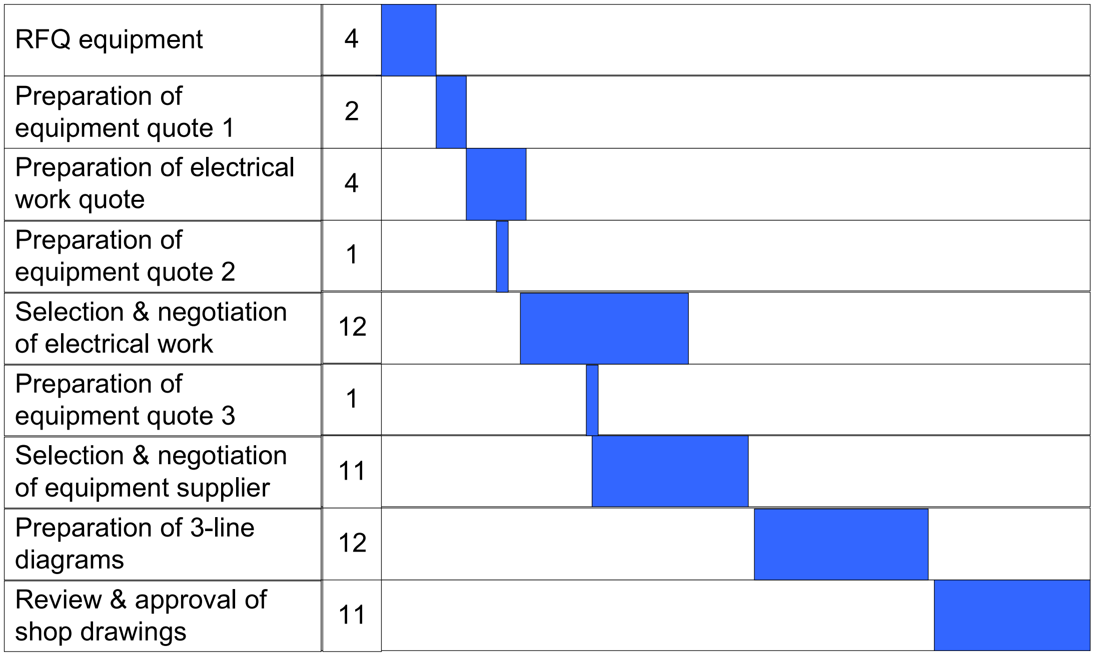


Figure 23: Timeline of procurement in Novo (unit: week)

4.3.4.3 *MANUFACTURING AND SHIPPING*

The value-added time with respect to PDE was 27% during the manufacturing phase. Because there was no separation of purchase order and order release, I considered the manufacturing as the tasks between approval of shop drawings and the equipment arrival date on site. The approval of shop drawings can be considered equivalent to the order release in the US cases because the manufacturer does not start production before shop drawings are approved.

The manufacturer’s cycle time was 13 days for the switchboards. Less than three weeks of buffer time was reserved for manufacturing. The buffer time was needed to order components and level the production. Due to the short information flow and physical closeness of sales and shop operations, the manufacturer's internal information flow was very efficient. Most of the communication had already taken place during the quoting. The switchboards and MCCs were shipped overnight.

4.3.5 Causes of long lead time

The value-added time of the whole delivery process was 13%, which is somewhat higher than in the other two cases, but the value of some of the tasks in the delivery process are questionable (e.g., four rounds of competitive bidding).

4.3.5.1 DESIGN

The design phase was not integrated into the procurement and manufacturing of the equipment. Rather, all three tasks were managed independently and considerations of inter-task relations were not taken. The main causes for the long lead time were lack of resources for decision-making (time and knowledge), changes due to early commitment, changes due to errors, coupling of PDE with other electrical systems, and low level of standardization.

4.3.5.1.1 LACK OF RESOURCES FOR DECISION-MAKING

Most of the electrical engineer's time went to waiting for inputs. Particularly, the owner and tenant did not have enough resources to deliver timely inputs, which was caused both by lack of time and knowledge. The PDE is technically demanding and the owner had to hire a consultant. Evidently, this also added one more step to the already slow information processing and decision making. The owner blamed this on his inability to get timely information from the tenant, whose performance in this regard is not surprising when we consider that the tenant's main business was far from capital facilities or PDE. There may have also been room for the engineers and PM company to better clarify the options for the owner and tenant.

4.3.5.1.2 Changes due to early commitment

The tenant was requested input two and half years prior to the completion of the project. Evidently, and particularly for a company operating in the information technology business environment, this led to many assumptions, including power requirements. The assumptions ranged from number of workstations per space to power reliability. As the completion day approached, the assumptions were updated, which lead to changes and re-documentation.

4.3.5.1.3 Changes due to errors

The electrical engineer was relatively inexperienced, which led to design errors that had to be corrected several times. In fact, the PM company requested that the electrical design be reworked and corrected three times; particularly feeders, conduits, and breakers were over-dimensioned. Part of the errors were also explained by the fact that the electrical contractor had to copy design solutions from prior projects due to the rush caused by the owner's and tenant's late design input.

4.3.5.1.4 COUPLING OF PDE WITH OTHER ELECTRICAL SYSTEMS

The PM company waited until all electrical design was completed before requesting quotes directly from the PDE manufacturer. The design of the PDE consumed only a minor part of the whole electrical design time; hence, for most of the design time, the power distribution design was on hold.

4.3.5.1.5 LOW LEVEL OF STANDARDIZATION

There is a low level of standardization, especially in detailing. Because the manufacturer does not prepare and have control over the 3-line diagrams, the shop drawings are basically developed from “scratch” every time an order is placed. The 3-line diagrams had thousands of CAD-pages, which were very tedious to prepare and prone to errors. A third of the design and engineering hours went to 3-line diagrams. Even minor changes in specifications could require numerous hours of rework. Most of the changes occurred while the 3-line diagrams were being prepared or had already been completed, which further frustrated the contractor and manufacturer.

4.3.5.2 PROCUREMENT

Procurement was characterized by fierce bargaining. Competitive bidding was the applied procurement method. The PM company and the electrical contractor both applied it twice just for the PDE. As a result, the manufacturer quoted three times for the equipment. Consequently, competitive bidding did not only consume much time but also consumed significant resources. Also, the material take-off and estimation was not centralized. Each bidder did their own take-offs, which created process waste.

4.3.5.2.1 LEAD TIME IMPACT BY COMPETITIVE BIDDING

Competitive bidding consumed 27 weeks of the total delivery process. However, it was estimated that eliminating the slack and flexibility during the bidding caused many of the changes that took place after the procurement of the equipment. The electrical contractors received about 10 major changes with respect to the PDE, and each change caused 8-16 hours of work for the electrical contractor's CAD draftsman alone. However, the draftsman had 1-2 weeks backlog of work every time; thus, the correction of the 3-line diagrams always had to wait. The electrical contractor estimated that the changes increased his work, procurement and site installation up to 12 weeks.

4.3.5.2.2 RESOURCE CONSUMPTION BY COMPETITIVE BIDDING

Competitive bidding consumed 554 labor hours. When the workshop participants multiplied the hours by an estimated average cost of an employee per hour (40 euros/h), it turned out that the bidding practice cost more than 10% of the value of all the PDE required in the building. Since the range of the manufacturers' low bids were within 4%, the bidding process consumed more money than was gained[37].

---

[37] However, one can always ask what the equipment price would have been without competitive bidding.

However, the changes that occurred after procurement were estimated to be even higher in cost than the cost of bidding. The electrical contractors and manufacturer alone estimated that they used 205 hours and 80 hours, respectively. The PM company's, electrical engineer's, and owner's hours probably fell in the same range, though no data was available to confirm the precise number.

4.3.5.2.3 Reinforcement of adverse project goals by competitive bidding

The competitive bidding also reinforced the adverse goals of the owner and contractors. The owner aimed to reduce the life cycle cost of the equipment; thus, the equipment had to be properly assembled and components had to be high quality brand components. The PM company and the electrical company could often in fierce price competition lower the price only by substituting lower quality components[38]. As a result, the owner insisted on reviewing and approving all the bidders and BOMs, which caused additional waiting for the electrical contractors and manufacturers.

4.3.5.2.4 De-centralized take-off

The electrical contractors and manufacturers did the take-off manually. For the electrical contractor it took about 80 hours. As 10 electrical contractors quoted, 800 labor hours were spent for the electrical take-off. The problem from a lead time approach is that the owner had to go through the take-offs and make sure

[38] "Low-quality" component may be up to 25% less expensive.

they were correctly done. Every time anything had to be reviewed or approved by the owner, a week's time period was reserved contractually.

4.3.5.3 Manufacturing

Compared to the other phases, manufacturing and shipping was short. Four main reasons pushed the manufacturing lead time: (1) lack of configuration software, (2) component lead time, (3) assembly method, and (4) changes.

The manufacturer had separate software to draw the shop drawings, for materials management, and production planning. However, the different software packages did not talk to each other and data had to be moved manually between them. This led to repetitive work and caused errors during data entry. Also, the CAD drawings and BOMs did not necessarily match.

Almost three weeks of the 10 week equipment lead time went to ordering the long lead time components. A same amount of time went to assembling the product. Rest of the time went to confirm the customer requirements. The cycle time was 13 workdays, because only one or two installers could work simultaneously on one piece of equipment. The reason was that the various sections of the equipment were attached to the main frame from the beginning and no workspace to work on individual sections was available.

Finally, the large number of changes caused all sections to be delivered later than the original shipping date. The pieces of equipment were ordered in the summer, which is a peak period for the manufacturer, and there is little excess capacity available if the equipment is removed from its original production slot.

4.3.6 Opportunities to improve the process: Future state

The improvement opportunities were identified and the future state process was developed with help of the industry partners in the workshop. I used the TFV-theory as a framework as I facilitated the workshops. Numerous ideas were put on the table, but the most significant ones were (1) Information-Flow-Card, (2) Direct and negotiated procurement method, (3) Systematic measurement of change order hours, and (4) Shielding uncertainty from site installation.

4.3.6.1 DESIGN

The most frustrating element in design and engineering was the tedious collection of input values and their high unreliability. The Information-Flow-Card, decoupling of electrical systems, and simplification of 3-line diagrams address these issues.

4.3.6.1.1 INFORMATION FLOW CARD

The purpose of the Information-Flow-Card is to make it as easy as possible for the person needing input to receive that input from the customer or other stakeholders. Also, part of the waiting for input was due to the owner's or tenant's lack of knowledge; thus, the card has to be simple enough so that the input provider is able to fill it out or to review it. A prototype of an Information-Flow-Card is shown in Figure 24. The criteria of the card are (1) the consumer of the input will develop the card and pass it to the input provider, (2) the input is requested and the cards are managed based on the rules of set-based design,

(3) the Information-Flow-Card is one piece of letter-sized paper that includes the following key information:

- Who needs the information
- When is information needed
- Who has to provide the information
- What inputs are requested
- A potential clarifying figure
- Default input values

Several cards could be used to actively provide alternatives and support for the decision-maker, which would be further enhanced if the Information-Flow-Card were Internet based. Then a shared databank could be established, with past Information-Flow-Cards, links to further information, pictures, etc.

Although the card was not implemented in Novo, it was commonly agreed that part of the problem of inputs is related to the current, non-customer-friendly method of collecting inputs, which has to be changed in the future. Finally, the Information-Flow-Card was considered as a good alternative and an Information-Flow-Card for electrical rooms were developed and planned to be used in future projects.

Information-Flow-Card on Electrical room

Room number: ______________________

From:	______________________	Min. height of space:
To:	______________________	Min. width of space:
Date:	______________________	Min. length of space:

SPECIAL REQUIREMENTS

Floor surface:

Other surface material:

Electrical room's relation to other spaces and suggested of use of adjacent spaces:

Fire protection requirements:

Ventilation and cooling requirements:

Below a schematic location drawing of the piece(s) of equipment, showing safety distances, utility connection, feeders, and other horizontal and vertical cabeling:

Figure 24: Prototype Information-Flow-Card on electrical room

4.3.6.2 One equipment flow

With a different procurement method (chapter 4.3.6.3.2) it would also be possible to pursue a different design strategy. The design of the equipment could be executed in smaller batches and decoupled from other electrical work. In an ideal case, the design and manufacturing of each piece of equipment would be tightly integrated, so that the design of each piece of equipment would be completed before the next piece of equipment was designed. The detailed engineering would also be postponed to take place as close as possible to the site installation. In Novo's case, it would mean that the detailed engineering of a piece of equipment could start two months prior to its site installation. The sequence of detailed engineering would follow the electrical contractor's work sequence on the site. Considering that the non-value-added time is 90%[39], and most of this is waiting, the decoupling of the detailed engineering from the rest of the design would make it possible to postpone the detailed engineering up to 24 weeks or 50%.

4.3.6.3 Procurement

The current state process of procurement (Figure 19) illustrates how cumbersome it is. The following improvements were suggested in the workshops, simplification of 3-line diagrams, alternative procurement methods, and measurement of change order hours and actions to reduce them.

---

[39] 90% from the 47 weeks design and engineering lead time is 42 weeks!

4.3.6.3.1 SIMPLIFICATION 3-LINE DIAGRAMS

The preparation of the 3-line diagrams was the single most time consuming design task, and a notable number of design changes took place during this task. It was suggested that in the future the preparation of 3-line diagrams could be done by the manufacturer and that he would aim to standardize, at least, the switchboard and panelboard diagrams. Also, if the diagrams were standardized the customer would not need to spend as much time reviewing them every time. In any case, the customer rarely has the time or resources to review them in a sufficiently detailed manner. In the Novo case, the review and approval took over two weeks, though effective time used was only 8 labor hours. The proposed changes would bring, time-wise, the design closer to the actual site installation and hence reduce the probability of changes. It would also help the manufacturer to standardize its assembly of boards and synchronize the generation of drawings with sequence of equipment assemble. Finally, the manufacturer would not need to deal with and interpret the wide variety of 3-line diagrams that he currently receives from his customers. Comparing to the two US cases (Bay Street and Paradise Pier), I believe that from the nearly four months of preparing and approving 3-line diagrams an estimated three months could be eliminated with the proposed changes.

4.3.6.3.2 NEGOTIATED AND DIRECT PROCUREMENT METHOD

Changing the current procurement practice would bring the design closer to the site installation and release resources to other tasks. In the future, the workshop participants, including the electrical contractor[40], proposed that the PM company would procure the PDE based on negotiated contracts directly from the manufacturer. In US, some PM companies have specialized in procuring long lead time items for owners, for example Turner Construction. Ideally, the owner had taken the role because it would required least “middlemen”.

However, since he was lacking resources, it was considered that the PM company would perform the task just as well. If labor hours of all the bidders, not only the one who got selected, are included, an estimated 800 labor hours would be saved if the competitive bidding would be changed to a negotiated contract. Also, the order of the equipment could be released in smaller batch sizes; ideally, one piece of equipment at a time based on the site conditions. Accordingly, the procurement time could be reduced to an estimated four weeks instead of the current 27 weeks. More importantly, the detailed engineering could be postponed to only 8 weeks prior to site installation instead of the current 24-32 weeks. The proposed future procurement practice is illustrated in Figure 25. Note that the 3-line diagram and the shop approval activities would now be incorporated into the manufacturing task (Figure 26).

---

[40] However, if the electrical contractor would “voluntarily” give up procurement of the equipment, he would require measures, such as long-term cooperation agreements with PM company and dramatic reduction of changes during the construction phase to compensate for the potential revenue loss from material purchase. Even so, this would expose the electrical contractor to additional risks for which rewards should be provided.

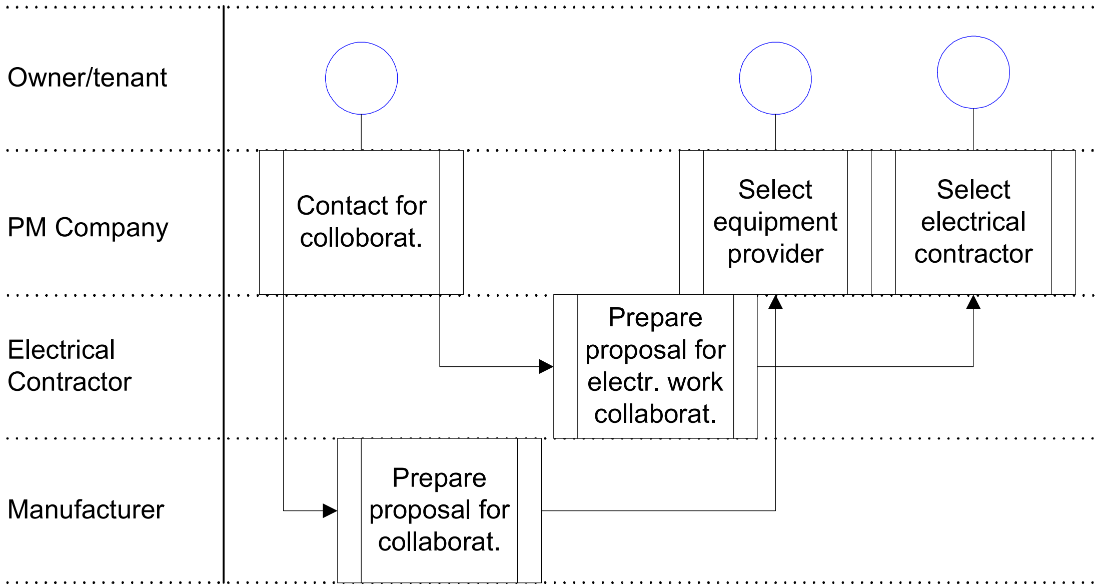


Figure 25: Streamlined procurement practice in Novo

4.3.6.3.3 MEASUREMENT OF CHANGE ORDER HOURS

All participants remarked that a significant part of their time was spent dealing with changes and add-ons to the equipment. Therefore, it was proposed that in the future the change order and add-on hours would be measured throughout the delivery process of the PDE. Then, with the help of collaboration, they could systematically investigate means to reduce the “wasted hours”. Percentage of change order or add-on hours of the total delivery process could also be used, along with other lean measurements, such as value-added time, waste, batch size, and cycle time as a common performance measure to indicated the efficiency of the delivery process.

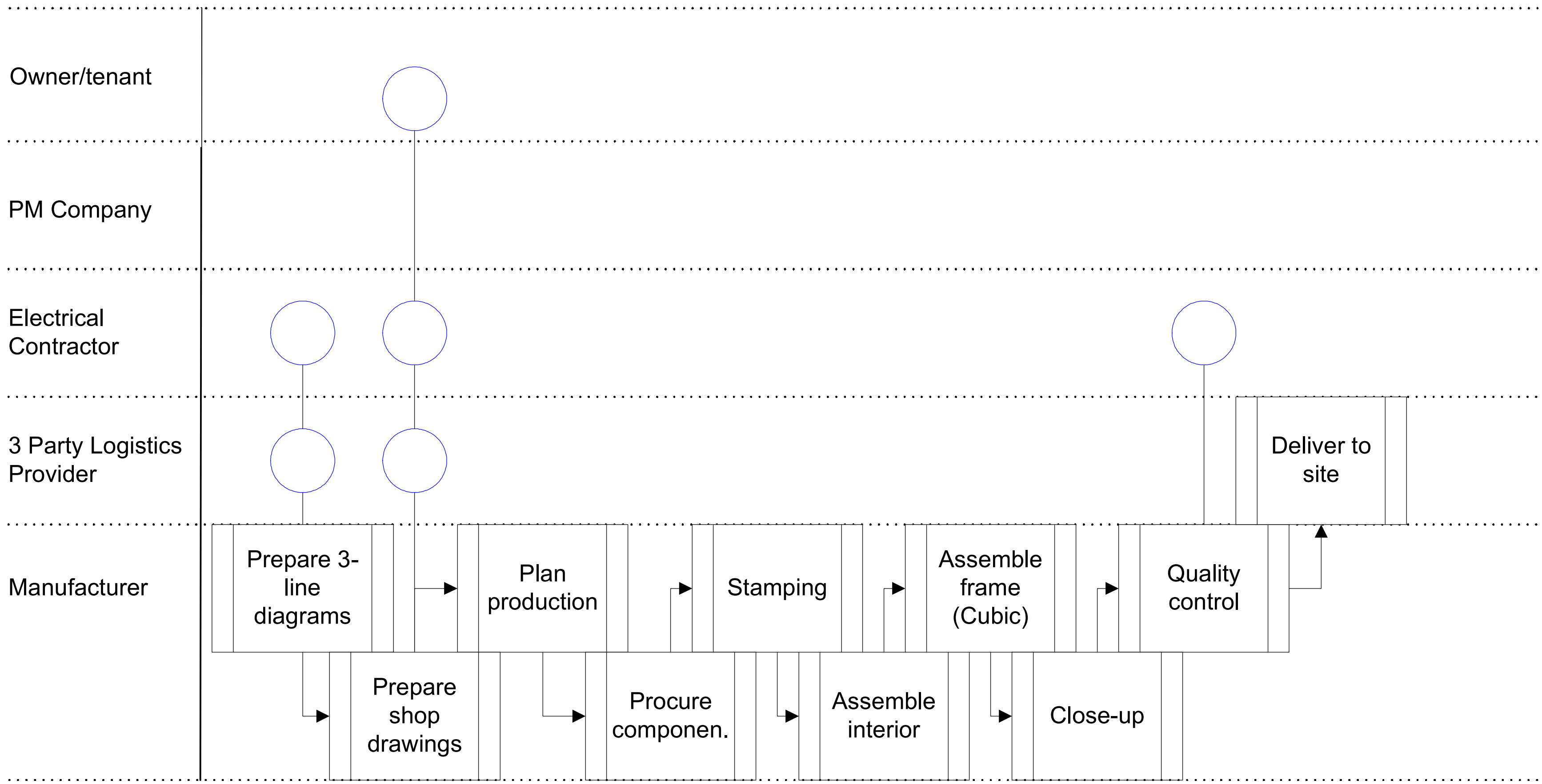


Figure 26: Proposed manufacturing practice in Novo

4.3.6.4 MANUFACTURING

With respect to manufacturing, the two main suggestions were to reduce the cycle time and to make the workflow more reliable for the electrical contractor.

4.3.6.4.1 REDUCE CYCLE TIME

The 13 day cycle time was considered relatively long, though typical among the manufacturers of PDE in Finland. One suggestion was to reduce the size of the batch from eight sections to one during the assembling and wiring. Even if the time saving were only one week, the manufacturer could save inventory cost because the components would wait less in storage before being installed and sold. However, this would require completely redesigning the configuration of boards and the production method of the manufacturer. Currently, the manufacturer does not consider this feasible and urgent. Nevertheless, stiffer competition may force them to change the current production method, because the manufacturing technology is already available as discussed in chapter 4.5.2.3.

4.3.6.4.2 MAKING WORK FLOW RELIABLE FOR THE ELECTRICAL CONTRACTOR

The electrical contractor experienced lots of uncertainty during the site installation phase, which according to him significantly lowered his productivity. Furthermore, every piece of equipment was delivered late. It was suggested that all the participants would collaborate to help shield the site from uncertainty. The electrical contractor was introduced to and is preparing to implement the Last Planner tool (Ballard 2000, Koskela and Koskenvesa 2003), which was particularly designed to shield site production from uncertainty. The main idea in having common tools, such as the Last Planner, and performance measures is to reinforce the collaboration within the delivery process of PDE and to better integrate the process from design and engineering to site installation. The estimated impacts of the improvement suggestions on the current delivery process are summarized in Table 13.

Table 13: Summary of key improvement suggestions in Novo

Improvement suggestion	Number of reduced tasks	Reduced lead time [weeks]
Decoupling and postponement	-	24[41]
Simplification of 3-line diagrams	4	4[42]
Redesign of procurement	6	23
Reduce manufacturing time	-	1
Total	**10**	**28**

4.3.7 Summary

The main causes for the long lead time were:

- The tedious collection of design input values and their unreliability.
- Coupling the power distribution design with the rest of the electrical design.

---

[41] The 24 weeks postponement of detailed engineering does not mean that the systems design can be postponed as much as a 24 weeks. Therefore, I do not include it in the total reduction of lead time.

[42] The 4 weeks refer to the approval time for the 3-line diagrams. The total lead time saving of the simplification of 3-line diagrams was estimated to be 16 weeks. However, the 3-line diagrams were generated in parallel with other shop drawings, hence, only the approval of the 3-line diagrams are considered in Table 13.

- The labor intensive generation of 3-line diagram caused by non-standardization.
- The “repetitive” application of competitive bidding the procurement process.
- The large document batch sizes.

4.4 CASE 3: PARADISE PIER

Paradise Pier is part of Walt Disney's amusement park Disney California Adventure, in Anaheim, California. Paradise Pier includes 19 facilities of which 9 are rides and the remainder is shops, restaurants, and maintenance facilities. Along with the vertical construction[43], Disney also developed and built the electrical infrastructure, including two switching stations for the park. However, this study concentrates only on the vertical construction, because the local utility company normally handles electrical infrastructure. The exclusion of infrastructure also made the case study easier to compare to the two other cases.

Feasibility design of Paradise Pier started in March 1997, electrical design in October 1997, and construction in April 1999. The project was completed in November 2000. The project was executed as a Design-Bid-Build project. Walt Disney Imagineering (WDI), who operated as the developer, was in charge of the planning and design. The architects and most of the engineers were from WDI and thus part of the owner's organization. Disney's construction management acted as a PM company, coordinating the design and construction interface and supervising the construction work. Five general contractors were selected to execute the site work. Through competitive bidding they hired one electrical

---

[43] Vertical construction refers to buildings that house indoor power distribution equipment and horizontal construction refers to subsurface electrical infrastructure and outdoor power distribution equipment.

contractor as the sole electrical contractor. Disney's construction management hired another electrical contractor towards the end of the project to help the first electrical contractor to complete the remaining electrical work. The complete case study is documented in (Elfving et al. 2003a).

4.4.1 Overview of the delivery process

The project has 40 electrical rooms in 19 facilities, housing 7 General Electric low-voltage switchboards, 12 MCCs, and 148 panelboards. Every switchboard is different due to the different purposes of the facilities. The electrical load for the switchboards varied between 600A for the vending building and 2500A for the California Screaming roller coaster. The design of the electrical system (load calculation, logic) started in October 1997, the contact drawings were finished in November 1998, and the electrical contactor was selected in March 1999. The equipment purchase order was placed in March 1999. The manufacturing of the first equipment started in May 1999. The first equipment was delivered in June 1999. The installation of the first equipment (for Sun Wheel) started in June 1999 and the installation of the last equipment (for California Screaming) finished in October 2000. Until the first submittals of shop drawings, the design of all 19 facilities was processed as one batch. After that, the batch size was reduced to 19 smaller batches based on each facility, so that the site installation could proceed according to planned construction schedule.

4.4.2 Description of current state

The delivery process of the PDE had three main phases: design, procurement, and manufacturing. The outcome of the first phase was equipment specifications, also referred to as contract documents. The outcome of the second phase was purchase order release, which also included approval of shop drawings. The outcome of the third phase was equipment-on-site (Figure 10). The complete current state process maps is presented in Appendix 3.

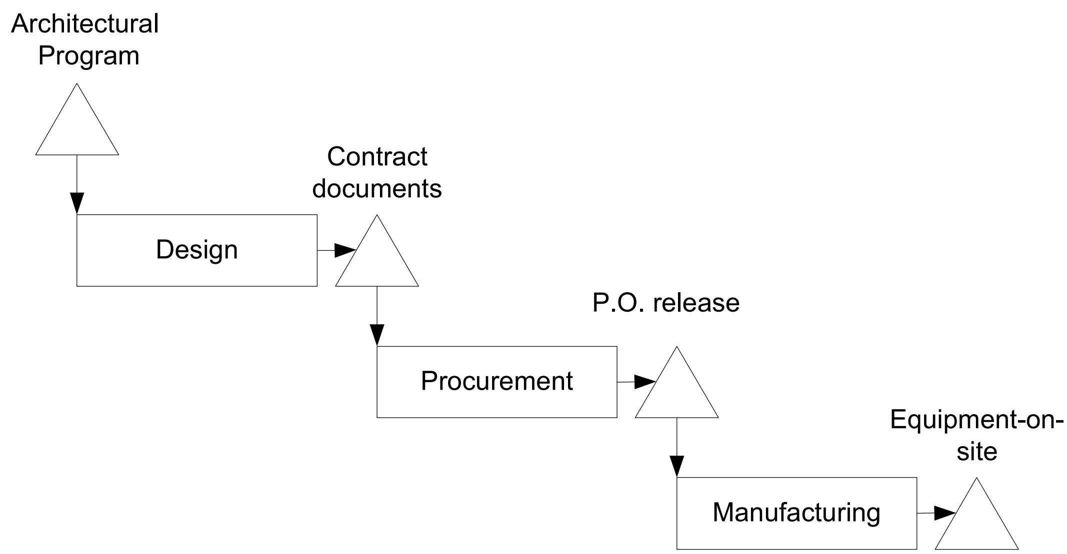


Figure 27: Main phases of the delivery process in Paradise Pier

4.4.2.1 Design

Most of the facilities have unique characteristics; therefore, the power distribution design and equipment also required close consultation with several specialists, e.g., acoustic, lighting, maintenance, ride, show, and hydraulic specialists. Hence, one of the major challenges with the design was to collect input information and to coordinate the PDE design with other design disciplines. The owner's advantage was that most of the design was conducted in-house, which somewhat eased the coordination.

Also, the equipment had to support the existing facilities in the Theme Park. Notable weight was placed on the maintenance and availability of spare parts for the equipment. Therefore, only those manufacturers that had already provided equipment to the Theme Park were considered in the design phase. The early selection of the manufacturer made the design easier because the design crew did not need to deal with every manufacturer's components, and the equipment would more probably fit to the space that was reserved for it. Due to the large quantity of construction work that the owner executes annually, the owner is well aware of the city and utility company requirements and they all worked closely together already in the development phase.

The specific activities in designing the equipment were (1) design utility infrastructure, (2) estimate electrical load, (3) prepare pre-bid documents, (4) define electrical system, (5) design MCC, and (6) finalize design and specifications (Figure 28).

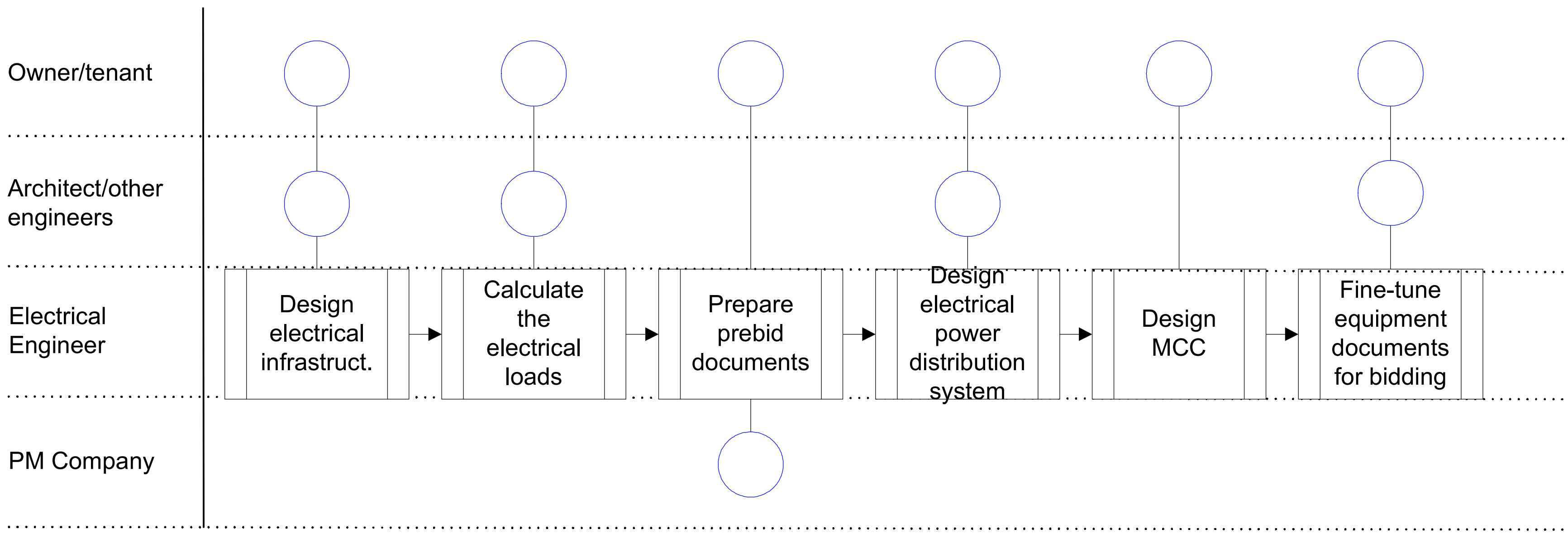


Figure 28: Design activities in Paradise Pier

4.4.2.1.1 Design utility infrastructure

After the preliminary architectural program was available, the area infrastructure of the Theme Park, of which Paradise Pier was only one part, was developed. The owner's user/operator crew designed the infrastructure together with the owner's developer crew. The utility company was also involved at this stage. The main elements in the infrastructure are switching stations, pieces of pad mounted equipment (PME), transformers, and main distribution boards (MDP).

After the infrastructure was built, the owner's operators acted as the utility company and specified how the buildings were connected to the power distribution infrastructure. Because the owner's operators own the infrastructure there was no need to file a separate connection application with the utility company. The only outside approval that was required was from the city.

4.4.2.1.2 Estimate electrical load

The owner has a database from past projects about applied electrical loads of various spaces, which was used in estimating the electrical loads. However, the database could not be used for all electrical loads; e.g., a big electrical load was the exterior load (audio, lights and parking). At this stage, the architect asked the electrical engineer to also define the space requirements for the electrical equipment. Consequently, besides trying to estimate the exterior electrical load, the electrical engineer also had to define what would be the best space to house the equipment for exterior and all other loads.

4.4.2.1.3 Prepare pre-bid documents

The design crew urged early as possible selection of the equipment manufacturer, thus they prepared the request for pre-bid of electrical equipment simultaneously with the load estimation. The pre-bid documents were a list of estimated type and amount of PDE, e.g., number of panelboards, breakers, etc.

4.4.2.1.4 Define electrical system

At this stage, the electrical engineer assigned the PDE to dedicated spaces and defined the configuration of the equipment. The electrical engineer did not need to know the final mechanical equipment because he was able to estimate the approximate loads based on the use of the space. The output from this stage was a one-line diagram of each building, the site location for the electrical rooms, and the equipment location plan (size of the equipment so that it fit the room).

4.4.2.1.5 Design MCC

MCCs are the most customized electrical equipment in the power distribution design. The MCCs went through much iteration because the mechanical engineering was executed simultaneously with the electrical engineering. Also, the MCC had interfaces and input requirements from several other disciplines such as fire controls, AHUs, fire alarm system, energy management, kitchen equipment, etc.

4.4.2.1.6 Finalize design and specifications

The electrical engineer specified some details of the switchboards, like the model type and components. Then he updated the one-line diagrams and conducted short circuit analysis and voltage drop analysis for each facility. Then he consolidated all the electrical drawings for a bid package. Finally, a breaker coordination analysis was conducted.

4.4.2.2 Procurement

The procurement was arranged in an unusual way, because the owner selected the equipment manufacturer in an early phase based on a pre-bid, where the manufacturers were requested to provide a reduction percentage of their list prices. However, the owner did not actually purchase the equipment. Rather the equipment was purchased through another three layers of competitive bidding. First, general contractors were competing for the construction work including electrical work and PDE. Second, the general contractors placed Request-For-Quotations to electrical contractors for electrical work. Third, the electrical contractors placed Request-For-Quotations to the distributors of the equipment.

The bidding time for electrical work was only two months and the P.O. was placed to the manufacturer's sales representative one month later; though the last equipment was released for production almost a year after the P.O. was placed. The approval of shop drawings played a major role in the procurement lead time. The specific tasks in the procurement phase were (1) preparation of pre-bid, (2) quotation for pre-bid, (3) Request-for-Quotation (RFQ) of electrical work, (4) RFQ of equipment, (5) preparation of equipment quote, (6) preparation of electrical work quote, (7) selection of electrical contractor, (8) placement of purchase order P.O., (9) preparation of shop drawings, (10) review of shop drawings, and (11) release of order (Figure 29).

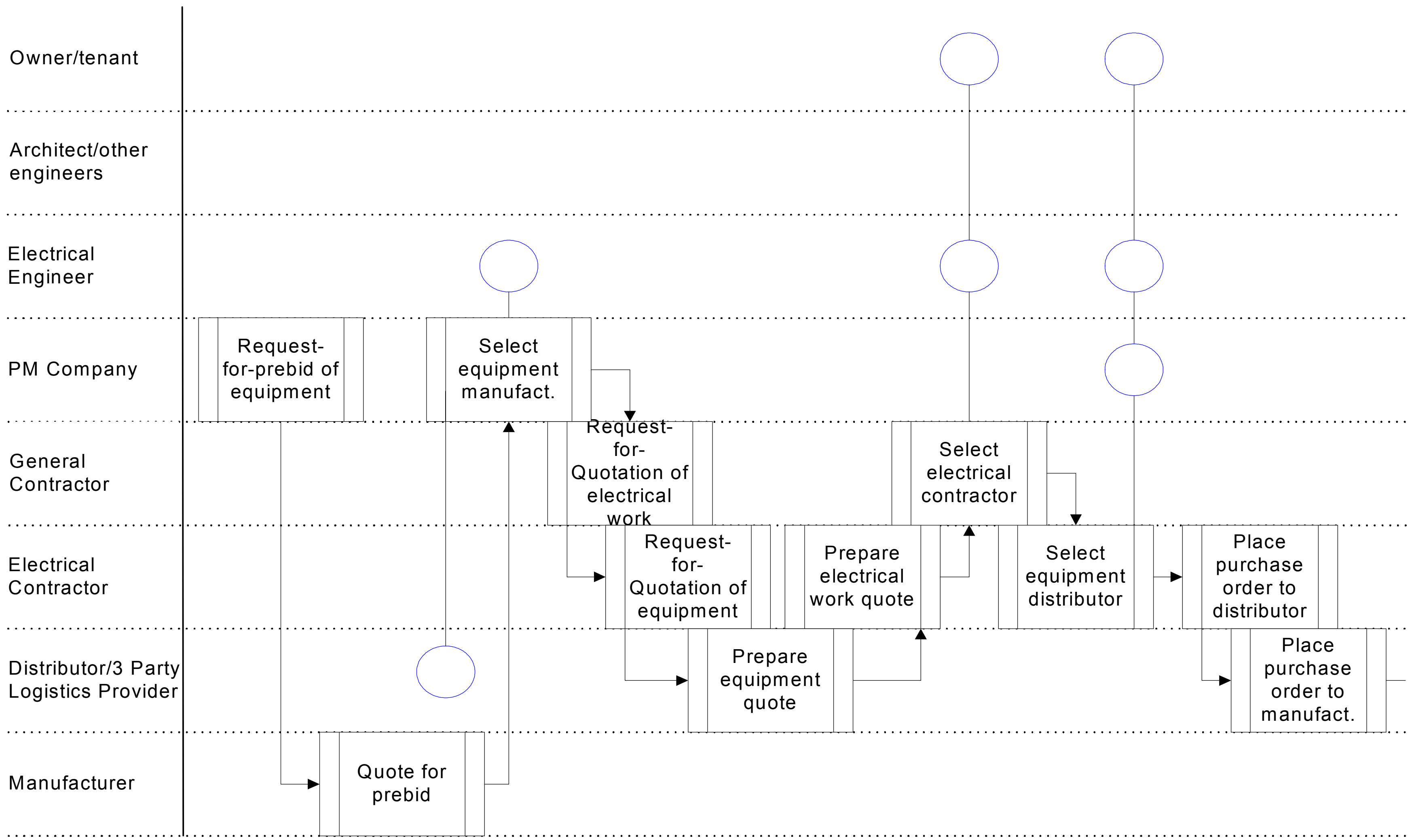
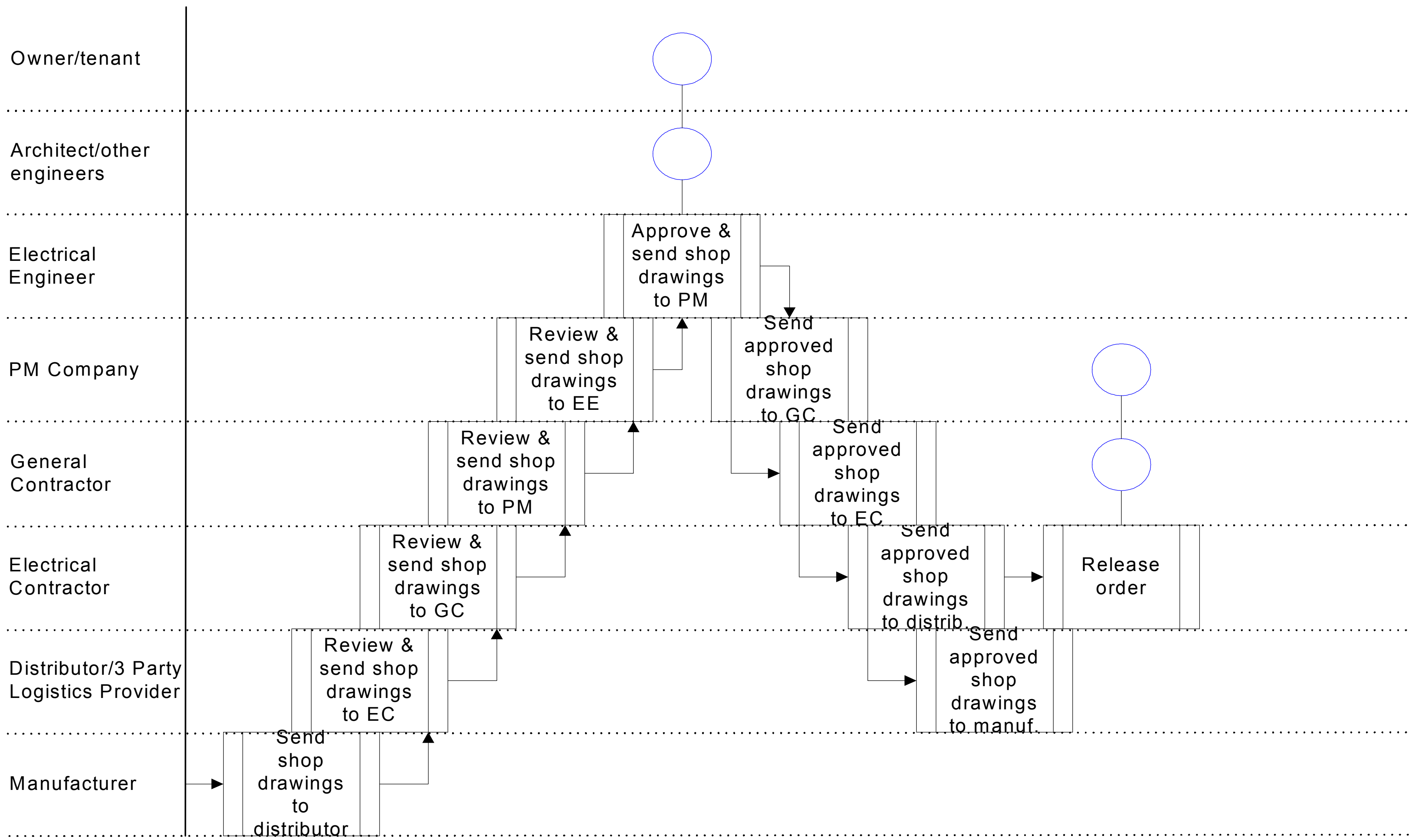


Figure 29: Procurement activities in Paradise Pier



Procurement activities in Paradise Pier (Figure Continues)

4.4.2.2.1 Preparation of pre-bid

The overall design was 60% complete when the pre-bid was requested. The pre-bid of electrical equipment followed these steps: (1) Define package strategy, (2). Generate the scope documents, (3) Identify pre-qualified bidders, (4) Generate bidders list, (5) Initiate bid period, (6) Receive bids, (7) Review bid tabulation, (8) Send Letter of Intent (LOI), and (9) Award equipment provider/ contractor. The manufacturers were requested to quote a reduced percentage off their list prices. Most of the equipment's components were "off-the-shelf" items which can be bought as a single breaker or as a board with breakers and other instruments.

4.4.2.2.2 Quotation for pre-bid

This stage was very unclear to all participants, because the purpose of the pre-bid was very differently understood among the participants and some did not even recall that there was a pre-bid!

4.4.2.2.3 Request-for-Quotation of electrical work

There were four general contractors on Paradise Piers and two electrical contractors (one came later to ease the workload of the earlier one). The general contractors chose the primary electrical contractor based on low bids and the owner's equipment pre-bid. The general contractors did not get involved in defining the content of the various procurement packages, for lighting, substations, MCCs, etc

4.4.2.2.4 Request-for-Quotation of equipment

Even though the manufacturer was pre-selected, the electrical contractor could buy the equipment through several distributors, all of which represent the manufacturer. Each distributor then placed the RFQ with the manufacturer's sales representative. The distributor may be able to lower the pre-bid price for the electrical contractor in two ways: (1) he may lump other items, including PDE and lighting packages from the current and/or other projects, with the same deal with the manufacturer and thus gain an overall reduction for his total material needs due to quantity-of-scale. (2) He can also try to reduce the cost of just the PDE by buying other material from the distributor as well. The manufacturer's sales representative did the take-off of PDE for the electrical contractor.

4.4.2.2.5 Preparation of equipment quote

One sales representative quoted the same price for all five electrical contractors. The sales representative input the information from the one-line diagrams into the pricing and configuration software, which generated the BOM, the price, and preliminary shop drawings. The configuration software has been made foolproof for the national and local code and regulation requirements so that a user could not input certain values without the software automatically changing the default values to avoid errors in the board configuration. Price was given as lump sum.

4.4.2.2.6 Preparation of electrical work quote

The quote included all electrical work, not only the PDE. The quoting took about eight weeks for two estimators on Paradise Pier. However, most of the time went to waiting for information from the vendors (manufacturers, distributors).

4.4.2.2.7 Selection of electrical contractor

The general contractor evaluated the bid documents. The electrical contractor was chosen based on lowest price.

4.4.2.2.8 Placement of Purchase Order

The switchboard and MCC P.O.s were written in an early stage in order to “lock” the design, and to enable the manufacturer to finalize the shop drawings. The early P.O.s also helped the manufacturer to reserve manufacturing capacity, though the orders were not yet at this stage scheduled into the production.

4.4.2.2.9 Preparation of shop drawings

The shop drawings were generated with help of the pricing and configuration software. The shop drawings include BOMs, bussing diagrams, front and side views of the boards, and 3-line diagrams. The 3-line diagrams were only generated for the main switchboard and the MCC. The manufacturer has standardized 80% of the required 3-line diagrams, and the software just indicates which 3-line diagram applies to which section; then the drawings were pulled out from the drawing library.

4.4.2.2.10 *Review of shop drawings*

The shop drawings were passed through the manufacturer's sales representative, distributor, electrical contractor, general contractor, construction management to the electrical engineer. All the "middlemen" skimmed through the documents but the electrical engineer approved them. There were 19 approval packages and they were delivered all at once. This was a large effort for the electrical engineer, and there was far too little time reserved for the task. Some shop drawings were not approved before the equipment was already installed.

4.4.2.2.11 *Release of order*

After the owner had approved the shop drawings, the electrical contractor released the order and then the manufacturer scheduled the job for production. When the P.O. is sent, the manufacturer reserves a production slot, but does not schedule it until the release of the order. At this point the electrical contractor requested a shipping schedule of all the boards (day accuracy).

4.4.2.3 *Manufacturing*

The switchboards, MCCs and panelboards were manufactured in different plants. The manufacturer fabricated most of the components in-house. Even the painting was done in-house. The standard lead time is eight weeks after the sales representative has placed the order with manufacturing plant, and all necessary information and components are available. The specific tasks in manufacturing were: (1) purchase components, (2) plan production, and (3) fabricate and assemble parts (Figure 30).

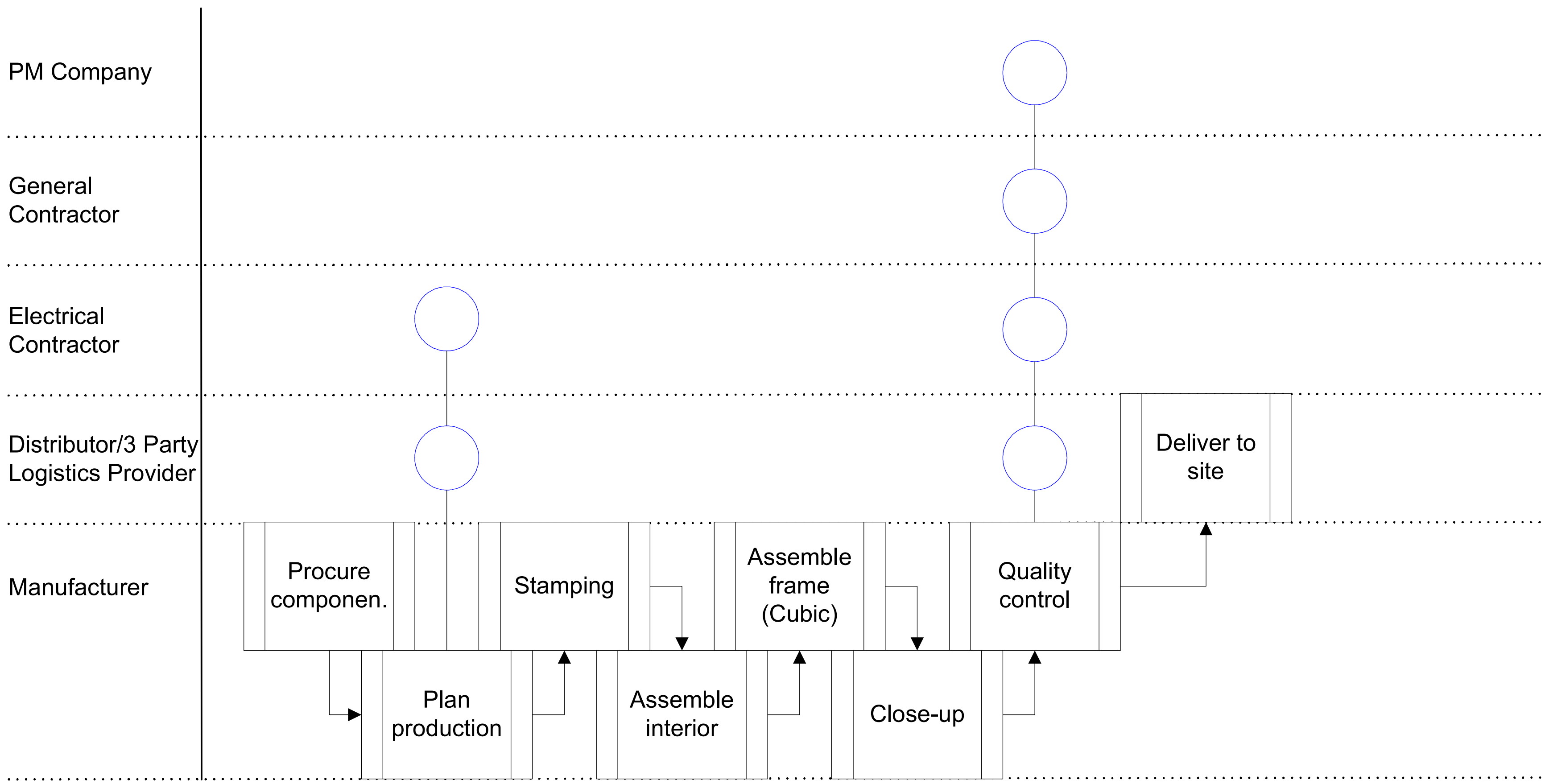


Figure 30: Manufacturing activities in Paradise Pier

4.4.2.3.1 Purchase components

The procurement department sources material for the jobs in three different ways: (1) It looks to see if the material can be pulled from surplus material (excess material from previous jobs) and then allocate it to the current job; (2) it allocates (reserves) material from the manufacturer's current inventory; (3) it orders the long lead time items from suppliers. The inventory status is checked every day, though inventory planning is done monthly. The longest component lead time for low voltage switchboard varied mostly between two and four weeks depending on season and demand.

4.4.2.3.2 Plan production

Production planning is done for a two-week window. Production planning or loading is made based on dollar volume. Production planning reserves two weeks for the production of switchboards.

4.4.2.3.3 Fabricate and assemble parts

In general, the steel parts are processed through three machines before they are painted and assembled. These machines: (1) cut into shapes, (2) punch the steel, and (3) separate steel sheets and stack them together. The bus is processed through cutting, bending, and stamping. The switchboard assembly had four workstations framing, assembling and wiring, cover-up, and quality control. The section frames are assembled separately; and based on customer requests; the sections are joined together after the quality control. In framing, the main bus was also placed. In assembling and wiring, the components and remaining bus was installed and wired. In close-up, the exterior covers were placed; and partition walls, labels and lifting eyes were installed. In quality control, the inspector made routine check of the main parts. Finally the sections of the equipment were shipped mostly the same day they passed the quality inspection. The average manufacturing cycle time was around 3.5 days in 2002.

4.4.3 **Process performance measures**

26 performance measures were measured and calculated (Table 12).

4.4.3.1 LEAD TIME OF THE DELIVERY PROCESS

The lead time of the PDE delivery process includes the design, procurement, and manufacturing lead times. The design started October 22nd, 1997 (Schematic electrical design) and the last switchboard and panelboards arrived May 12th, 2000, thus the time between is 133 weeks or 665 days.

4.4.3.2 DESIGN LEAD TIME

The design lead time started when the electrical engineer received the design task October 22nd 1997, and ended when electrical contract documents were completed November 19th 1998. This results in a design lead time of 56 weeks or 280 days. The dates were captured from design documents. Note that manufacturer's CAD drawings were approved December 12th, 1999. If this had been included in the design lead time, it would have been 112 weeks or 560 days.

4.4.3.3 PROCUREMENT LEAD TIME

The procurement lead time is measured as the time between preparation of electrical RFQ and release of the P.O. This includes the generation and approval of shop drawings. The preparation for electrical RFQ began November 19th 1998, after the electrical design was completed. The last P.O. was released February 20th 2000. Thus, the procurement lead time is 69 weeks.

4.4.3.4 MANUFACTURING LEAD TIME

Manufacturing lead time started when the order was released from the electrical contractor and ended when the last switchboard was received at the site. The contractor released the last order in February 20, 2000, and the last switchboard arrived in April 20 2000. This results in a lead time of 8 weeks or 40 days. Note that if the manufacturing lead time would have been measured from P.O. the lead time would have been 56 weeks or 280 days, because the P.O. was placed March 15th 1999 and the last equipment arrived April 20th 2000.

4.4.3.5 MANUFACTURING CYCLE TIME

The manufacturer did not have data available from 1999 and 2000 thus it was not possible to afterwards measure precisely the cycle time for the pieces of equipment (line-ups). However, the manufacturer kept statistics for some key performance measures, such as cycle time, from the previous year (2002). The average cycle time for low voltage switchboards from 2002 was 3.5 days (28 hours). This number is used here. The cycle time did not include production planning or inventory management.

4.4.3.6 *MANUFACTURING LEAD TIME-CYCLE-TIME RATIO*

The manufacturing lead time-cycle time ratio calculated from the contractor's order release is 11 (8 weeks*5days*8h/28h). The manufacturing lead time-cycle time ratio would be 80 (56weeks*5days*8h/28h), if it were calculated from the P.O.

4.4.3.7 *MANUFACTURER'S BOTTLENECK PROCUREMENT LEAD TIME*

The longest component lead time for the manufacturer with respect to the switchboards is 20 days. The manufacturer's purchasing manager provided the number. All bulked items including some high volume breakers were stocked at the manufacturing facility.

4.4.3.8 *NUMBER OF CHANGE ORDERS*

The project had officially six change directives but there were about 200 smaller design changes and add-ons. On average the manufacturer had one change per switchboard and power panelboard. The numbers were captured from interviews with the owner and manufacturer, and procurement documents.

4.4.3.9 *NUMBER OF DESIGN ITERATIONS*

The project had 5 documented design iterations. However, since the architect and engineers (electrical and mechanical) worked in the same organizations, many of the design iterations were handled without "official documentation". Therefore, this performance measure could not be properly verified.

4.4.3.10 *VALUE-ADDED TIME*

This measure compares the ratio between the actual hours spent for the activities and the total lead time required for the delivery process. Site installation and third party approvals are not included in the calculation. All the value-added times are captured from interviews. I measured the ratio of the whole delivery process by adding the proportional value-added shares from design, procurement, and manufacturing together (i). The sum of all value added hours is 2285. For the three main phases, I used the below equation (i) to calculate the value-added time (VAT):

(i) VAT = LH/(W*LT), where

LH = sum of labor hours spent on each activity within a phase

W = number of workers that were simultaneously occupied with an activity during the phase, e.g., number of electrical engineers that were working on systems design.

LT = lead time of the phase

For design LH is 1710 hours, the average W is 10, and LT is 2240 hours (56 weeks), thus VAT is 8% (1710h/(10 workers*2240h)), when measured per facility it is 0.4%. For procurement LH is 161 hours, the average W is 2, and LT is 2760 hours (69 weeks), thus procurement VAT is 3%. Because it was not possible to verify how many workers were involved during the fabrication a slightly different method was applied to measure the manufacturing VAT[44]: Here the cycle time was divided with the manufacturing lead time. The cycle time is 28 hours and manufacturing lead time is 320 hours (8 weeks); thus, manufacturing VAT is 9%. The VAT for the whole delivery process (ii) is then calculated as the sum of the proportional shares of the tree phases:

(ii) VAT (delivery process) = [(VAT(design) * LH(design))/LH(delivery process] + [VAT(procurement) * LH(procurement)) / LH(delivery process] + [VAT(manufacturing) * LH(manufacturing)) / LH(delivery process]

=> [6%*1710 hours / 2285hours]+[2%*161 hours / 2285hours]+[9%*414 hours/ 2285 hours] = 8% (Figure 31). The ratio per facility is much lower, 0.3%.

4.4.3.11 Number of different components within one product

The total number line items were between 20-50 items per switchboard section. The numbers were taken from manufacturer's BOM.

4.4.3.12 Percentage of standard components

Those parts that were not manufactured by the manufacturer were considered as non-standard components. The percentage of standard components is 85%.

[44] With respect to switchboards 414h were spent on the manufacturing activities.

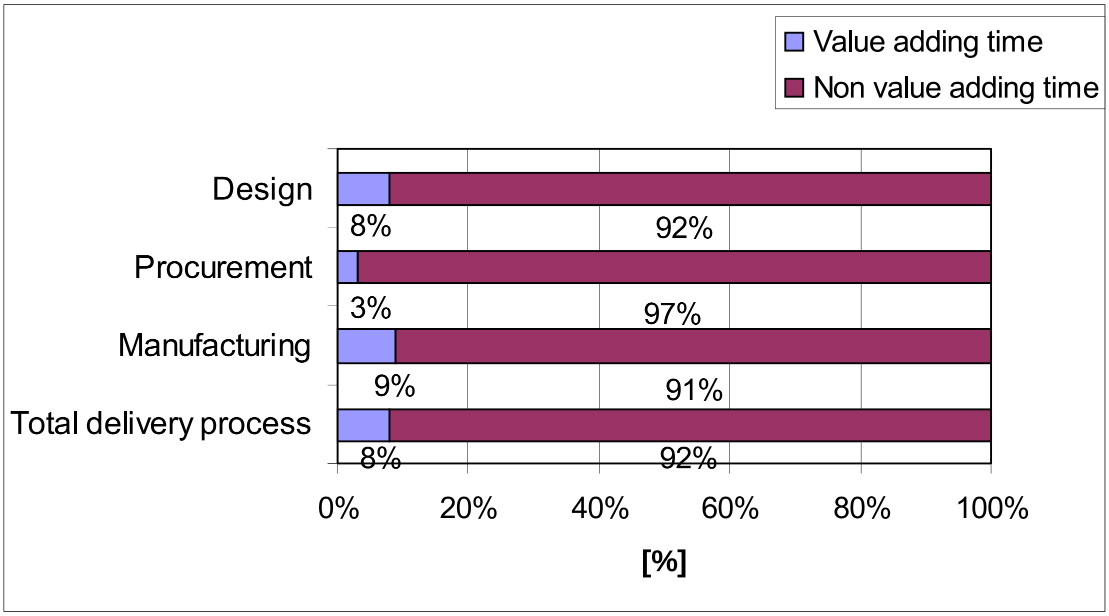


Figure 31: Value-added times in Paradise Pier

4.4.3.13 Number of batches and batch sizes

The unit of the batch is one job (equipment). There were 19 facilities which had 7 switchboards, 12 MCCs, and 148 panelboards, thus a total of 167 jobs The number of batches and the batch size varied throughout the project. In the design and engineering phase, the drawings were generated as one batch (with 167 jobs). Also, all the equipment was procured and shop drawings were generated as one batch (batch size 167 jobs). The shop drawings were approved one facility at time and each facility and between 4 and 20 jobs. In the manufacturer's production planning, the process was broken down to 167 batches (each job/ equipment was one batch). Also, all the switchboards and MCCs were fabricated and shipped as a separate batch (19 batches, batch size 1). The panelboards were shipped as 5-15 jobs per batch. The sequence of the batches did not remain the same throughout the delivery process.

Table 14: Summary of performance measures in Paradise Pier

Performance measure	Unit	Value
Lead time of the delivery process	Week	133
Design lead time	Week	56 (112)
Procurement lead time	Week	69
Manufacturing lead time	Week	8 (56)
Manufacturing cycle time,	Hour	28
Manufacturing lead time-cycle time ratio	N/A	11 (80)
Manufacturer’s bottleneck procurement lead time	Days	20
Number of change orders/ add-ons	N/A	200 (6)
Number of design iterations	N/A	5
Value- Added Time, total	%	8
Value- Added Time, design	%	8
Value- Added Time, procurement	%	3
Value- Added Time, manufacturing	%	9
Hours consumed in design[45]	Hour	1710
Hours consumed in procurement	Hour	161
Hours consumed in manufacturing	Hour	414
Hours consumed in the whole delivery process	Hour	2285
Number of different components in equipment	N/A	20-50
Percentage of standard components	%	85
Batch size in design	Job	167
Batch size in procurement	Job	1-167
Batch size in manufacturing	Job	1-15

4.4.4 Elements contributing to lead time of delivery process of PDE

The delivery lead time was 133 weeks, of which design took 56 weeks, procurement including shop drawing approvals 69 weeks, and manufacturing including shipping 8 weeks (Figure 32).

[45] The 1140 hours of design coordination is excluded from PDE design 1710 hours so that the cases are better comparable. The complexity of Paradise Pier was much higher than the two other case, hence it does not seem justified to compare one-on-one the design coordination hours.

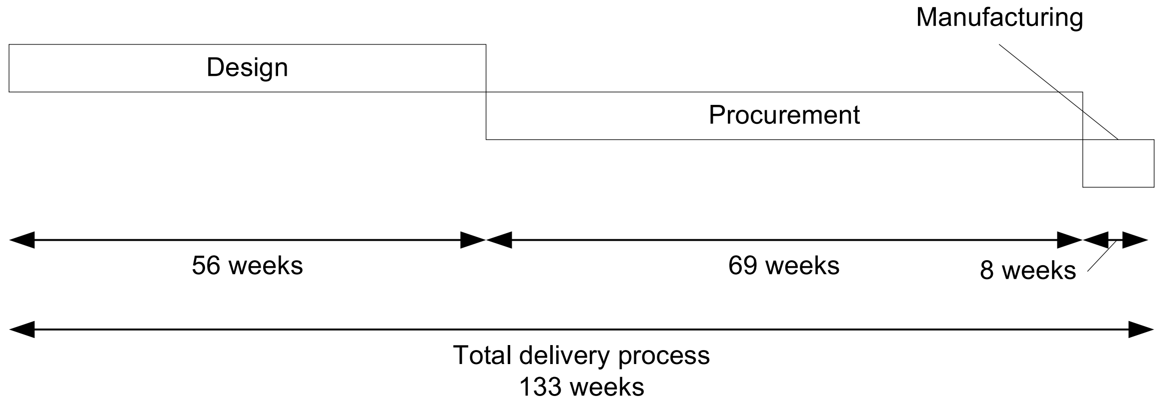


Figure 32: Design, procurement, and manufacturing lead time proportions of the total delivery time in Paradise Pier

4.4.4.1 DESIGN

The value-added time with respect to PDE was only 8% during engineering. The design lead time was 56 weeks. After the RFQ for electrical work was placed, PDE related changes and add-ons were steadily introduced. Even though there were only six official change directives, based on the manufacturers contract and billing documents, the manufacturer estimated that there were about 200 minor changes. Therefore, the specification of the equipment continued until the installation of the equipment, and the last corrections were done during the actual site installation of the equipment. Also, the shop drawings were generated first after the RFQ was placed. The manufacturer developed the shop drawings, which took about two months.

However, there was no need for a connection application with the local utility company because the owner owned the infrastructure within the Theme Park.

4.4.4.2 PROCUREMENT

The value-added time in the procurement phase was 3%. The procurement lead time was 69 weeks. The pre-bid is not included in the procurement lead time, because I considered it as part of the scoping and framing of the equipment design. Of the total procurement lead time, 69 weeks, the electrical contractor quoted eight weeks, including one week for the distributors' equipment quotation (Figure 33).

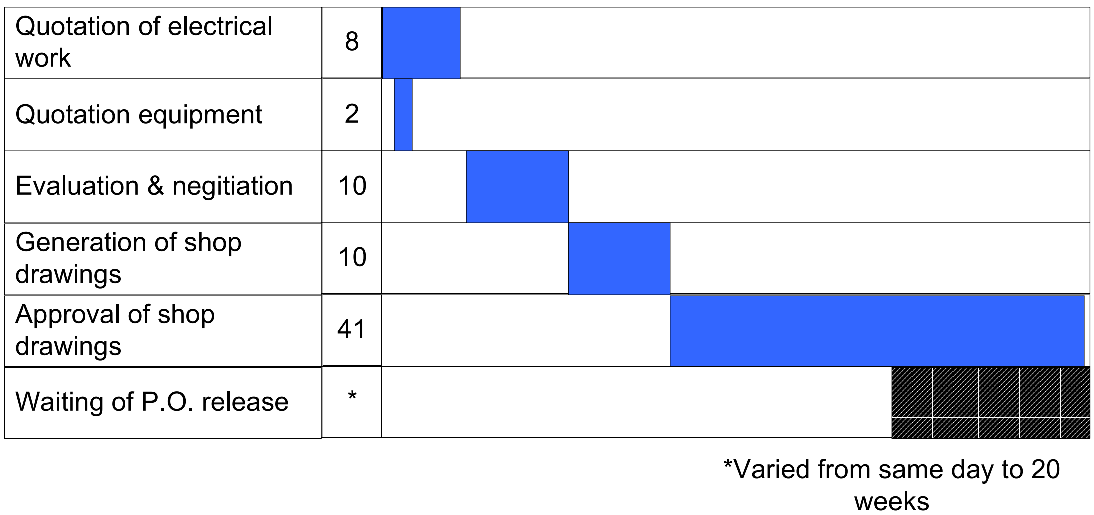


Figure 33: Relative time shares of procurement activities in Paradise Pier

The evaluation and negotiation of electrical work took 10 weeks; the generation of shop drawings took 10 weeks; and the approval of shop drawings took 41 weeks. The electrical contractor placed the purchase order to the distributor immediately after the electrical contract was sealed. The release of the order to manufacturing varied from same day to 20 weeks after the first round of shop drawings had been reviewed. However, all the pieces of the equipment were released before the second round of reviews were completed.

4.4.4.3 *MANUFACTURING*

The value-added time during the manufacturing phase was 9%. The manufacturer's cycle time was only 3.5 days, but he wanted to reserve up to seven weeks of buffer time. Five weeks buffer time was reserved to clarify all equipment specifications between the manufacturer's sales representative and the manufacturer's shop floor. Also, up to three weeks were required to purchase all the components. The procurement of components was conducted simultaneously with the confirmation of equipment specifications. Then, one week was reserved for fabricating parts. Finally, one week was reserved to assemble the equipment. Reserving two weeks for the shop floor operations gave the manufacturer flexibility to deal with rush orders and solve problems in operations, e.g. if a part was missing. After manufacturing, 72 hours was needed for the shipment of one switchboard. Each switchboard and MCC was shipped separately, but several panelboards were batched into one shipment.

4.4.5 Causes of long lead time

The value-added time of the whole delivery process was 8%. 8% from 133 weeks is about 11 weeks, so what contributed to the remaining 122 weeks? Again, the explanation is not within one task or one factor. It is a long list of issues from design to manufacturing, which accumulate into the 133 weeks.

4.4.5.1 *DESIGN*

It was not explicitly considered that the design would impact the delivery process. The main causes that pushed the design lead time were (1) large document batch sizes, (2) design coordination and iteration, (3) changes/add-ons due to early commitment, (4) non-sequenced, push-driven document flow, and (5) coupling with other systems.

4.4.5.1.1 Large document batch sizes

The design of all the 19 facilities was conducted in one large batch. Even the manufacturer submitted the shop drawings to the electrical engineer as a batch that included all 19 facilities. The problem with this is that the design cycle time per equipment became very long, 56 weeks. Every piece of equipment had to wait until all 167 pieces of equipment were specified before a single drawing could be moved to the next phase of the delivery process.

4.4.5.1.2 Design coordination and iteration

The complexity and size of the whole construction project led to the involvement of a large variety of specialists. The specialist provided the electrical engineer input values that they updated as the design evolved. There were five main design iterations. From the accounting documents, the electrical engineer estimated that about 1140 labor hours were used just for coordination of the PDE. 1140 labor hours is about a third of all electrical design hours.

4.4.5.1.3 Changes/add-ons due to early commitment

The design of the equipment had to be “frozen” up to two years prior to site installation of the equipment, so that there was enough time to procure the equipment, approve the shop drawings, and manufacture the equipment. However, the facilities and the drawings were still being developed during the construction phase. Thus, the probability of changes or add-ons to the equipment during that two year period was significant, and, as described in the later chapters, the processing of these changes or add-ons was very tedious and consumed lots of resources.

4.4.5.1.4 Non-sequenced, push driven document flow

The design document batches were pushed downstream based on overall project milestones instead of being pulled from the downstream activities. In other words, e.g., all the shop drawings were submitted at the same time regardless of the actual need on the site. Also, because of the procurement method the final specifications of all the equipment were defined simultaneously and lumped into the RFQ.

4.4.5.1.5 Coupling with other systems

Finally, the PDE was not the only part of the electrical design, which also included lighting, wiring, non-power systems (data/voice), etc. Therefore, the completion of the PDE design had to wait until all the other electrical designs were completed before the next phase of the delivery process, procurement, could be executed.

4.4.5.2 Procurement

The procurement method had a major impact on the delivery lead time. It forced the design to early commitment and large design document batches as described above. Moreover, it caused (1) confusion among the stakeholders, (2) large resource consumption, (3) gaming, and (4) long and slow document flow.

4.4.5.2.1 Confusion among the stakeholders

The owner's purpose for the pre-bid was just to have a price cap for his planning and budgetary purposes. However, this was not clearly communicated to the electrical contractor and the manufacturer. As a result, they all had their own interpretation. The equipment provider thought that it would be consulting in the power system design because they got selected so early. The electrical contractor assumed that the manufacturer's task also included the design coordination and completion. Therefore, the electrical contractor presumed that the manufacturer was constantly aware of the design progression and had access to all the drawings. Ironically, as the manufacturer got involved in the project, it did not even recall that the owner had requested a pre-bid. In reality, the manufacturer's only access to the project data was through the electrical contractor. This resulted in the manufacturer having far too little time to properly prepare a quote, causing errors in the quote that had to be corrected later.

4.4.5.2.2 Large resource consumption

The competitive bidding consumed many more resources than expected. The main phases in the bidding included preparing the RFQs, executing the bidding process and controlling the post-contract issues. However, these phases included a wide variety of tasks. Below is a list of tasks that had to be executed for the competitive bids on Paradise Pier.

Owner (prebid):

- Prepare prebid request documents.
- Prepare bidders list and send prebid request documents.

- Tabulate bids.
- Negotiate with manufacturer.
- Award and approve contract.

General contractor (electrical work):

- Prepare RFQ documents for electrical work.
- Send RFQ documents.
- Compare quotes.
- Negotiate with electrical contractor.
- Award and approve the contract.

Electrical contractor (Quote and RFQ PDE):

- Prepare RFQ documents for electrical equipment.
- Send RFQ documents.
- Compare equipment quotes.
- Negotiate with distributor.
- Award and approve the contract.
- Quote for general contractor
- Negotiate with general contractor

Manufacturer's sales representative:

- Quote for owner
- Negotiate with owner
- Quote for electrical contractor
- Negotiate with electrical contractor through distributor.

4.4.5.2.3 GAMING

The competitive bidding also caused destructive gaming, where stakeholders postponed information sharing until the latest possible moment. For example, the manufacturer's sales representative received the RFQs from the electrical contractor very late and did not have time to go through the details, which was one reason for product related errors on the site. The reason why the electrical contractor wanted to postpone the RFQs to as late as possible was that he was expecting changes, and he did not want the manufacturer to take advantage of the later changes by marking them significantly higher than the originally quoted items. Similar behavior was noted between the owner's construction management team and the general contractor and the electrical contractor.

4.4.5.2.4 LONG AND SLOW DOCUMENT FLOW

The documents of the PDE followed the pattern: electrical engineer (owner), construction management (owner), general contractor, electrical contractor, distributor, manufacturer's sales representative, electrical engineer (manufacturer), and production planning (manufacturer). When something had to be clarified for the manufacturer's production planning, it could easily take several months before the information had traveled back and forth. Also, keep in mind that there were around 200 changes or add-ons related to the equipment, which combined with the document pattern created an information "ball-of-yarn".

4.4.5.3 Manufacturing

The manufacturer’s shop did not have control over the input variability caused by the upstream phases of the delivery process. However, even though the order information was handled through the sophisticated configuration software, the manufacturer needed up to five weeks to sort out internally the product specifications. The reason was that the sales representative requested features that were not standard and the software was not able to generate them automatically. Also, the manufacturer’s component supplier lead times were up to three weeks but the procurement was for the most part performed based on forecast. Thus, the inventory did not always match the actual need.

4.4.6 Opportunities to improve the process: Future state

Based on suggestions in the workshops and interviews, and applying the TFV concept, considerable improvement opportunities were identified, with special importance for, closer cooperation between the owner and manufacturer.

4.4.6.1 Design

In the design phase two main improvement suggestions were introduced. First, the design batch was proposed to be one facility instead of the whole project. Second, the owner would generate the shop drawings with the manufacturer’s configuration software. These changes were estimated to eliminate up to year from the detailed engineering and approval phases. Also, up to 400 labor hours could be saved.

4.4.6.1.1 *OWNER GENERATED SHOP DRAWINGS*

In the current state map, the shop drawing approvals took 49 weeks and caused plenty of problems and uncertainty for the manufacturer and electrical contractor; in addition, the electrical engineers were overwhelmed by the task. However, generating shop drawings from the one-line diagram (panel schedule) with help of the manufacturer’s configuration software takes at most a few hours per piece of equipment. On Paradise Pier, the manufacturer’s sales representative spent approximately 25 hours for the initial shop drawings for all 19 facilities.

If the owner’s electrical engineer used the software and generated the shop drawings, it would radically impact the delivery process. First, there would be no need for the tedious approvals because the owner (end customer) would generate the shop drawings and he would straight away be able to compare various configurations, be informed of the price impact, and informed of the requirements of the equipment. Thus the manufacturer would not need to “guess” some of the obscurities that the electrical engineer would then need to approve. The equipment would be detailed and specified from the beginning according to the owner’s requirements. Second, there would be less of the type of gaming that currently occurs, where each middleman in the process tries to postpone the release of his information for as long as possible to protect himself from potential changes. This would diminish simply because there would not be a middleman to handle the shop drawings and the changes in shop drawings.

The proposed changes in the current state map would perhaps yield the greatest benefits. It would eliminate 10 activities, with very attractive potential savings in process time and resources. The process time could be reduced up to 48 weeks (36% of the current total process time) and the labor hour savings would be at least 330h[46] but probably much higher.

4.4.6.1.2 ONE FACILITY DOCUMENT FLOW

On Paradise Pier, the document batch size related to PDE was improperly or not at all planned. The design and procurement documents including shop drawing documents were mostly transferred between the various organizations as one large batch that included the documents of all 19 facilities. Moreover, every facility had its own one-line diagram that could have been designed relatively independently of the other facilities' one-line diagrams. The large document batch had a major impact on the lead time of the whole delivery process and was one reason for temporary overloading of the resources, which led to useless rush

[46] The approval of the shop drawings took about 230h for the electrical engineer, who spent 16h to review the shop drawings, and another hour each time shop drawings were re-released or approved (28 times). This gives an estimated 44h for the electrical contractor. On top of this, each middleman (distributor, general contractor, construction management) spent an estimated average of 1h for submitted and approved shop drawing instances (29 instances). This adds up to 57h. Even without considering the manufacturer's required hours to fix the shop drawings, the cumulative labor hours for only shop drawing approvals and document distribution were about 330h

and unnecessary errors. Therefore, it is suggested that the batch size be reduced from 19 facilities to only one.

This means that every participant is working on only one facility at a time and does not start to process any other facility before the documents of the prior facility is passed to the next downstream player. For example, the electrical engineer would not wait until all the one-line diagrams are completed before passing a single drawing to the electrical contractor or manufacturer. Instead he would pass one one-line diagram at a time. Also the manufacturer would submit only one shop drawing at a time for approval instead of all facilities at once as happened on Paradise Pier. In case the electrical engineer would generate the shop drawings, as proposed in the previous chapter, the electrical engineer would complete the one-line diagram for one facility and generate the required shop drawings respectively, before fine tuning the next one line diagram. In the manufacturer's shop every piece of equipment (line-up) is processed as its own job and each piece is assembled and delivered to the site separately from the others. Hence, the concept of batch-size-one exists already in the downstream of the process.

The proposed change would reduce the cycle time from the completed one-line diagram to the approved shop drawings by a factor of 18[47]. Since the cycle time for this process was 69 weeks, this would mean that time-wise the cycle time of the document flow could be reduced to less than 4 weeks, if the set-up

---

[47] When the processing batch size is 19, the last job in the batch needs to wait that all 18 jobs gets processed before the last job gets processed.

time was ignored. The set-up time refers to the time that it takes for preparatory work before the actual processing of the documents can start, e.g. the electrical engineer would need to pull out the latest specifications before approving the shop drawings, the manufacturer would need to pull the job code from the database with related job information, etc. However, the set-up time is relatively small compared to the processing time of the documents; thus, it is justified to ignore it.

Nevertheless, the proposed batch-size-one document flow would take more resources to execute than the current batch size of 19 if the PDE were bought through competitive bidding. The reason is that the procurement would be executed 19 times (for each facility separately), e.g. the general contractor would place 19 RFQs, the electrical contractors would quote 19 times, and there would be 19 contract negotiations. Therefore, the proposal of batch-size-one would require to be implemented along with the proposal that the owner furnish equipment. In production theory terms, the batch-size-one proposal would address the flow view of the process.

4.4.6.1.3 SET-BASED SYSTEMS DESIGN

The current systems level design is mostly based on a point-based design strategy, where the various design disciplines provide the electrical engineer definitive input values instead of a range of input values as in set-based design. Hence, coordinating and matching the various input values in order to achieve a feasible design solution was very tedious and consumed an estimated 1140 hours for the electrical engineer only in the case of the PDE. Set-based design may be a superior approach.

On Paradise Pier, e.g., the HVAC engineers could have provided the electrical engineer a list of alternative equipment with their horsepower and control requirements. Then the electrical engineer could develop a design or a few alternative designs that would have considered all the HVAC alternatives and narrowed down the solution space as little as possible (not as much as possible) as the design evolved. The methodology is fairly new in the construction industry; thus, little data is available about its implementation.

4.4.6.2 Procurement

The current way of procuring equipment consumes lots of resources and time in the delivery process. Moreover, since the owner locked in the upper boundary of the equipment price already during the feasibility phase, there seems to be little justification for letting the electrical contractor buy the equipment through his distributor. Therefore, other contracting alternatives that would reduce the waste from the current competitive bidding, such as owner furnished equipment or design-build electrical contracting are worthwhile to evaluate. For example, the owner furnished equipment could reduce the procurement time by an estimated 20 weeks, saving hundreds of labor hours. At the same time there would be fewer interfaces for miscommunication, because the manufacturer would not need to deal with the electrical engineer through the distributor, electrical contractor, general contractor, and construction management. Instead the manufacturer could communicate directly with the electrical engineer, who is the actual decision maker. The change would remove approximately 9 tasks from the current state map. Figure 34 provides a general view of the redesigned delivery process.

This type of arrangement would also require some incentives for the electrical contractor, because there have been cases where the electrical contractor has not purchased the equipment and therefore has not felt responsible for the timeliness and correctness of equipment delivery. One of the incentives would be to reduce the electrical contractor's document flow burden, on which the electrical contractor spends lots of time. The large document flow is mainly caused by the shop drawings, changes, and add-ons, and in most cases the electrical contractor is just a middleman. Part of the document flow could be eliminated if the owner used the manufacturer's software to generate shop drawings.

4.4.6.3 Manufacturing and site installation

On Paradise Pier, the power distribution documents of all 19 facilities were mostly handled as one big lump and they were pushed through the process until the approval of shop drawings without much attention paid to the actual needs on the site. Only when the shop drawings were under the electrical engineer's approval, did the electrical engineer and the electrical contractor begin to prioritize the more urgent facilities. Therefore, the engineering and procurement schedule of the equipment had to be forecasted and it did not necessarily correspond with actual site installation needs. As a result, some engineering

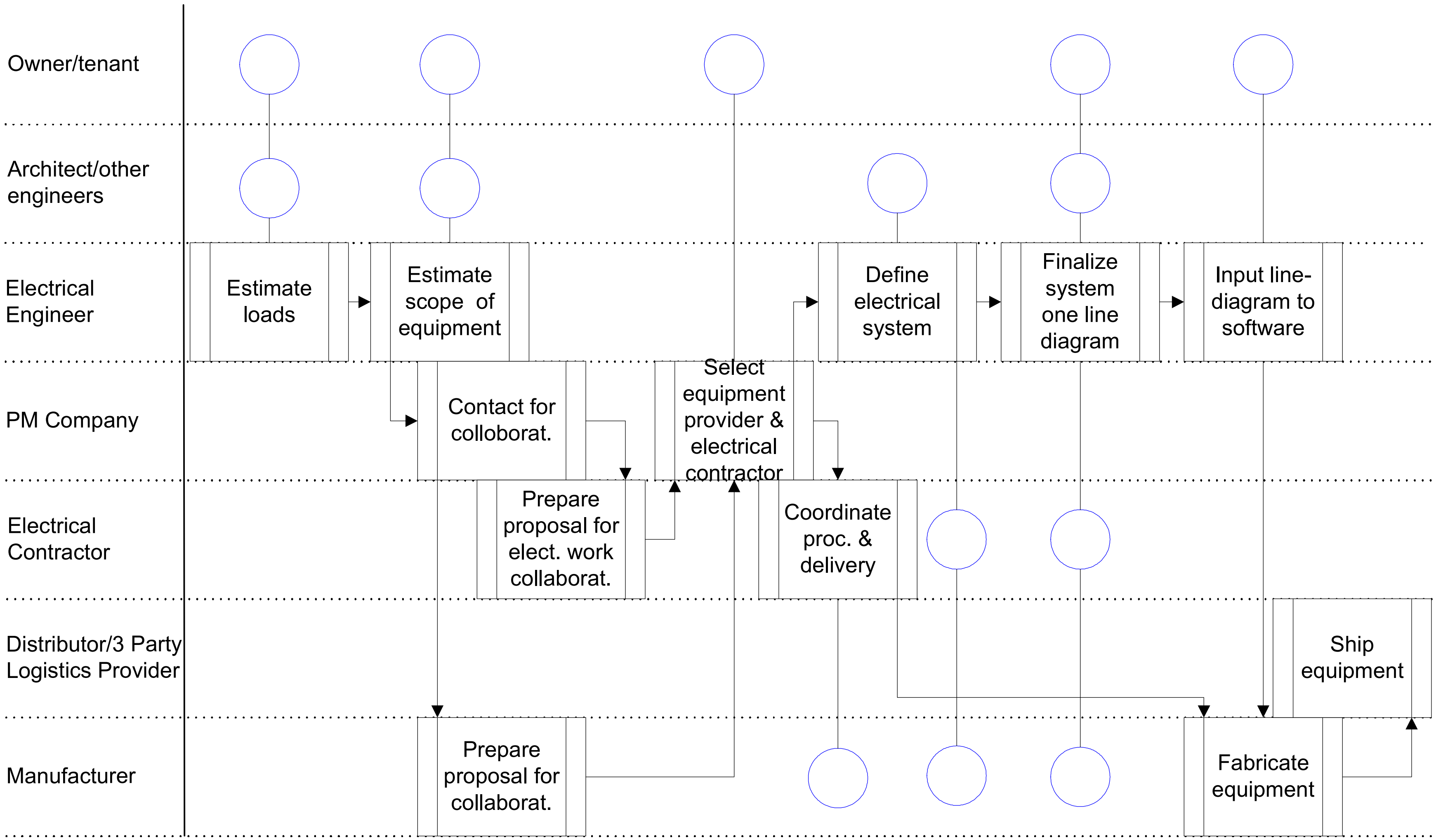


Figure 34: Future delivery process for PDE in Paradise Pier

documents were completed too early and others too late. Because the equipment was on a critical path, the documents that were late became an issue of dispute. The push based document flow could not properly adjust to the continuous changes in the project and on the site, which further increased the number of documents that had to be sent back and forth.

Consequently, it is proposed that the electrical contractor on site pull the required drawings and equipment from the electrical engineer and manufacturer. If all the previous changes were implemented, the time from one-line diagram to equipment on site could be reduced to two months. In the case of the above suggestion, the electrical contractor would request the manufacturer to deliver the equipment two months before the actual site installation of the equipment. Then, the manufacturer would request the electrical engineer to generate the shop drawings with help from the manufacturer's software. As a result, the first set of drawings would already be much closer to the final revision of the project. Most of the design iteration related to the PDE that occurred during the year before the actual construction commencement could be avoided. The resource savings, in the form of rework (redesign, document updates), transfer of documents, and inspections (shop drawing approvals, reviewing approved and corrected documents) would be significant throughout the process[48].

---

[48] The participants of the case study did not want to estimate the actual savings of the labor hours due to too many factors that would have needed to be assumed and estimated. Nevertheless, it was generally agreed that the labor hour savings would be notable.

Moreover, it would make the whole process more reliable because everything would be based on recent site information rather than on information that was applied for the forecast. In production theory terms, the pulled based document and equipment hand-off would address the flow and value views of the process.

The estimated impacts of the improvement suggestions on the current delivery process are summarized in Table 13.

Table 15: Summary of key improvement suggestions in Paradise Pier

Improvement suggestion	Number of reduced tasks	Reduced lead time [weeks]
Owner generated shop drawings	10	48[49]
One facility document flow	-	65[50]
Redesign of procurement method	9	20
Total	**19**	**68**

4.4.7 Summary

The main causes for the long lead time were:

- Large non-sequenced document batch sizes
- Collection and coordination of design input values
- Complexity of the project and the large number of specialists
- Coupling PDE with other electrical work
- Use of competitive bidding as procurement method
- Hierarchical document flow

[49] The 48 weeks would be a reduction in the procurement lead time, because in the current state the shop drawing approval was considered as part of the procurement process.

[50] The 65 weeks refer to postponement of detailed engineering, not a direct reduction in design lead time.

- Shop drawing approvals
- Misconception about the role of the stakeholders
- Gaming
- Manufacturer’s internal confirmation of equipment specifications.

4.5 Comparison of the cases

All three cases were different in scope and complexity. In addition, they were conducted in two different countries, which also gave insights to cultural and trade practice issues. In spite of the different settings the problems seem to be similar in all cases though some of the methods in various stages differed.

4.5.1 Commonalities in the cases

The delivery process in all three cases can be characterized as fragmented, complex, and uncertain with numerous changes and add-ons. Generally, the lead times of the delivery processes were long, one and half years or more; and the value added times of the delivery processes were low, 13% or less. The reasons for these were surprisingly similar. The cases also provided further evidence of the "vicious circle" behavior, which was identified in the pilot study (Elfving et al. 2002).

In the vicious circle longer manufacturing lead time causes more engineering uncertainty and more engineering uncertainty leads to longer manufacturing lead time (Figure 35). The downstream players of the delivery process, manufacturer and contractor, strives to "freeze" the product specification as early as possible having significantly more time available as actually needed for executing the task. Conclusively, the designers upstream in the delivery process are force to make their design decision at a very early stage. As a result, design decisions are often based vague assumption with a high probability that they will be later corrected. However, the downstream players, who are aware of the high uncertainty of the upstream information, are hedging against the uncertainty by requiring even more “slack time”.

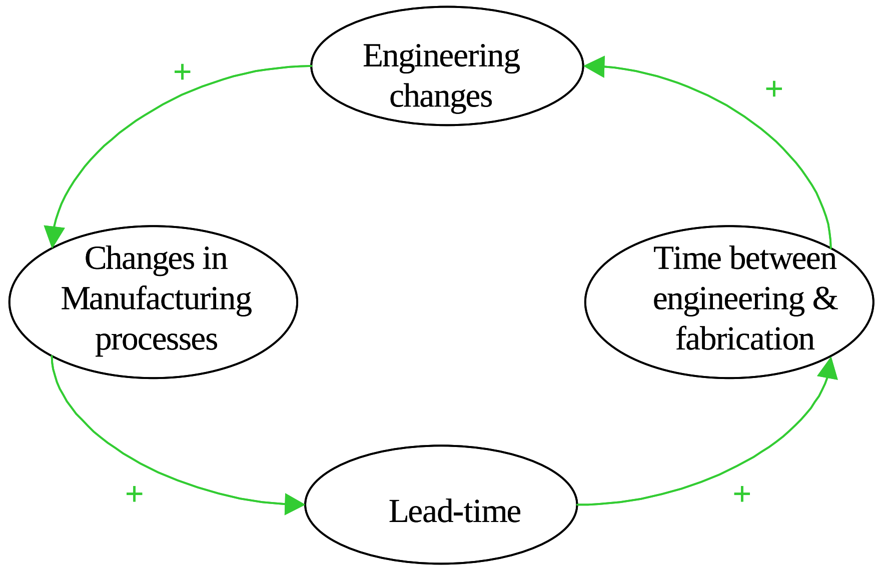


Figure 35: Vicious circle in the delivery process

The vicious circle is further complicated by the fact that some players in the delivery process seem to rely on change orders for their profitability. The process and organizational structures have been settled and unchanged for a long time. In this type of static environment where everyone has about the same, fixed production system and replaceable products, the competition is often restricted to cost. However, in the PDE, the cost has not been based on systems cost, it is based on minimum component cost.

4.5.1.1 Design

With respect to design, the following findings were identified in all three cases:

- The power distribution design was coupled with the whole electrical design, and time-wise consumed less than 10% of the overall electrical design time.
- Collection of input values was the most frustrating design task because it was tedious and the input values had poor reliability. This was further complicated by the fact that several stakeholders had to provide design input, which then had to be coordinated among the parties.
- All the equipment in every building was designed and specified before a single item of equipment was procured; thus, the design document batch sizes were large, ranging from 78 to 167 equipment items per batch; consequently, the design cycle times per equipment were long, ranging from 22 to 56 weeks.

4.5.1.2 PROCUREMENT

With respect to procurement, the findings below were identified in all three cases:

- Competitive bidding was the procurement method of choice.
- Competitive bidding was the main reason for large design document batches, because the design was driven by the need for contract documents.
- Competitive bidding increased the lead time of the delivery process more indirectly, than directly; i.e., by increasing the duration of the document cycle, as opposed to increasing time spent on procurement activities.

- The equipment was always bought through several organizational layers, e.g., PM company, electrical contractor, distributor, manufacturer's sales representative.
- The value of competitive bidding is not clear as it comes to product and process cost.
- Procurement consumed more time than originally planned.
- The document flows between the electrical engineer-of-record and the manufacturer were sequential, where the documents had to travel through several organizations that did not have the authority to approve documents.

4.5.1.3 Manufacturing

With respect to manufacturing and shipping, the findings below were identified in all three cases:

- Of the three main phases; design, procurement, and manufacturing, the last had by far the shortest lead time.
- Manufacturers had in-house capabilities for detailed engineering.
- Manufacturers had no control over design variability, and they used lead time as the primary buffer against that uncertainty.
- Early involvement of the manufacturer would have helped to reduce the lead time of the delivery process, by allowing postponement of detailed engineering; and reducing waste, e.g., by reducing rework caused by changes and by reducing waiting through better synchronizing the design with manufacturing.

4.5.2 Differences in the cases

The design, procurement, and manufacturing methods of Paradise Pier and the Bay Street case had only minor differences compared to some fundamental differences in the methods between the US cases (Bay Street, Paradise Pier) and the Finnish case (Novo).

4.5.2.1 *DESIGN*

Table 16 compares the value-added design hours in the 3 cases. The Finnish case consumed clearly more design hours per facility and/or equipment. The main reason was the laborious generation of 3-line diagrams. One third of the total electrical design hours were spent on the 3-line diagram in the Finnish case, whereas in the US cases at most a ninth of this time was needed.

Table 16: Comparison of value-added design hours

Design hours	**Case 1: Bay Street, USA [h]**	**Case 2: Novo, Finland [h]**	**Case 3: Paradise Pier, USA [h]**
Systemes design[51]	336	220	445
Detailed engineering[52]	580	363	1265
3-line diagrams	38	274	32
Total	**954**	**857**	**1710 (1260)**
Per equipment (total number of equipment)	**5.6 (164)**	**10.1 (78)**	**10.2(167)**
Per building (total number of facilities)	**77 (6)**	**857 (1)**	**72 (19)**

[51] Systems design includes the review of architectural program, electrical load estimate, grouping of the equipment, preparation of utility documents, and 30% design approval.

[52] Detailed engineering includes one-line diagrams, location plan, panel schedules, equipment specifications, site delivery plan, and 60% and 90% design approvals.

The 3-line-diagram (Figure 36) defines the electrical wiring of the equipment. One main switchboard can have over 100 CAD-pages of 3-line diagrams, and the Finnish case had over a thousand pages of 3-line-diagrams. Thus, the way they are generated has a major impact on the engineering time.

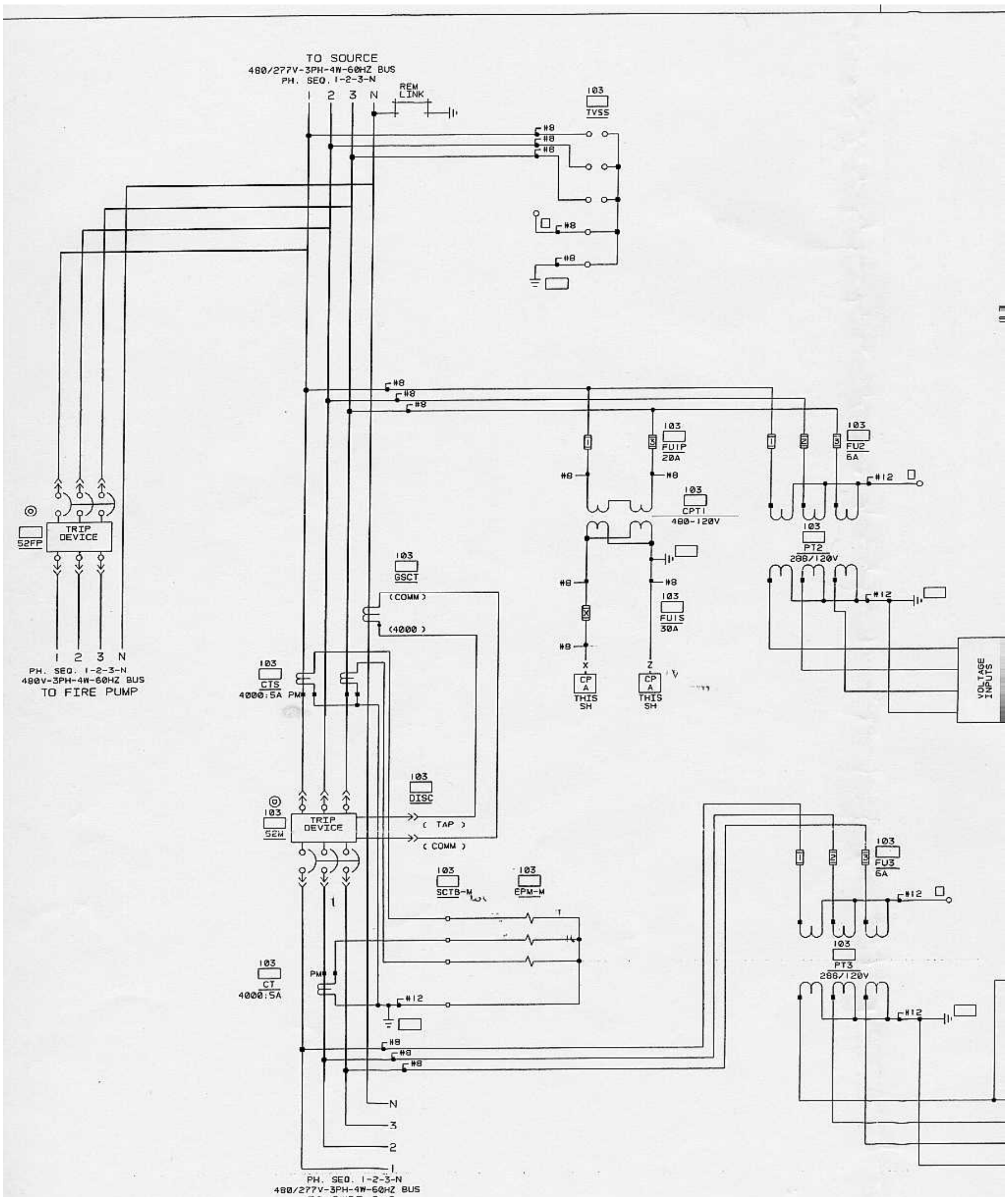


Figure 36: Example of a partial 3-line diagram

The Finnish case had also more changes and add-ons than the US cases (Table 17). At least, the types of standards and configuration software that are used in the two countries can explain part of the differences in design hours and changes.

Table 17 Comparison of number of changes and add-ons

Performance measure	Case 1: Bay Street, USA	Case 2: Novo, Finland	Case 3: Paradise Pier. USA
Number of change orders/ add-ons	337	300	200
Average number of changes/equipment	2.1	3.8	1.2

In the US, several standard setting bodies, especially the National Electrical Manufacturer Association (NEMA), Underwriters Laboratories Inc. (UL), and the large equipment fabricators, have standardized the switchboards and panelboards at the product level, whereas in Finland the standardization, which is based on the European EN-standard, has gone from a product level standardization to a performance level standardization. This means that in Finland the detailed engineering, like 3-line-diagrams, has to be custom-drawn for each board every time compared to standard diagrams in the US. Earlier, e.g., Smeaton (1987) noted the differences between the European and the US standards and their impact on design of PDE.

The custom-drawn diagrams are not only time consuming to generate, another disadvantage is that they are prone to errors. Also, changes are very tedious and time consuming to implement into the custom-drawn drawings, because in some cases the electrical engineer has to go through numerous CAD-pages to make sure that no wiring conflicts exist in the diagrams. A small error in the diagrams can have serious consequences for the power distribution in a building and cause both operational and safety hazards.

In addition, in the US cases, equipment manufacturers have advanced software that automatically identifies which 3-line-diagram has to be used in the ordered equipment. Therefore, sometimes the 3-line diagram can be pulled directly from the drawing library without any need to further process it. The development and implementation of such configuration software requires a significant level of product standardization, is expensive, and takes many years, which may be one reason why the relatively small Finnish equipment manufacturers do not yet have one. Moreover, in the US, the manufacturers generate the diagrams, not the electrical engineer-of-record or the electrical contractor as in Finland. This has further helped the manufacturers to standardize the diagrams and also the assembly on the shop floor.

Finally, in the US cases, the design lead times were clearly less than the procurement lead times, whereas in the Finnish case it was the opposite. Two main reasons may explain the phenomenon. First, the electrical engineer had to spend relatively more time in collecting input values in the Finnish case than in the US case, which indicates poorer design coordination and/or lower owner and tenant commitment. Second, the US procurement methods were more hierarchical and the documents had more hand-offs (2-3) than in the Finnish case.

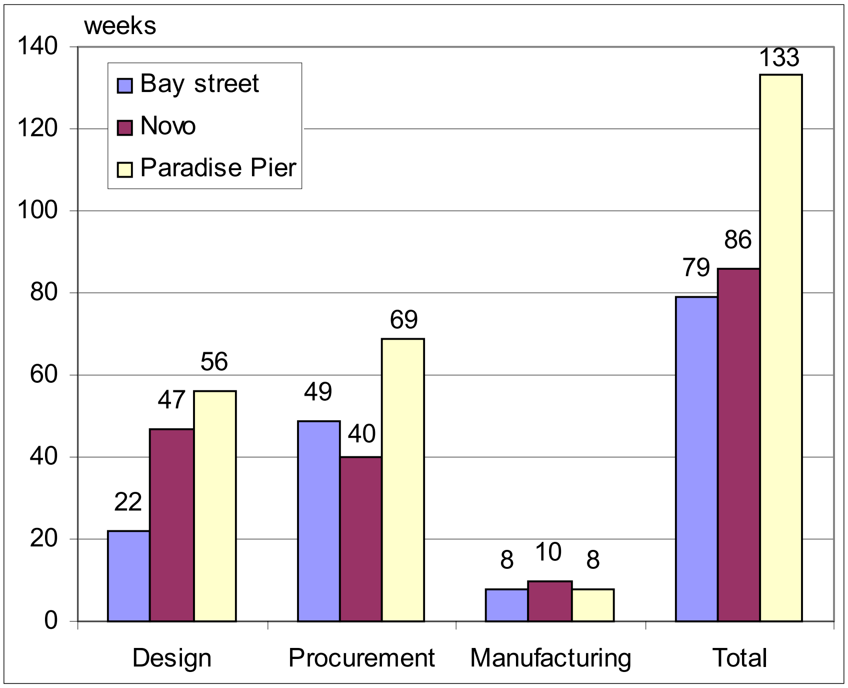


Figure 37: Comparison of delivery phases and lead times between cases

4.5.2.2 PROCUREMENT

The procurement lead time was 20% and 70% longer in the US cases than in the Finnish case. In the US cases, a distributor and a manufacturer's sales representative were involved in procurement, whereas in Finland the electrical contractor bought the equipment directly from the manufacturer. The US practice added about one month to the whole delivery process, because the manufacturer needed some additional information from the customer, and it easily took one month before the information had traveled back and forth from the manufacturer to the customer through the two middlemen. Besides the more hierarchical procurement practice in the US cases, also the two-phased procurement caused both a purchase order and a release of the order to be placed. One reason for the two phased procurement is that the electrical contractor wants to procure the equipment as early as possible so that as the project evolves and changes and add-ons occur he gets compensated with better margins than in his initial contract.

The Finnish case used significantly more labor hours for the procurement than the US cases, though the ratio of value added time (VAT) was higher (Table 18). This is explained by the complex bidding practice in the Finnish case, where the manufacturer had to quote three times for the same job compared to one time on Bay Street. In fact, on Paradise Pier, the manufacturer actually quoted twice (pre-quote and actual quote). The first quote, where the owner fixed a price cap for the PDE by a pre-bid, was four years prior to the purchase order. The owner placed RFQs during the feasibility phase, when there were only rough schemes about the design. This stage is not actually considered in this study, because it included several other capital projects and proper data was not available. In the second quote, the manufacturer's sales representative quoted only Paradise Pier.

Table 18: Comparison of value-added time in procurement

Performance measure	Unit	Case 1: Bay Street, USA	Case 2: Novo, Finland	Case 3: Paradise Pier, USA
Value-added hours in procurement	H	217	554	161
Proportion of VAT in procurement	%	6	9 and 12	3

Another major difference between the Finland and US cases was in the take-off. In the US cases, the manufacturer's sales representative came to the electrical contractor's office and did the take-off. In Finland, the electrical contractor sent the bid documents to the manufacturer. The advantage of the US practice is that the sales representative has access to all the project drawings, so that if questions arise, the sales representative is better able to make adjustments than in Finland, where the manufacturer has to rely on the documents he receives from the electrical contractor. For example, in Finland, the manufacturer does not have the floor plans, though they would be helpful for the quotation and to help to ensure that the owner's needs are met. The disadvantage of the US practice is that, even if the sales representatives do the take-off only for the large and mid-size electrical contractors, it requires a large sales organization.

In the US cases, the take-off was also better integrated with the downstream tasks. Through a high degree of standardization, the large US manufacturers have been able to integrate the detailed engineering into their pricing and configuration software. In this case, during the take-off for the quotation the manufacturer fed the BOM from the RFQ into the pricing software, which at same time as it generated the price also generated the shop drawings, including the 3-line diagram. Some configuration software has been made foolproof for the national and local code and regulation requirements so that a user cannot input certain values, or the software automatically changes the default values to avoid errors in the board configuration. In the Finnish case, the estimation, materials management and drawing software were not integrated and did not have the above capabilities.

Finally, the RFQ documents differ between the two countries. This relates back to the 3-line-diagrams. In the US, a one-line-diagram (also called elevation drawing), which includes the panel schedules, is the main RFQ document. In

Finland, in addition to the one-line diagram, a detailed board design, which demonstrates how the various components will be connected to each other, is needed as well. The extra drawings are required because the manufacturer does not have control over the 3-line-diagram, which greatly impacts the structure of the boards.

4.5.2.3 *MANUFACTURING AND SHIPPING*

In manufacturing, the most significant difference was in the cycle time. In the US cases, the cycle time for the main switchboard was between 2 and 3.5 days, and in Finland the cycle time for the main switchboard was about 13 days[53] (Table 19).

Table 19: Comparison of value added time, cycle time, and lead time

Performance measure	**Unit**	**Case 1: Bay Street, USA**	**Case 2: Novo, Finland**	**Case 3: Paradise Pier. USA**
Value added hours	H	229	216	414
VAT	%	5	27	9
Manufacturing cycle-time	Day	2	13	3.5
Manufacturing lead time	Week	8	10	8
Manufacturing lead time-cycle time ratio	N/A	20	4	11

The reason for the dramatically shorter cycle time is in the batch size. In the US, the frame, the installation of components and wiring are made separately for each section, and the sections are first connected together at the end of the

[53] The main switchboards that were compared were similar in size (8-12 sections) and complexity (wiring and number of components). The study did not compare MCCs because they can vary over a much larger range and are much more customized than switchboards and panelboards.

assembly. In Finland, the frame, the installation of equipment and wiring of the sections are done together from the beginning (Figure 38).

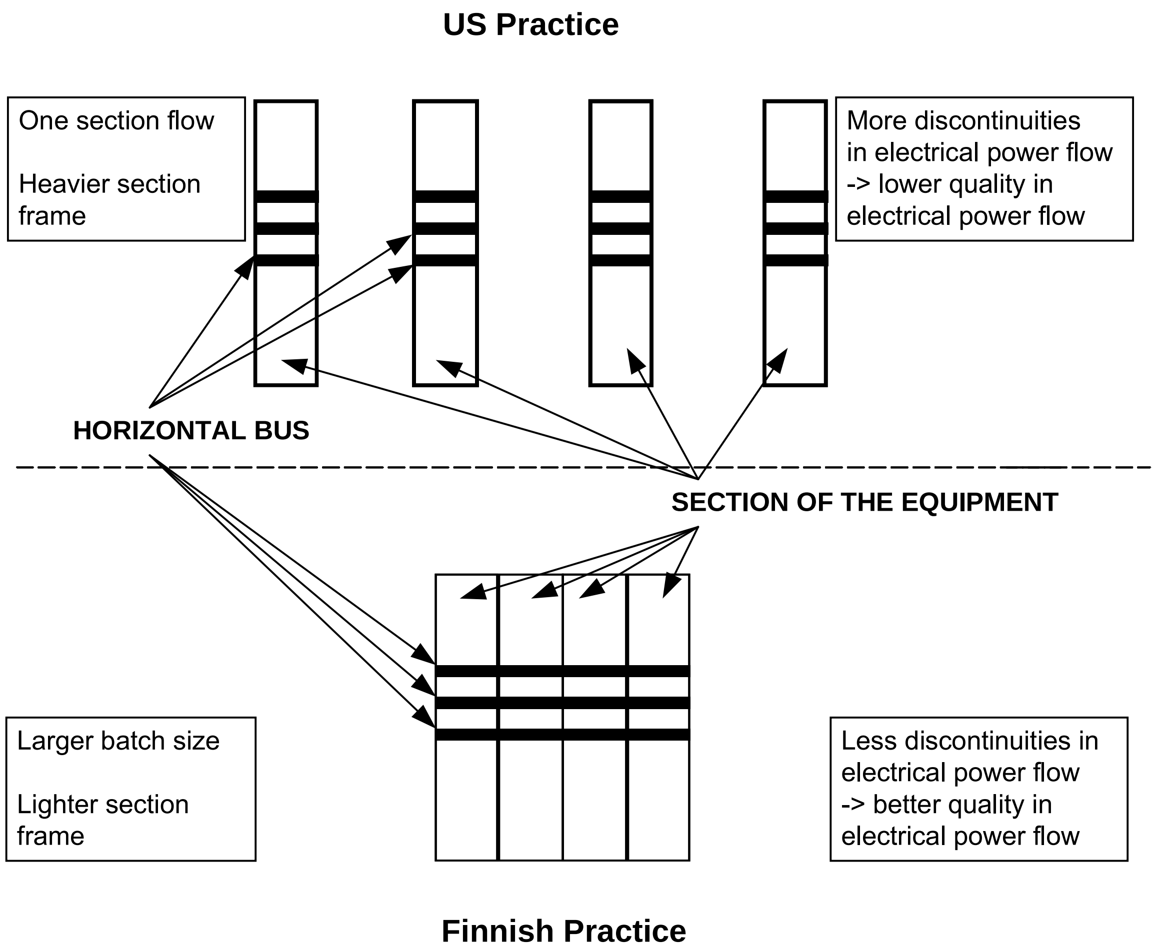


Figure 38: Differences in US and Finnish manufacturing practice.

The advantage of US manufacturing practice is the smaller batch sizes and one-section-flow. When the sections are built separately, one worker can work with each of the sections and the sections can be built simultaneously in parallel. If the sections are joined together straight from the beginning only one or two workers can assemble the switchboard due to space constraints around the equipment and the completion of each work stage takes much longer as there are sections in the equipment. This insight is not new, several other researchers and practitioners (e.g., Shingo 1988 pp. 132-5, Hopp and Spearman 2000 pp. 305-11) have demonstrated the relation between parallel operation, batch size, and cycle time.

The disadvantage in building the sections separately or according to the one-section flow, is that every discontinuity or split in the horizontal bus may cause a failure in electrical power flow, and the more discontinuities there are, the higher is the probability for error. According to one manufacturer's shop manager, about 1% of their connections have problems in his US plant. In Finland, the horizontal busses, which need to go through several sections, are installed as one piece. Also, the frame requires less material when several sections are built together than when each section is built separately, requiring a self-supporting frame.

In addition, due to the high level of product standardization in the US, the installation of equipment and wiring is also on average faster. However, the manufacturing lead time is about the same, though there is a large difference in cycle time between the Finnish case and the US cases. The lead time-cycle time ratio is 4 for the Finnish case, and 11 and 20 for the US cases. The difference cannot be explained by differences in manufacturers' component procurement lead times, because they were about the same, 2-3 weeks. The main cause is that the manufacturers in the US cases have large organizations with hundreds of sales representatives that are rarely able to confirm the manufacturing status without one or two middlemen, hence the internal information exchange is sequential and slow, and required up to five weeks of buffer time. In the Finnish case, sales personnel are located in the plant and they visit the shop floor daily and talk with the CAD draftsmen directly, thus the organizational structure is flat and internal information exchanges are fast. The argument is also supported by findings from e.g., Schonberger (1996 p. 166, 180) and Wortmann et al. (1997 p. 224), who emphasize the integration of decision-making and information integration as techniques for reducing manufacturing lead times.

4.5.3 Future state

Many of the issues where the same in all three cases, thus a general characteristics of a future state process, which was developed in cooperation with the industry participants is presented below.

4.5.3.1 DESIGN

There is an opportunity to significantly reduce the design time and make it more robust against changes. This would require that:

1. PDE design is decoupled from the rest of the electrical design and not driven by the schedule of overall contract documents of electrical work.
2. Input information from other engineering disciplines and the owner is collected with Information-Flow-Cards (IFC) possibly with default values, and the IFC are stored in a database for future projects.
3. The systems level design is based on a set based design strategy, where several solutions are developed simultaneously and maintained until the last responsible moment (Gil 2001).

4. The detailed engineering, including panel schedules and shop drawings, is postponed as close to the manufacturing start date as possible.
5. The detailed engineering is executed in one-equipment batches and based on the status of site installation.
6. The shop drawings, particularly 3-line diagrams, are standardized with help of intelligent configuration software.
7. The manufacturer is involved in the systems design phase.

4.5.3.2 Procurement

Procurement and shop drawing approval were considered the most wasteful in the whole process. They also caused many of the problems in the earlier and later tasks, forcing early design commitments and large design batches, and reducing product flexibility. In the future state process:

1. Alternative procurement methods, such as owner furnished equipment or design-build electrical contracting, may considerably reduce waste from current state maps where serial competitive bidding was the applied procurement method.
2. All the owners and PM companies were repetitive builders; therefore, they should consider engaging in long term collaboration with the equipment manufacturer based on negotiated contracts that would also require process development and improvement.
3. The manufacturer sends the shop drawings directly to the electrical engineer-of-record or even better if the electrical engineer-of-record

generates the shop drawings with manufacturers configuration software. Then there would not even be a need for shop drawing approvals.

When these improvement suggestions are considered along with design improvement suggestions, the detailed engineering could have been postponed at least one year in every case. The magnitude of the expected labor savings is hundreds of hours. The savings stem mostly from the omission of competitive bidding, streamlined document flow, and more reliable input values resulting in fewer changes and add-ons.

4.5.3.3 Manufacturing

Compared to the two prior phases, manufacturing consumed a relatively short time, but this does not mean that there is no room for improvement. Further reduction of the lead time of the PDE requires that:

1. The manufacturer's internal information flow is short, which can be achieved through a flat organization structure and/or application information technology.
2. Products are further standardized, so that the time of assembly operations can be reduced and materials management simplified.
3. Measures are taken to reduce manufacturer's supplier lead times.
4. Alternative assembly methods are explored to reduce cycle times without the cost of product quality or safety, e.g., one-section flow, reduced need of horizontal buses, and installation of horizontal buses after the installation of components and wiring.

It is worth noting that most of the suggestions do not require any significant financial investments[54]. Education and training are often the only cost. In one of the cases, the electrical engineer-of-record began to generate shop drawings using the manufacturer's configuration software: this training took only three days. However, most of the future state suggestions require close cooperation and fair incentives among the process stakeholders, which did not take place in any of the cases observed. Therefore, it would be beneficial to explore what kind of incentives and aids are required for closer cooperation, e.g., outside facilitators.

4.5.4 Validation of the findings

According to Robson (2002 pp. 168-77) "the essential test of validity of a finding in natural sciences is that it can be directly replicated by an independent investigator". However, the problem in flexible research design[55] is that identical circumstances cannot be re-created to attempt replication; hence, "scientific validation" cannot be established. Robson suggests that instead the validation of flexible research should focus on "dealing with the threats to validity" or establishing a "good quality of research". For the latter purpose four tests, (1) construct validity, (2) internal validity[56], (3) external validity, and (4) reliability[57],

---

[54] Only the development or licensing of configuration software and the redesign of assembly would require a more significant financial investment.

[55] Flexible research design is also commonly called qualitative research design (Robson 2002 p. 4).

[56] Internal validity is not required in descriptive case studies (Yin 2003 p 37).

have been used (Yin 2003 p. 34). Yin also provides tactics for each of the test. I applied Robson's and Yin's approach to validate the case study findings. Table 20 summarizes how the various tests were fulfilled in this research.

Table 20: Establishment of the quality of research

Tests	**Case study tactic**	**Test measures that were applied**
Construct validity	-Use of multiple sources of evidence	-Semi-structured interviews -Participant-as-observer observations on manufacturing shop floor and construction site -Case workshops -Records-analysis.
	-Key informants review case study reports	-Case results reviewed in workshops -Cross reviewed by case study participants -Cross reviewed by academics and practitioners through published reports
Internal validity	-Cross case synthesis	-Three independent case studies were executed -The findings were compared with other studies and findings
	-Logic models (Pattern matching)	-Matching findings with the TFV theory
External validity	-Theoretical framework	-The TFV theory was the applied theoretical framework
	-Replication logic	-Three independent case studies were conducted, which revealed similar findings
Reliability	-Case study protocol	-The case methodology was documented
	-Case study database	A database was established in an archive format, including: -Transcripts and audio tapes from the interviews -Notes from observations and project documents -Tabular material and summary matrices -Process maps, charts, and case reports

---

[57] Yin (2003, p 37) emphasizes that the reliability in flexible research such as case study means that the same case study can be done over again, not on replicating the results of one case by doing another case study.

Next, I further clarify what I mean by "relating to theoretical framework" and present weaknesses in the data.

4.5.4.1 RELATING TO THEORETICAL FRAMEWORK

I applied the TFV theory as the theoretical framework. It calls for a simultaneous assessment and management of transformation, flow, and value concepts. Many of the causes contributing to the long delivery lead time could be explained with help of the TFV theory, e.g., the danger of early commitment, large batch sizes, non-sequenced document flow, mere focus on transformation and lack of a holistic view of the delivery process. The transformation, flow, and value concepts were not considered as complementary management abstractions in the cases being observed. Findings in earlier construction process studies (e.g., Santos 1999, Koskela 2000) have reported similar findings. Particularly, the application of the flow view led to significant process improvements and dramatic reduction of lead times, which is also supported by a number of other practitioners and researchers, e.g., Ford 1928, Shingo 1988, Womack et al. 1990, Schonberger 1996.

4.5.4.2 WEAKNESSES IN DATA

Even though most data points were confirmed by triangulation, on a few occasions, the interviewees' responses were contradictory. One of the details that remained unclear was the amount of time the electrical contractor needed to generate a quote in the Bay Street case. According to the PM company, this time was exaggerated, but the electrical contractor repeatedly insisted that it took 40h.

Also, in a few instances I was not able to interview all process stakeholders, e.g., on Paradise Pier, only one of two electrical contractors that were involved participated in the case study; therefore, I had to rely on the other electrical contractor's, the manufacturer's, and electrical engineer's statements and descriptions of the primary electrical contractors tasks. As a result, I may have missed some details related to the electrical contractor's tasks. Nevertheless, reasonable enough evidence was considered to be available from other sources to describe and explain the behavior. Also, in the Novo case, the primary electrical engineer did not but the "potential future electrical engineer" participated in the research.

Finally, some observations I left unreported because I was not able to collect enough evidence to validate them, even though there were several indicators pointing in that direction. These include the actual labor hours spent to manage change orders and add-ons, and the positive correlation between lead time and changes. Instead I propose these as future research topics.

4.5.4.3 Conclusions

The case studies may not have revealed all the issues in the delivery process of the PDE; however, the findings that are presented here fulfill the generally accepted "four tests of good quality research" (Yin 2003 p. 34) as described in the earlier chapters. In conclusion, it can be stated that the case study findings are valid.

4.5.5 Summary

Similar types of problems were identified in all three case studies and their roots were mostly in the two first phases, namely, design and procurement. The main problems include tedious collection of input values and their poor reliability, slow information processing caused by large document batch sizes and hierarchical information flow, local optimization caused mainly by competitive bidding, and misconceptions.

However, there were also fundamental differences in design, procurement, and manufacturing methods between the US cases and the Finnish case. Standards, information technology, and established trade practices were the main reasons for the differences. Nevertheless, with the help of suggestions from case study participants and with guidance from the TFV-theory, qualities of a future state process was developed.

5 SIMULATION OF PROCUREMENT

5.1 INTRODUCTION

Construction projects are becoming increasingly complex, requiring more experts to contribute knowledge (Laufer 1997, Egan 1998, Best and de Valence 2002). In addition, many of these people are involved in the delivery of not only one but several projects at the same time, that is: they multitask. Increased complexity and multitasking pose major challenges for project managers, charged with delivering projects on time and within budget. Some methods and tools have been developed to cope with the complexity (Koo and Fisher 2000, Jin and Levitt 1996, Ballard 2000, Kankainen and Seppänen 2003). Nevertheless, many particularly off-site processes still lack an analytical investigation and understanding of their impact on overall project performance. Industry practitioners often treat these processes as a “black box”. For example, in each of the case studies conducted in this research, procurement of power distribution equipment (PDE) seems to be managed as a “black box”.

An indication of this is that very little attention was paid to variability and uncertainty of the procurement times even if the procurement took significantly longer than anticipated in all of the cases and the applied procurement method caused a significant amount of waste throughout the delivery process. Moreover, the procurement times in the project schedules were deterministic values based on past experience and ad hoc assumptions, apparently without explicit consideration of the contributing factors. For example, in Novo’s case, the procurement was scheduled to be completed February 7th but the actual contract was signed June 11th, nearly four months later than anticipated. What makes it so difficult to estimate procurement lead times? With a simulation experiment I demonstrate that procurement times can vary significantly depending on the prevailing circumstances. The disregard for the variability and reliance on "received traditions" (Schmenner 1993 p. 379) not only lead to underestimated procurement times but also creat numerous problems for the project participants downstream in the supply chain, as discussed in chapter 4.

5.2 PROCUREMENT PRACTICE

Procurement is an activity scheduled to start when an appropriate degree of design has been completed and resulting in the delivery of materials needed for construction on site. Estimating the duration needed for procurement is not easy. Even so, the time needed from start to completion includes actual work time but also extensive delays or wait times because specialists need to get input from various sources. Because the task is not performed uninterruptedly (as is commonly assumed in master-level or milestone schedules), it is better to use the term "procurement lead time" rather than task duration.

In case of Novo[58], the electrical project manager was involved in over 20 projects. Each of the projects had a different set of PDE ranging from few pieces to nearly hundred pieces. In addition, the electrical project manager had to procure other types of products, such as light fixtures and cable trays. As a result, he had numerous tasks that he had to cope with simultaneously. The

---

[58] All the project specific data from here on is from Novo.

manufacturer had nearly a 15% success rate in quoting, which means that he had to quote almost ten quotes to gain one. As a result, he had to quote simultaneously numerous quotes during the same time period in order to generate revenue and profit for his company. Before the electrical project manager could place the RFQ he had to check with the owner, HVAC project manager, general project manager, and construction site that the RFQ fulfilled their requirements. If someone delayed his feedback on the RFQ, the procurement halted. The quote evaluation followed the same review practice as the RFQ. Consequently, the process got easily interrupted due to missing data. Realizing the level of multitasking and specialists involved, it is easy to see how difficult it was to estimate the procurement lead time in Novo. Therefore, rather than trying to estimate the procurement lead time only based on past experience, it seems to make sense to also have some level of insight about the sensitivity of the variables impacting the procurement lead time, e.g., by using simulation.

5.3 RELATED RESEARCH

Simulation has been widely used to analyze various systems ranging from manufacturing policies to organizational behavior (e.g., Law and Kelton 2000, Sterman 2000). Forrester (1961) used simulation to demonstrate how policy and organizational structures distorted the production and distribution system. Later, this became known as the “bullwhip effect” in supply chains (Lee et al. 1997). However, Forrester’s and Lee et al.’s studies were focusing on make-to-stock products. Supply chains of engineered-to-order products have been simulated to some extend but not in the same scale as make-to-stock products.

In construction, simulation has been mostly used on project level, where e.g., 4D modeling has been applied to study sequencing and constructability issues of various trades (e.g., Clevelande 1987, Koo and Fisher 2000) and discrete event simulation has been applied for productivity analysis of various site operations (Halpin 1973, Paulson et al. 1987, Martinez 1996). Gil (2001) applied simulation in a creative way to study early design involvement of specialty contractors and postponement of design commitment in the delivery of a semiconductor facility.

In recent years, simulation has also been applied to model construction supply chains. Ericsson (1999) evaluated the applicability of simulation on managing construction supply chains. Hong-Minh (2002) used simulation to improve private housing supply chains in UK. Tommelein (1998) applied discrete event simulation to compare alternative ways to sequence and batch pipe spool deliveries. Walsh et al. (2002) used simulation to determine optimal inventory location in the pipe spool supply chain. Arbulu (2002) discussed the issue of multitasking with the help of simulation in his study on the pipe support supply chain. All these studies led to further understanding about construction supply chains; accordingly, it was considered appropriate to use some sort of simulation as complementary support for the case studies.

In the case studies, particularly one area, the procurement[59] practice and its time components, would benefit from further investigation by simulation. Next, simulation is applied to demonstrate how two key factors; namely, multitasking

---

[59] Naturally simulation could also be applied to other problems areas in the cases, such as design coordination, sequencing hand-offs between process stakeholders.

and merge bias may impact the procurement lead time. The idea of simulating workload and commitment in projects is not new (e.g., Jin and Levitt 1996, Tommelein et al. 1999, Arbulu et al. 2001); however, the framework and approach used here provide specific insights into the impacts on procurement of multitasking and merge bias.

5.4 DESCRIPTION OF SIMULATION MODEL[60]

The developed simulation model builds on Sigma (Schruben and Schruben 1999), an event scheduling simulation engine, and uses various input scenarios to show how sensitive the procurement lead time is to the effects of multitasking and merge bias. Reference data was collected from the case studies and used as input in the model.

5.4.1 Definition of model variables and tasks

The procurement simulation model includes the following tasks: (1) preparing a RFQ, (2) providing input for the RFQ, (3) quoting, (4) evaluating the quote, (5) providing input for contract negotiation, and (6) negotiating the contract.

Table 21 describes these tasks in detail. All the processing times are beta distributed with shape parameters Beta {2:3} and a range specified by task. This distribution is skewed to the right towards the lower values of the range, because extremely large durations are less likely than shorter durations.

---

[60] This chapter is largely taken from Elfving and Tommelein's (2003) paper that was published in the annual Winter Simulation Conference in New Orleans, LA.

Table 21: Definition of simulation tasks

Task	Definition
Prepare RFQ	The Project Manager collects data and prepares the RFQ documents, which may include specifications, drawings, and schedules.
Provide input for RFQ	Engineers, owners, users, and others provide detailed data for the RFQ, e.g., energy and reliability requirements.
Quote	The Manufacturer reviews the RFQ and prepares a quote, which specifies the equipment, price, and delivery information.
Evaluate the quote	The Project Manager evaluates the quote, compares it to the requirements, and conducts a price check.
Provide input for contract negotiation	Engineers, owners, users, and others review the quote and recommend needed changes to the requirements prior to approval.
Negotiate	The Project Manager and Manufacturer negotiate details of the contract, e.g., price, scope of contract, and delivery schedule.

The corresponding event graph model (Figure 2) has 19 events and 33 edge conditions that describe the execution of these 6 tasks. The model has 24 variables of which 5 variables were investigated in this study. Table 22 describes these variables in more detail.

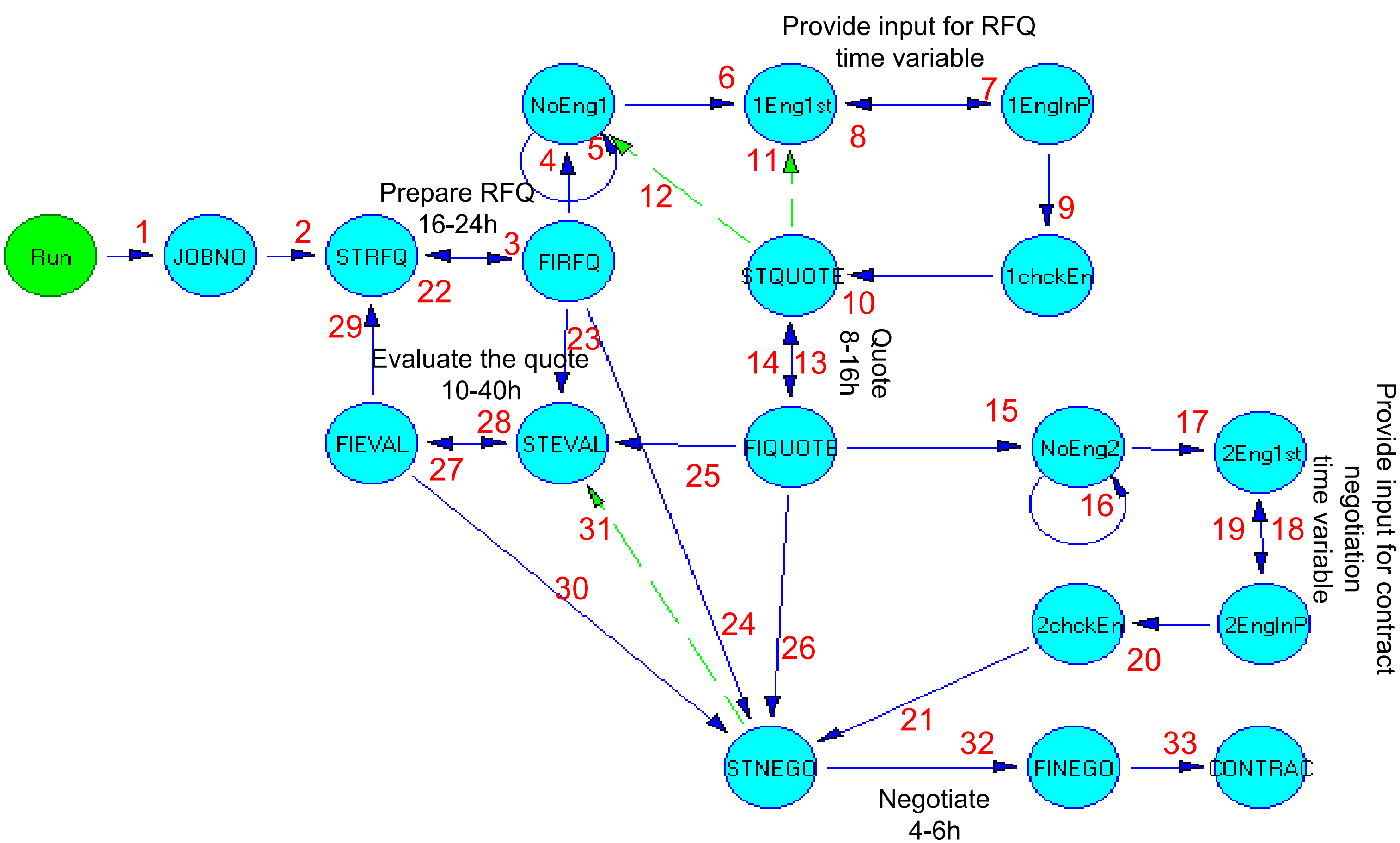


Figure 39: Event graph model of the procurement process

The investigated 5 variables and their respective default values were PMMT=1, MMT=1, ENG=5, ENG/h=1-8h (Beta {2:3}), and ENG/c=10%. Resources that get generated and 'flow' in the model are RFQs and QUOTEs. Because of multitasking, numerous RFQs and QUOTEs appear in the model at different times, but metrics are collected only on the so-called 'focus job'.

Table 22: Definition of variables

Variable	Definition
PMMT	Number of RFQs the Project Manager multitasks with
MMT	Number of QUOTEs the Manufacturer multitasks with
ENG	Number of experts that need to provide input
ENG/h	Duration for generating expert input [hours]
ENG/c	Expert's commitment level to the focus job [% of their workweek]

The focus job is the job that is being tracked from start through completion in the simulation. For example, job B in Table 3 could be a focus job being studied. It requires the joint input from three project participants: the Project Manager, the Manufacturer, and the Domain Expert (ENG=1). Note that each of these participants may be working on other jobs at the same time. For example the Project Manager is assigned to jobs A and D in addition to B. However, the three participants do not work on the same jobs all the time.

Table 23: Jobs assigned to various project participants

Project Manager	A	B		D	
Manufacturer	A	B	C		E
Domain Expert		B	C	D	

5.4.2 Description of simulation run

The simulation time is the time it takes from the launch (RUN) of the simulation to the issuing of the procurement contract (CONTRAC) between the Project Manager and the Manufacturer. As the simulation is launched (RUN) the event JOBNO generates a JOB for the Project Manager, who will then start (STRFQ) to process it. The processing time has a range of 16-24 hours. At the end of the processing time (FIRFQ), a RFQ has been generated. However, if the Project Manager has other RFQs waiting before the JOB was launched, he has to process all of them prior to sending the focus RFQ that was generated by the JOBNO, to the experts (ENG) for input. Then, the event NoENG1 sends the RFQ to a specified number of experts for input. The default number of experts was 5.

The experts start (1Eng1st) simultaneously to evaluate the RFQ. The processing time has a default range of 1-8 hours. At the end of the processing time (1EngInP), an input for the RFQ is been generated. Because the experts are working on multiple jobs at same time, they are committed to spending only a certain percentage of their time to the focus RFQ. We used a default value of ENG/c=10% which equals 4 hours per week. Therefore, based on the commitment percentage the output from 1EngInP is either true or false. If it is false, a new processing of the RFQ is required. If it is true, it will be added to the event 1chckEn, where all true inputs from the various experts are collected.

After a specified number of expert inputs have been generated the Manufacturer can start to quote (STQUOTE) the RFQ. The processing time has a range of 8-16 hours. At the end of the processing time (FIQUOTE), a QUOTE has been generated. However, if the Manufacturer has other RFQs waiting before the focus RFQ arrives he has to process all of them prior to sending the focus QUOTE for evaluation to the experts (ENG) and the Project Manager.

The expert evaluation of the focus QUOTE follows the same logic as the expert evaluation of the RFQ. The Project Manager starts to evaluate (STEVAL) the QUOTE as soon as he is available. He is available when he is not preparing another RFQ for another job. The probability of STRFQ and STEVAL are set equal. The processing time has a range of 10-40 hours. At the end of the processing time (FIEVAL), the Project Manager has an equal probability to start contract negations (STNEGO) for the focus QUOTE, or STRFQ or STEVAL for another job, providing their conditions are satisfied. The conditions for the STNEGO are that the Project Manager and all required experts (ENG) have evaluated the focus QUOTE and both the Project Manager and Manufacturer are available. The Manufacturer can with equal probability STNEGO for the focus QUOTE or quote another RFQ. The processing time for the negotiation has a range of 4-6 hours and by the end of the processing time the events FINEGO and CONTRACT occurs simultaneously.

5.4.2.1 MODELING OF MULTITASKING

Multitasking means that a person is occupied with two or more jobs during a time period before either one results in an output or handoff, hence the resource is shared among the jobs. For example, in Table 23, the letters in a row represent the tasks being ‘multitasked’ by the person listed on that row.

The impact of multitasking on the procurement lead time is modeled by changing 2 of the variables, namely, PMMT and MMT. The rest of the variables are kept at their default values. Three scenarios were generated, (1) only the Project Manager multitasked, (2) only the Manufacturer multitasked, and (3) both the Project Manager and Manufacturer multitasked. E.g., if PMMT was 5, the Project Manager had to prepare five RFQs within the same time period. Therefore, before the focus RFQ was prepared one had to wait for the 4 other RFQs to be prepared as well, because they share the same server (Project Manager).

5.4.2.2 MODELING OF MERGE BIAS

Merge bias means that two or more inputs from different sources have to be available before an event can start. A delay of any of the inputs delays the start-up of the event. For example, in Table 23, the letter in the columns refers to the corresponding people from whom input is needed (the level of merge bias) for that job.

Three factors contribute to merge bias, (1) the number of resources or inputs that need to merge prior to an event taking place, (2) the processing times of the merging tasks, including their variability, and (3) the availability of the server who needs to process the merging task. The impact of merge bias on the procurement lead time is modeled by changing 3 variables, namely, ENG, ENG/h and ENG/c. All other variables are kept at their default values.

5.4.3 Simulation assumptions

The most relevant modeling assumptions are the following:

1. No deadlines were enforced and no deliberate withholding of information took place. I wanted to filter out issues of gaming and focus only on multitasking and merge bias.
2. Every RFQ led to a contract with the manufacturer. The process did not get canceled.
3. Information distribution between the servers (participants) was always complete and the servers were capable of performing their task, e.g., no server needed to send a Request-For-Information (RFI).
4. The Project Manager and Manufacturer are treating every RFQ and quote, respectively, with equal priority and value. I am investigating the average practice thus high and low priority practices were discarded.

5.5 SIMULATION RESULTS

As a baseline for the simulation a hypothetical scenario was created, where the simulation was run with settings where no multitasking or merge bias occurred (PMMT=1, MMT=1, ENG=0). The average procurement time of ten runs was 61 hours and the standard deviation 4 hours. Then, the model was infiltrated with with various kinds of multitasking and merge bias.

5.5.1 Multitasking and procurement lead time

The first actual simulation scenario investigated the impact of multitasking on the procurement lead time. The variables PMMT and MMT had values 1, 5, 10, and 20. The duration for preparing the RFQ was double (16-24h) that of the duration for quoting (8-16h). This relation is based on data from the case studies. The three other variables ENG, ENG/h, and ENG/c, respectively, kept their default values 5, 1, and 10%. For each set-up 10 runs were executed, then the mean, standard deviation, and lower and upper boundaries (with 95% confidence interval) of the procurement lead time were calculated (Table 24 to Table 26). Table 24 presents simulation results when only PMMT changed and MMT remained at its default value, 1.

Table 25 presents the results when only MMT changed and PMMT remained at its default value, 1. Table 26 presents the results with PMMT and MMT taking on the values 1, 5, 10, and 20 at the same time. Figure 40 compares the impact of the various scenarios of multitasking on procurement time.

Table 24: Impact of project manager's multitasking on procurement lead time

PMMT	Procurement Time	Standard deviation	Lower bound	Upper bound
1	151	15	147	156
5	248	55	231	264
10	341	33	331	351
20	513	36	502	524

Table 25: Impact of manufacturer's multitasking on procurement lead time

MMT	Procurement time	Standard deviation	Lower bound	Upper bound
1	151	15	147	156
5	208	33	198	218
10	257	25	250	265
20	362	30	353	371

Table 26: Impact of project manager's and manufacturer's multitasking on procurement lead time

PMMT &MMT	Procurement Time	Standard deviation	Lower bound	Upper bound
1	151	15	147	156
5	294	37	283	306
10	427	39	415	438
20	719	17	714	724

The results show that increasing the number of tasks to be worked on concurrently increased the lead time. Because the project manager's average task duration was longer than the manufacturer's, the number of tasks the project manager multitasks with had a greater impact on the procurement lead time than the manufacturer's number of multitasks. If both multitasked with only 5 jobs — which is very common in practice — the procurement lead time doubled (306 hours), and if they were very busy jumping between 10 jobs the required procurement time almost tripled (438 hours) compared to the baseline values. That multitasking increases the project duration is intuitive, though it is common that contractors reserve fixed procurement lead times from project to project regardless of the prevailing procurement environment.

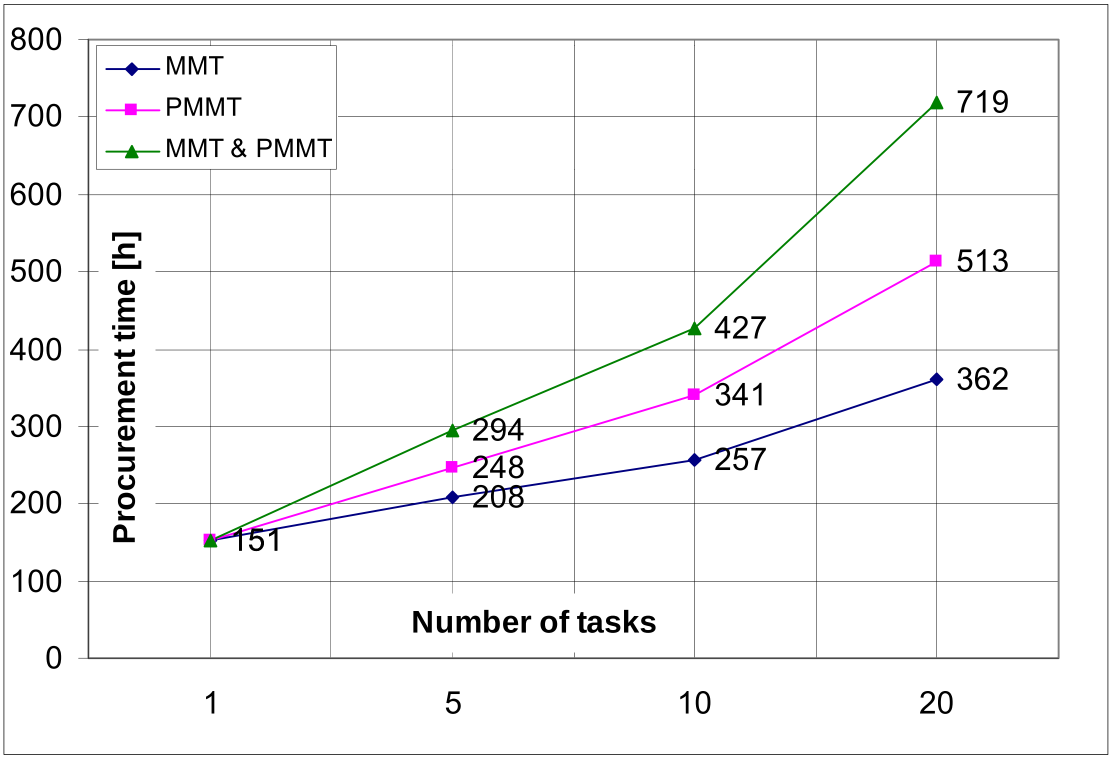


Figure 40: Comparison of various multitasking set-ups on procurement lead time, ENG=5, ENG/h=1-8h, ENG/c=10%

5.5.2 Merge bias and procurement lead time

Three scenarios of merge bias were investigated. For each only one variable was changed at a time and the other four variables were kept at their default values. Again each set-up was run 10 times, then the mean, standard deviation and the lower and upper boundaries (with 95% confidence interval) of the procurement lead time were calculated.

The number of experts that had to contribute information has a lesser impact on the procurement lead time even in the extreme cases, where only 1 (135 hours) or up to 10 (198 hours) experts were needed. The reason was that the average duration for generating the input was set as low, only 1-8 hours (Figure 41).

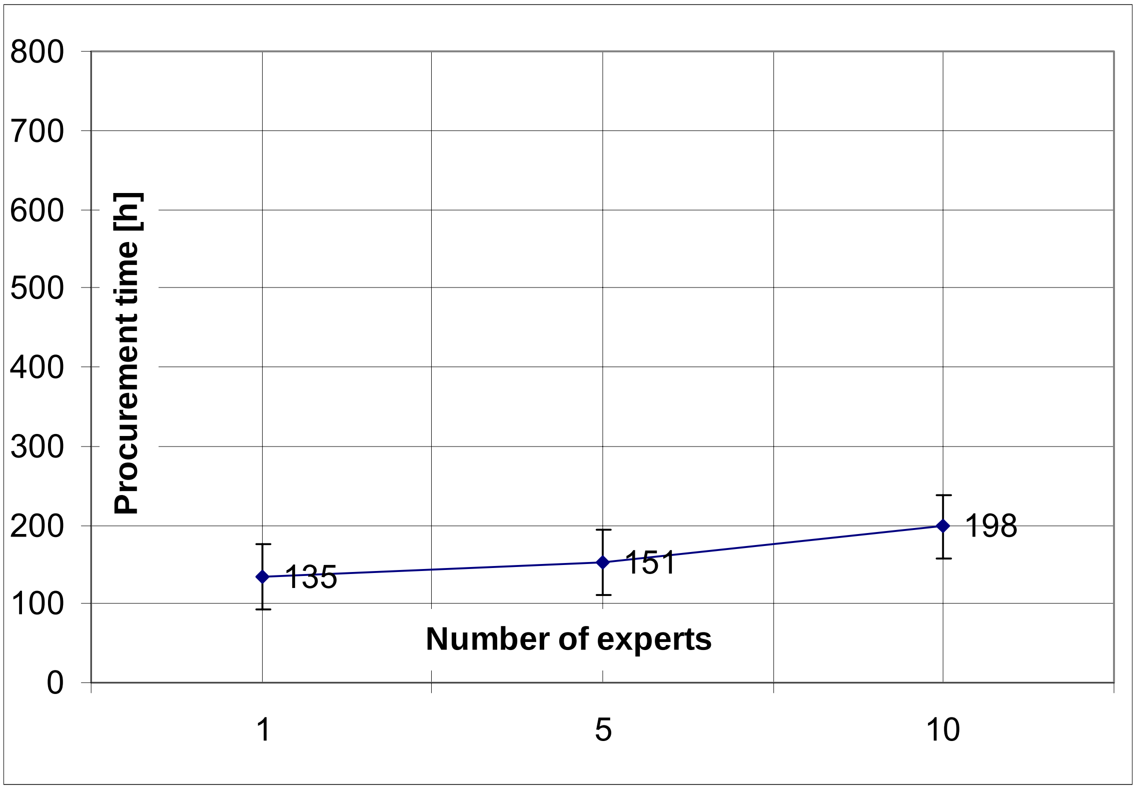


Figure 41: Impact of the number of contributing experts on procurement lead time, PMMT=1, MMT=1, ENG/h=1-8h, ENG/c=10%

In the next set-up, the expert's task duration was changed (Figure 42). The horizontal axis describes the range of task duration based on beta distribution. The value 1 represented the range between 1-8 hours, the value 8 represent the range between 8-16 hours, and the value 40 represent a range between 40-48 hours.

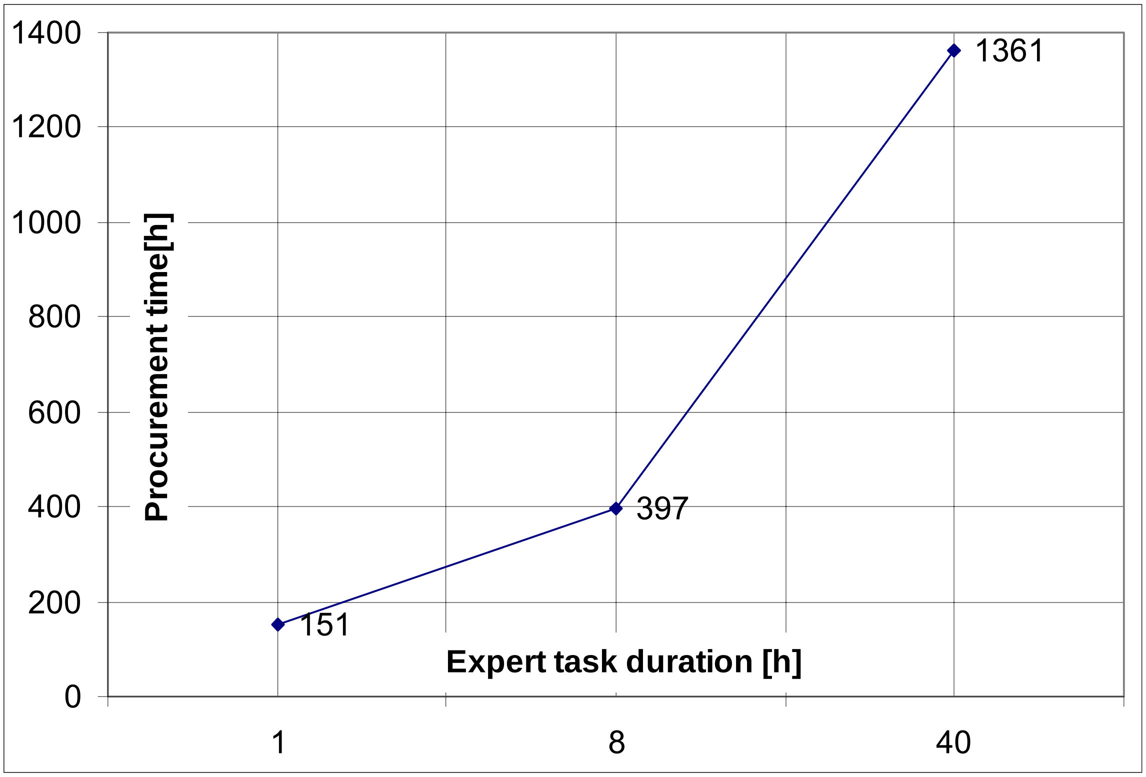


Figure 42: Impact of expert task duration on procurement time, PMMT=1, MMT=1, ENG=5, ENG/c=10%.

The expert's task duration had a major impact on the procurement lead time, if one day (8 hours) instead of 1 hour was needed to generate the input, the required procurement lead time increased nearly three times. If a task required serious calculation and design work up to 40 hours, the required procurement lead time was nine-fold compared to the default case. The standard deviation was high in this set-up, for the mean 151 hours it was 15 hours, for the mean 397 hours it was 154 hours, and for the mean 1361 hours it was 523 hours, respectively. The reason was that after the completion of the expert tasks (1EngInP and 2EngInP) the simulation randomly decided, based on the default commitment percentage of 10%, if the expert should work on the focus task or on some other task. Thus the longer the expert task duration, the more the procurement lead time extended.

Next, the expert's commitment percentage was changed. This percentage describes the fraction of time the person is actually ready to commit to this particular procurement item. We assumed four scenarios, 50% of the workweek (20 hours), 10% of the workweek (4 hours), 5% of the workweek (2 hours), and 1% of the workweek (15-20 min). The 50% and 10% commitment could reflect a project manager or engineers who are primary involved in the project. The 5% and 1% commitment could reflect an owner, user, or an authority whose primary business is not the project.

The results are very interesting (Figure 43). If the commitment percentage increased from 10% to 50% it only reduced the procurement lead time with 30%. However, if the percentage was reduced to 5% and 1% the impact on procurement lead time became significant. The procurement lead time increased to an average of 294 hours and 1,132 hours, respectively. The standard deviation was also relative high in this set-up, 20 hours (ENG/c=50%), 15 hours (ENG/c=10%), 66 hours (ENG/c=5%), and 379 hours (ENG/c=1%).

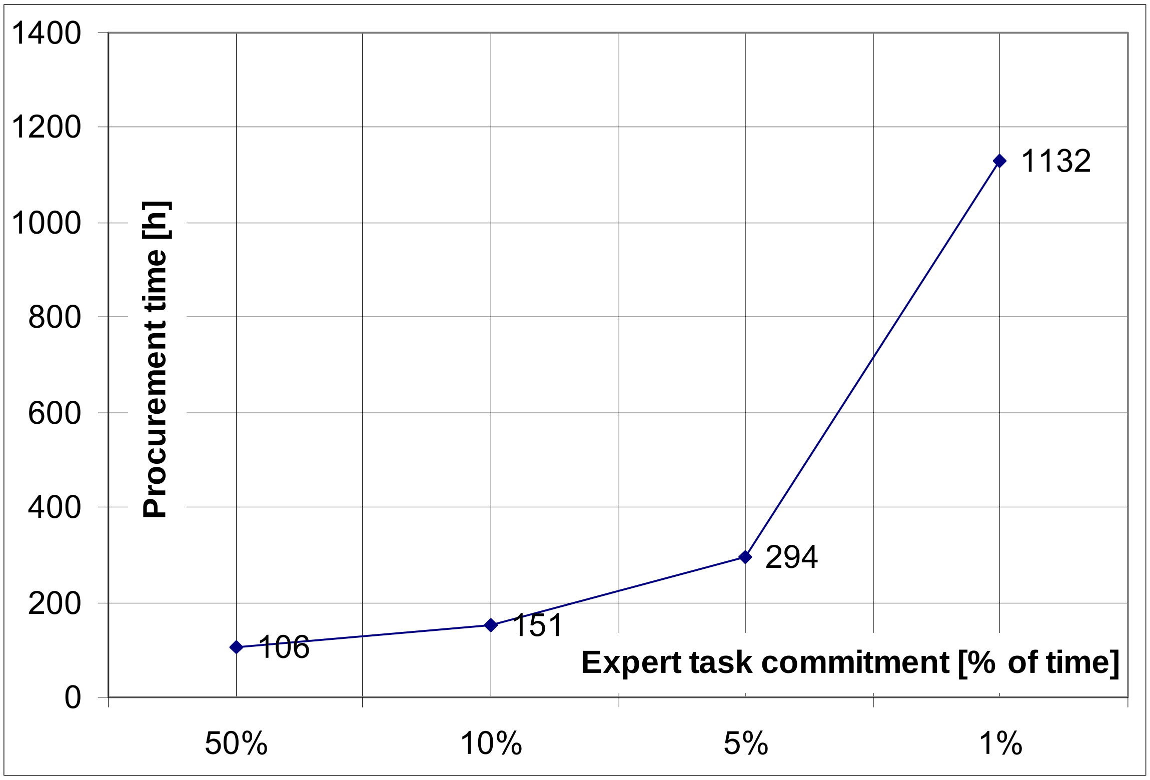


Figure 43: Impact of expert commitment on procurement time, PMMT=1, MMT=1, ENG=5, ENG/h = 1-8h.

5.6 VALIDATION OF SIMULATION RESULTS

According to Sterman (2000, p. 846): “no model can ever be verified or validated”. The reason is that “all models, mental or formal, are limited, simplified representations of real world”. The argument is widely supported by the simulation community (e.g., Law and Kelton 2000, Schruben 2003). So, what do we actually mean by the validation of simulation results?

Sterman (2000, p. 850) answers this question by arguing that the goal of modeling is to build shared understanding that provides insight and helps to solve problems. In conclusion, the model should be useful and its logic should be tested through multiple sources of data and a wide range of tests. The purpose of the simulation model presented here was to demonstrate that there exists significant variability in the procurement process, even if the variables were only varied within a "reasonable"[61] range. I asked practitioners through interviews and workshops to verify the sequence of activities, their dependencies, and their estimated durations, which tested the model logic. This is also known as face validation (Law and Kelton 2000). In addition, particularly with respect to multitasking, other researchers have also reported findings that support the findings in this study (e.g., Arbulu et al. 2002).

From a technical point of view, the model is not known to have any errors while running. The model, including its variables and conditions, are documented and available in Appendix 4, hence the simulation can be replicated by an independent third party. Because, a random number generator (RNG) was applied in the model, there was a risk that same set-ups may give very different results. Hence, as a variance reduction method, the model was run with same set-up but with different seed numbers 10 or more times thereafter the average values of all runs were applied and 95% confidence intervals were calculated.

The results were not tested on empirical data, which means that I did not try to match the outcomes from the simulation with real world data. Although this is not necessary when the "general behavior" of the process is investigated, it will come an issue if the simulation model is applied to more accurate predictions of outcomes. Therefore, testing the simulation results on empirical data is

---

[61] With "reasonable" I mean that the practitioners provided a range of values that they had experienced while performing the activity.

suggested to be an area of future studies. Another, area to improve the model is to relax some of the assumptions that were established. Nevertheless, understanding the limitations of the model, it can still be stated based on the face validity and the “internal technical” tests that the current model is sufficient to provide insights and to help to understand the impact multitasking and merge bias may have on procurement lead times. Accordingly, ignoring the variability may lead to serious under- or overestimating of the procurement lead time.

5.7 DISCUSSION OF SIMULATION RESULTS

It was especially surprising to find the significant role played by merge bias, particularly when experts have a low commitment percentage and their task duration is long. The simulation results indicate that there are at least two factors at play that lead to optimistic duration estimates for procurement in practice: (1) estimators assume that project participants will have a small degree of multitasking and high levels of work commitment so that their duration estimates correspond to values on the left-hand side of the x-axis in Figure 40 to Figure 43; (2), when there is a low level of commitment there also is a greater amount of variability so that any deterministic estimate is more likely to be wrong. Moreover, people that multitask may not appreciate the value or importance of their contribution to the project, and thus erroneously judge how to prioritize their work.

The findings regarding the commitment percentage are also supported by Hopp and Spearman’s “law of utilization” (2000 p. 303): as utilization approaches

1, the cycle time approaches infinity. Similarly, when the commitment level approaches 0, the procurement lead time approaches infinity.

The insights may help to size buffers by more accurately including constraints. In case of multitasking (e.g., if a project manager has more tasks than usual) this has to be considered in the procurement schedule. In case of merge bias (e.g., if input is needed from non-procurement personnel, owner, user, or others, who normally have lower commitment levels for specific procurement items), significant input delays are to be expected. Hence, adequate time buffers in the procurement schedule are needed.

5.8 SUMMARY OF SIMULATION FINDINGS

- The simulation demonstrates that there is a large amount of variability in the procurement phase based on the prevailing environment.
- Both multitasking and merge bias have significant impact on procurement lead time.
- If the merging task takes one week instead of a few hours, the procurement lead time increased on average by 800%.
- If the expert availability is only 15-20 minutes instead of 4 hours per week, the procurement lead time increased on average by 650%.
- If participants had 10 tasks each to perform simultaneously, the procurement lead time increased nearly 300% compared to the base case where participants worked with one task each.

6 CONCLUSIONS

This chapter summarizes and discusses the research findings from chapter 4 and 5, presents the contributions to knowledge, and proposes future research directions.

6.1 RESEARCH FINDINGS

This research sought answers to the research question:

"How can the performance of the delivery process of ETO products be improved?"

I was interested in understanding: 1) what are the elements of and the stakeholders in the delivery processes of power distribution equipment (PDE); 2) what factors contribute to process lead times; 3) what are the weaknesses in the current processes and what causes them; and 4) what can and cannot be done in order to reduce the lead time of the processes.

Data from three case studies demonstrate that the tasks performed in the delivery process of PDE were relatively similar. However, task responsibilities and inter-organizational relationships differed. The elements and stakeholders of the delivery process are illustrated in three current state maps in Appendices 1-3.

6.1.1 Relative time contributions of process phases in delivery process of PDE

Although in the Finnish case (Novo), design took the longest time, procurement, which included the approval of shop drawings, consumed a significant part of the total delivery lead time in all three cases (Table 27). Moreover, the scheduled procurement time for the equipment was initially underestimated in all cases. The equipment was bought through several "middlemen", which added to the procurement time. In Bay Street, the proportion of procurement compared to other phases was particularly high because RFQs were placed early in the process, and they incorporated significant assumptions regarding the equipment specifications because the project design was still incomplete. Therefore, design overlapped with procurement in the form of "changes".

Table 27: Summary of lead times

Performance measure	Bay Street	Novo	Paradise Pier
Total delivery lead time [week]	79	86	133
Design lead time [week]	22	47	56
Design lead time / total process delivery lead time [%]	28	55	42
Procurement lead time [week]	49	40	69
Procurement lead time/ total process delivery lead time [%]	62	47	52
Manufacturing lead time [week]	8	10	8
Manufacturing lead time/ total process delivery lead time [%]	10	12	6
Number of pieces of equipment	166	76	167

Besides procurement, design also consumed a large amount of the total delivery lead time. However, manufacturing lead time consumed only 12% or less of the total delivery time. Manufacturers were able to drop the lead time to three weeks or less if required. In the US cases, the manufacturing cycle time was less than a few days. In Finland, the manufacturing cycle time was 13 days but the manufacturer's average lead time for the two least busy months in 2002 was only 3 weeks or 15 days.

6.1.2 Causes of long lead time

A wide array of causes contributed to the long delivery lead time. However, a major reason why causes had not been addressed earlier was that stakeholders were not aware of the delivery process as whole; they lacked a systems view of the process. Therefore, improvements to date had been local, focused on a certain functional unit, rather than on global process improvements.

Current improvement efforts, except for product standardization in US, have concentrated on transformation of inputs to outputs, e.g., automating the shop drawing phase. Though some of the changes have brought notable improvements for the particular stakeholder who introduced the change, the overall delivery process has not benefited by the same magnitude. Also, the danger of applying only the transformation concept is that it may fuel the "vicious circle" behavior as described in chapter 4.5.

In general, the flow and value concepts of production were not properly applied or applied at all; examples are large and non-sequenced document and material batches, fierce competitive bidding, and early commitment. Competitive bidding was one of the main reasons that upstream players had to commit early to design solutions and to pursue large design batches. Hence, it created waste not only in procurement but in other phases of the delivery process as well. Furthermore, as discussed in chapter 4, other issues such as industrial organization and types of standards also impacted the delivery time. Table 28 summarizes the main causes of long lead time. These were earlier explained in chapter 4.

Table 28: Summary of causes that pushed the delivery lead time

Phase	Cause	Bay Street	Novo	Paradise Pier
Design	Changes due to early commitment and lack of knowledge	X	X	X
	Changes due to design errors	X	X	X
	Coupling PDE design to other systems design	X	X	X
	Outdated practice of auxiliary design and approvals	X		
	Owner(s) and tenant(s) delayed design input	X	X	X
	Low level of design standardization		X	
	Tedious collection of design input (and poor reliability of input)	X	X	X
	Non-sequenced “push” driven design	X	X	X
	Complexity-Large number of specialists			X
Procurement	Serial competitive bidding	X	X	X
	Exclusion of product flexibility	X	X	X
	Large document batches	X	X	X
	Improper document sequence			X
	Commercial relationships	X		X
	Changes in product specifications	X	X	X
	Sequential and bureaucratic document flow	X	X	X
	Gaming	X	X	X
	Misunderstandings in scope of task			X
	Cumbersome and tedious shop drawing approval process	X	X	X
Manufacturing	Component lead time	X	X	X
	Capacity	X	X	X
	Sequential and bureaucratic document flow	X		X
	Production method		X	
	Data entry into software		X	
	Changes		X	X
	Non-sequenced equipment delivery	X		

Finally, owners and architects, particularly, consider the project environment to be dynamic, they find it is evident and normal to constantly revise the project, and design iterations and changes are part of this process. However, the delivery process of PDE is poorly structured for their dynamic needs. Specifically the approval of drawings and specifications is very slow and embedded with waste.

6.1.3 Opportunities to reduce lead time of delivery process of PDE

The value-added times in the delivery processes were only a few percentages of the total delivery lead time. In all three cases, significant opportunities to reduce the delivery lead times were identified (Table 29) and most of the changes (Table 30) do not even require financial investments as discussed in chapter 4.5.

Table 29: Lead time and number of activities in current and estimated future state

	Bay Street		**Novo**		**Paradise Pier**	
Performance measure	Current State	Future State	Current State	Future State	Current State	Future State
Lead time [week]	79	35	86	41	133	65
Number of activities	49	38	62	51	66	47

These changes were estimated to reduce the process lead time by 20-40% of total delivery time. Also, at least 15-20% of labor hours may be saved throughout the process.

Table 30: Improvement suggestions that industry partners shared

Phase	**Improvement suggestion**	**Bay Street**	**Novo**	**Paradise Pier**
Design	Reduce document batch	X	X	X
	Standardization of detailed engineering		X	
	Pulled-based design	X	X	X
	Application of manufacturer's configuration software	X		X
	Downstream players in upstream decisions	X	X	X
	Postponement of detailed engineering	X	X	X
Procurement	Alternative procurement methods	X	X	X
	Re-structuring organizational relations	X		X
	Smaller document batches	X	X	X
Manufacturing	Changes in manufacturing logic		X	
	Sharing software with customers	X		X

A central point in improving the delivery processes is to recognize that design, procurement, and manufacturing have significant interdependencies. Therefore, it is necessary to analyze them in an integrated manner, rather than as separated disciplines as is so common in the construction industry.

In addition, the TFV theory provides a new approach to traditional transformation-based process thinking. It contributes to better understanding of the process behavior and identification of improvement opportunities. Particularly, the consideration of the flow concept turned out to be helpful. For example, 90% of the waiting time of shop drawing approvals could have been eliminated if the batch size had been reduced to one piece of equipment instead of all the equipment in the project. However, there is a set-up time (to pull the right documents, to become familiar with requirement, etc.) to review the shop drawing; therefore, a more realistic batch size to review may be one floor or building section at a time instead of one piece of equipment. Also, the separation of systems design and detailed engineering and then the postponement of detailed engineering were considered as viable alternatives to current practice. Their pursuit will require close collaboration among project stakeholders.

Another major opportunity lies in streamlining the current procurement practice and exploring alternatives to competitive bidding. Competitive bidding does not seem to be an efficient way to procure customized products.

The simulation demonstrated that the procurement lead time had a large range even if playing with “reasonable values” and considering only multitasking and merge bias. However, industry practitioners commonly apply “standard” deterministic values in project schedules regardless of the prevailing environment. Also, when there is a low level of commitment, the amount of variability increases; thus, deterministic estimates are more likely to be wrong. Even a simplified simulation model can identify bottlenecks and be used to allocate resources and time buffers. Particularly, for the non-procurement personnel, simulation may be a good way to demonstrate how they may impact the procurement lead time and even timely project completion.

Finally, the workshops prove to be a valuable method to enhance the collaboration among process stakeholders and validate the research findings.

6.1.4 Main barriers to improvement

Barriers to redesigning the process may be the comfort with current practice, lack of cross-organizational collaboration, and lack of resources to implement the changes. The cases demonstrated that there are some well established, local, “received traditions” (Schmenner 1993 p. 379) among the stakeholders regarding procurement of PDE, which may be hard to change. A case in point is competitive bidding. Improving the delivery process from a systems approach requires cross-organizational collaboration; however, applying competitive bidding as the procurement method made the participants in all three cases reluctant to have cross-organizational collaboration. Competitive bidding did not provide incentives for long range process development. It aims to cut costs and not necessary to increase value. Accordingly, it may be very difficult to change these deep-rooted traditions. Besides organizational inertia, where firms may be reluctant to change inter-organizational relationships; people inertia, where individuals within organizations do not want to shake off familiar customs, may also be a strong force against change. Finally, people, particularly with a low degree of commitment to the delivery process, may not be aware of their impact on the process and thus ignore any improvement effort.

Although someone has to take a leading role to push for changes, the most radical improvements, such as owner furnished and negotiated contracts, reduced document batch sizes, discarding shop drawing approvals, and pull based delivery, require cross-organizational cooperation and can be successfully executed only if all the process stakeholders are committed.

Even though it is hard for any single stakeholder to radically change the current delivery process, owners are probably in the best situation to initiate change. Two of the three owners in this case study, who are major players in the industry, expressed great interest in changing the process. However, if owners lack resources, dedicated people with adequate knowledge and time, they will not be able to implement and manage the future state process.

6.1.5 Conclusions on hypothesis

My hypothesis established in chapter 1 is:

"There is a significant opportunity to improve the delivery process of ETO products with the help of shared knowledge among the process stakeholders and the underlying the TFV-theory".

Table 31 summarizes how the above research findings fall under shared knowledge and the TFV-theory. The improvement suggestions that primarily require knowledge transfer between firms are categorized in the "shared knowledge" column. Those that focus on improving the execution of a task are categorized in the "transformation" column. Those that focus on improving the handoff between tasks are categorized in the "flow" column. Finally, those improvement suggestions that primarily focus on reducing non-value-added activities, such as rework, are categorized in the "value" column.

Table 31: Improvement suggestions sorted by shared knowledge and TFV theory

Improvement suggestion	**Shared knowledge**	**Trans-formation**	**Flow**	**Value**
Reduce document batch			X	
Standardization of detailed engineering		X		X
Pulled-based design			X	
Application of manufacturer's configuration software	X	X		X
Downstream players in upstream decisions	X			
Postponement of detailed engineering			X	
Alternative procurement methods		X	X	X
Re-structuring organizational relations	X			X
Changes in manufacturing logic		X	X	X
Simulation of delivery process	X			
Workshops	X			

Although other approaches to dramatically improve the delivery process may exist, this study has shown that a combined approach of shared knowledge among process participants and the TFV theory provides a framework to improve the ETO delivery process. It is also worth noting that most of the suggestions do not require any significant financial investments beyond recognizing education and training.

6.2 CONTRIBUTIONS TO KNOWLEDGE

This dissertation contributes knowledge to both academia and industry. In academia it contributes to the field of project-based production and in industry it contributes to businesses operating in the ETO product environment. First, the dissertation describes three detailed delivery processes for PDE. Second, it highlights issues and improvement opportunities with the help of the TFV-theory. Third, it uses simulation to describe procurement behavior. Fourth, it introduces workshops as a viable case research method. Finally, it encourages further research in the emerging field of construction supply chain management.

6.2.1 Detailed process description

This dissertation details the delivery process of PDE from design to manufacturing, and thereby broadens understanding of the process in several ways. It helps understanding of the relationships and dependencies in the delivery process, and thus system behavior. It also provides an instrument to share information and knowledge among industry partners and scholars. The process description provides a foundation to identify major improvement opportunities. To my knowledge, it is the first time the process delivery of an ETO product in the construction industry has been described to this extent.

6.2.2 Identification of problems and improvement opportunities

With the help of various methods (literature search, simulation, and case studies) and broad process scope, a number of issues and possible remedies were revealed in the delivery process. Most of the issues are intuitive; however, narrow process specialization and shortsightedness in the past have prevented the process stakeholders from seeing the improvement opportunities available to them. Some of the findings related to design, procurement, and manufacturing and their interface could directly be explained through the TFV theory. The ability to link the findings to a theoretical framework is important, particularly, when it comes to knowledge transfer.

6.2.3 Application of simulation in procurement

The simulation provides understanding about the variability of procurement lead time and its possible sources. The variability of procurement lead time is not generally considered and its causes are even less understood in the construction industry. However, underestimating it may jeopardize project milestones. This dissertation recognizes the value of and supports further application and development of simulation models to investigate process behavior in the construction industry.

6.2.4 Workshops as case study tool

The workshops played a key role in the case study research. They brought the industry partners together so that they could collectively describe the process and agree on changes. In addition, they provided a bridge between academia and industry, whereby knowledge and information were shared in a constructive way.

6.2.5 Advancing of research in construction SCM

The significant improvement opportunities in the delivery process of PDE and their potential generalization to other ETO products and the whole delivery of construction projects support further research in construction SCM. This study has demonstrated that numerous actions can be taken to improve the delivery process but also that important future research opportunities exist both in PDE and by extension in other ETO products. The findings of this research can be used as a starting point and benchmark for future similar studies.

6.3 FUTURE RESEARCH DIRECTIONS

This dissertation has broadened understanding of the delivery process of PDE in many ways. However, it has also provoked a wide range of future research topics. These are, e.g.:

- Can the findings of this study be generalized within PDE and to other ETO products?
- What kinds of methods are needed to implement future state maps in a cross-organizational environment?
- What are the process wide impact of changes and add-ons?
- How can the procurement simulation models be expanded so that they could more accurately mimic real process behavior?

6.3.1 Generalization of findings beyond PDE

Two commercial projects in the US, and one commercial project in Finland were investigated; it would be valuable to know if similar findings can be made beyond the commercial construction sector. Do the findings apply to the residential, transportation, and process industry sectors of the construction industry? Especially the transportation and process industry sectors tend to have large owner organizations to support their capital projects, but are they able to take advantage of their in-house resources to better design, control, and improve the product delivery processes? In residential construction, the components should generally be simpler than in commercial construction, but does the process still follow the same pattern as that found in this research?

Another research area is to study other ETO products, such as precast concrete elements, steel structures, pieces of HVAC equipment, turbines, nuclear reactors, semi-conductor tools, custom software, and motion pictures. Earlier studies in some of these products (e.g., Tommelein et al. 2003) report findings similar to those I made in this study. However, ETO products have traditionally been less studied from the product delivery point of view (design, procurement, manufacturing) because of the belief that they are “one-of-a-kind”. Due to poor replicability and other challenges, there has been a presumption that there is little value in studying them. Nevertheless, as this study has demonstrated, the product may be very different but the delivery process is still largely the same, as chapter 4.5.1 describes.

Finally, even though ETO products are often critical items on construction products, they are only one type of product. Accordingly, what benefits could be identified by applying the TFV theory and describing in detail other types of product delivery processes, such as make-to-stock (MTS) products and assemble-to-order (ATO) products (see Figure 4)?

6.3.2 Implementation of future state maps

The purpose of this dissertation was to describe the current state of the delivery process of PDE and to design a future state process. However, real benefits of the redesign process will be confirmed only after real life testing and analysis of the cost and benefits. This raises two main questions: how to implement the future state map, and how to measure the costs and benefits?

Implementation often turns out to be the most challenging part of redesigning processes. Several issues need to be addressed, e.g.:

- What means can be applied to implement changes in cross-organizational processes?
- Who should be in charge of the implementation?
- Is there a need for a neutral third party facilitator or should, e.g., owners lead the task?
- What type of incentives and performance measures are needed in the implementation phase and after it?
- Who actually pays and who gains?

6.3.3 Measurement of process-wide impact of changes and add-ons

The impact of change orders on construction projects has been widely studied, as described in the literature review; however, these studies have mainly focused on the direct cost (changes in contact value based on material, labor, and overhead) and rarely on indirect cost (productivity loss of various stakeholders, cost of administration, cost of legal disputes, etc.). Especially with respect to ETO products, the whole delivery process including the work done by designers and manufacturers should be included. Currently, it seems that the cost of design iteration, change orders, and add-ons are generally underestimated because the estimates only consider the direct cost (material, labor, and overhead). The direct cost of change orders and add-ons was less than 10% of the contract prices in the cases studied. The indirect costs, such as the cost of managing the change order process and the loss in productivity, were not measured, but the order of magnitude was estimated to be at least the same as the direct cost. Other scholars have argued that the indirect cost is significantly higher than the direct cost of change orders (e.g., Burati et al. 1992, Love 2002). The exclusion of the indirect cost of changes may be one reason why there was not a stronger effort to improve and reduce the change order-approval cycle in the cases being studied. Hence, it would be interesting and valuable to see more complete studies in this area.

6.3.4 Expanding the simulation model

The simulation model in this dissertation focused on the procurement process. It included simplifying assumptions and investigated only two factors, multitasking and merge bias. In reality, many other factors may impact the procurement lead time, such as gaming or deliberate postponement, mistakes, deadlines, incomplete information exchange, release of new product information, and ranking of orders based on customer importance or value. Incorporating these in the simulation model will provide a more realistic estimate of the procurement lead time and further expand our understanding on variability of procurement and causes of variability.

Further testing and validating the simulation model presented in this dissertation on PDE and on ETO products at large may reveal valuable insights about the procurement lead time. As a result it could help to better design and load the resources in the procurement phase.

Finally, this study did not seek statistical evidence or prove statistically the correctness of the simulation model. As the simulation model is expanded, it would be valuable to sample numerical data on real cases and statistically demonstrate the accuracy of the simulation model.

6.4 FINAL THOUGHTS

Scholars who study project-based production systems are experiencing fascinating times, where vigorous research has begun to bear fruit, directing the construction industry to a new way of thinking. It is said that academia is a few steps behind the cutting edge in the industry, describing and analyzing past data; however, in the case of project delivery and its supporting processes, it seems that academia may currently be pushing the industry to change their received traditions.

The findings in this research call for a radical restructuring of the current delivery process of PDE. Hundreds of labor hours and months from the delivery process can be saved through better design and control of the process. The industry partners' skepticism at the beginning of this study and their enthusiasm towards the end of the study can be considered as evidence for the potential benefits revealed. Nevertheless, this study has revealed only the tip of the iceberg regarding construction supply chains. Moreover, this dissertation has perhaps provoked more questions that it could answer. This should not be considered as discouraging. On the contrary, because of the vast opportunities and the broadly acknowledged need to improve current construction industry practices, this research will hopefully inspire other scholars to further investigate and redesign the prevailing practices.

REFERENCES

Akel, N.G., Tommelein, I.D., Boyers, J.C., Walsh, K.D., and Hershauer, J.C. (2001). "Considerations of Streamlining a Vertically Integrated Company". *Proc. 9th Annual Conf. Int'l. Group Lean Constr. IGLC-9*, August held in Singapore. http://cic.vtt.fi/lean/singapore/singapore.htm

Alarcon, L. (editor) (1997*). Lean Construction*. A.A. Balkema, Rotterdam, The Netherlands, 497 pp.

Allen, J.H. (2000). "Make Lean Manufacturing Work for You". *Manufacturing Engineering*, 124(6), 54-64.

Alves, T.C.L.A. and Tommelein, I.D. (2003). "Buffering and Batching Practices in the HVAC Industry". *Proc. 11th Annual Conf. Int'l. Group Lean Constr. IGLC 11*, 22-24 July held in Blacksburg, VA. 369-381. http://strobos.cee.vt.edu/IGLC11/

Arbulu, R.J. (2002). *Improving Construction Supply Chain Performance: Pipe Hangers and System Interfaces*. Master of Engineering Thesis, Constr. Engrg. and Mgmt. Program, U.C. Berkeley, Berkeley, CA.

Arbulu, R.J. and Tommelein, I.D. (2002). "Value Stream Analysis of Construction Supply Chains: Case Study on Pipe Supports Used in Power Plants". *Proc. 10th Annual Conf. Int'l. Group Lean Constr. IGLC-10*, August held in Gramado, Brasil. 183-196. http://www.cpgec.ufrgs.br/norie/iglc10/

Arbulu, R.J., Tommelein, I.D., Walsh, K.D., and Hershauer, J.C. (2002). Contributors to Lead Time in Construction Supply Chains: Case of Pipe Supports Used in Power Plants. *Proc. Winter Sim. Conf.* (WSC02), San Diego, CA, 1745-1751. http://www.informs-cs.org/wsc02papers/239.pdf

Arrow, K. J. (1959). "Towards a Theory of Price Adjustment". Edited by Abramovitz, M. *The Allocation of Resources*. Stanford University Press, CA. 41-51.

Ashley, D. and Workman (1986). *Incentives in Construction Contracts*. Construction Industry Institute, Austin, TX.

Ayers, J.B. (2001). *Handbook of Supply Chain Management*. The St. Lucie Press, New York, NY, 460 pp.

Bajari, P. and Tadelis, S. (2000). *Incentives Versus Transaction Cost: A Theory of Procurement Contracts*. Department of Economics, Stanford University, Unpublished manuscript, 33 pp.

Ballard, G. (2000a). "Positive vs. Negative Iteration in Design". *Proc. 8th Annual Conf. Int'l. Group Lean Constr. IGLC 8*, 17-19 July held in Brighton, UK. http://www.sussex.ac.uk/spru/imichair/news/template.cfm?content=iglc-8.cfm

Ballard, G. (2000b). "Phase scheduling". *Lean Construction Institute*, White Paper No. 7. www.leanconstruction.org

Ballard, G. (2000c). *The Last Planner System of Production Control*. Ph.D. Dissertation, Faculty of Engineering, Univ. of Birmingham, Birmingham, UK.

Ballard, G. (2003). Personal commuication in Berkeley, CA. 10/22/2003.

Ballard, G. and Howell, G. (1994). "Implementing Lean Construction: Stabilizing Work Flow". *Proc. 2 Annual Conf. Int'l. Group Lean Constr IGLC-2*, July held in Santiago, Chile. http://cic.vtt.fi/lean/santiago.htm

Ballard, G. and Howell, G. (1998a) "Shielding Production: An Essential Step in Production Control." *Journal of Construction Engineering and Management*, ASCE, 124(1), 11-17.

Ballard, G. and Howell, G. (1998b). "What Kind of Production is Construction". *Proc. 6th Annual Conf. Int'l. Group Lean Constr. IGLC-6*, 13-15 August held in Guarujá, Brazil. http://www.ce.berkeley.edu/~tommelein/IGLC-6/index.html

Ballard, G., Tommelein, I.D., Koskela, L., and Howell, G. (2002). "Lean Construction Tools and Techniques". Edited by Best, T. and de Valence, G. *Design and Construction: Building in Value*. Butterworth-Heinemann, New York, NY, 504 pp.

Ballou, R.H. (1999). *Business Logistics Management*. 4th ed., Prentice Hall, Upper Saddle River, NJ, 681 pp.

Ballou, R.H., Gilbert, S.M., and Mukherjee, A. (2000). “New Managerial Challenges from Supply Chain Opportunities”. *Industrial Marketing Management, 29*, 7-18.

Barker, R C. (1994). “The Design of Lean Manufacturing Systems Using Time-Based Analysis”. *International Journal of Operations and Production Management*, 14(11), 86-96.

Bertalanffy von, L. (1968). *General System Theory: Foundations, Development, and Applications*. G. Braziller, New York, NY.

British Standards Institution (1997). *BS EN 1325-1: Value Management, Value Analysis, Functional Analysis Vocabulary – Part 1. Value Analysis and Functional Analysis*. BSI, London, UK.

Brockmann, H. (2001). “Transaction Cost in Relationship Contracting”. *AACE International Transaction*, 26(7), 61-68.

Burbidge, J.L. (1989). *Production Flow Analysis*. Oxford University Press, Oxford, UK, 179 pp.

Burati, J.L., Farrington, J.J., and Ledbetter, W.B. (1992). “Causes of Quality Deviation in Design and Construction”. *Journal of Construction Engineering and Management*, ASCE, 118 (1), 34-49.

Burt, D.N (1984). *Proactive Procurement: The Key to Increased Profits, Productivity, and Quality*. Prentice-Hall, Englewood Cliffs, N.J, 236 pp.

Cambell, D.T. and Stanley, J.C. (1963*). Experimental and Quasi-Experimental Design for Research*. Rand McNally College Publishing Company, Chicago, Il, 81 pp.

Chen, H., Harrison, J.M., Mandelbaum, A., Ackere van, A., and Wein, L.M. (1988). "Empirical Evaluation of a Queuing Network Model for Semiconductor Wafer Fabrication". *Operations Research*, 36(2), 202-215.

Choi, T.Y. and Rungtusanatham, M. (1999). "Comparison of Quality Management Practices: Across the Supply Chain and Industries". *The Journal of Supply Chain Management*, 35(1), 20-27.

Chopra, S. (2004). *Supply Chain Management: Strategy, Planning and Operations*. Prentice Hall, Upper Saddle River, NJ, 567 pp.

CII (1988). *Project Materials Management Primer*. Construction Industry Institute, Pub 7-2*,* Austin, TX, 21 pp.

CII (1998). *Reforming Owner, Contractor, Supplier Relationships: A Project Delivery System To Optimize Supplier Roles in EPC Projects*. Construction Industry Institute, Pub 130-1, Austin, TX, 44 pp.

Clark, K. B. and Fujimoto, T. (1991). *Product Development Performance*. Harvard Business School Press, Boston, MA.

Cleveland, A.B.Jr. (1989). "Real-Time Animation of Construction Activities". *In Proceedings of the 1st Construction Congress*, Reston, VA: ASCE.

Coase, R. H. (1972). “Industrial Organizations: A Proposal for Research”. Edited by Fuchs, V.R. *Policy Issues and Research Opportunities in Industrial Organization*. National Bureau of Economic Research, New York, NY.

Cox, I.D., Morris, J., Rogerson, J. H., and Jared, G. E. (1999). ‘‘A Quantitative Study of Post Contract Award Design Changes in Construction.’’ *Construction Management Economics*, 17(4), 427-439.

Daganzo, C.F. (2003). *A Theory of Supply Chains*. Springer, New York, NY, 123 pp.

Deming, W.E. (1986). *Out of the Crisis*. 11th printing, Cambridge University Press, Melbourne, Australia, 507 pp.

Dubois, A. and Gadde, L-E. (2000). “Supply Strategy and Network Effects-Purchasing Behavior in the Construction Industry.” *European Journal of Purchasing and Supply Management,* 6, 207-215.

Durham, M.J. (1995). “The Future of Sabre.” Edited by Jenkins, D. *The Handbook of Airline Economics.* Aviation Week Group, 726 pp.

Egan, J. (1998). *Rethinking Construction*. Department of Trade and Industry, United Kingdom. www.dti.gov.uk/construction/rethink/report/index.htm

Elfving, J.A. 2003. *Sähkökeskuksien Hankintaketjun Nyky- ja Tulevaisuuden Prosessi – Case Novo*. [In Finnish, title in English is “The Current and Future State of the Delivery Process and Installation of Power Distribution Equipment

– Case Novo"]. Research Report, Engrg. and Project Management Program, Civil and Environmental Engineering Department, University of California, Berkeley, CA, 80 pp.

Elfving, J.A. and Tommelein, I.D. (2003). "Impact of Multitasking and Merge Bias on Procurement of Complex Equipment." *Proc. Winter Sim. Conf.* (WSC03), New Orleans, LA.

Elfving, J.A., Tommelein, I.D., and Ballard, G. (2003a). *The Current and Future State of the Delivery Process of Power Distribution Equipment – Case Paradise Pier.* Tech. Report. Engrg. and Project Mgmt. Program, Civil and Environmental Engineering Department, University of California, Berkeley, CA, 80 pp.

Elfving, J.A., Tommelein, I.D., and Ballard, G. (2003b). *The Current and Future State of the Delivery Process of Power Distribution Equipment – Case Bay Street*. Research Report, Engrg. and Project Mgmt. Program, Civil and Environmental Engineering Department, University of California, Berkeley, CA, 70 pp.

Elfving, J. A., Tommelein, I. D., and Ballard, G. (2003c). "An International Comparison of the Delivery Process of Power Distribution Equipment". *Proc. 11th Annual Conf. Int'l. Group Lean Constr.* (IGLC 11), Blacksburg, VA, 357-368. http://strobos.cee.vt.edu/IGLC11/

Ellinger, A.E. (2000). “Improving Marketing/ Logistics Cross-Functional Collaboration in the Supply Chain”. *Industrial Marketing Management*, 29, 85-96.

ENR (2003a). “Project Delivery Is Still Evolving”. *Engineering News Record*, June 16, 38-40.

ENR (2003b). “Consulting As Virtual Enterprise”. *Engineering News Record*, August 4, 23.

Ericsson, H. (1999). *Managing Construction Supply Chain by Simulation*. Licentiate Thesis, Dept. of Civil and Envir. Engrg., Helsinki University of Technology, 104 pp.

Fisher, N. and Yin, S.L. (1992). *Information Management in a Contractor*. Thomas Telford Services Ltd, London, UK, 260 pp.

Fisk, E.D. (2003). *Construction Project Administration*. 7th ed., Prentice Hall, Upper Saddle River, NJ, 635 pp.

Ford, H. (1928). *Today and Tomorrow*. Productivity Press, Cambridge, MA, 286 pp. Reprinted in 1988 by Productivity Press, Cambridge, MA

Forrester, J.W. (1961). *Industrial Dynamics.* MIT Press, Cambridge, MA. 464 pp.

Foss, N.J. (1999). “Research in the Strategic Theory of the Firm: Isolationism and Integrationism”. *Journal of Management Studies*, 36, November, 725-754.

Freire, J. and Alarcon, L.F. (2000). "Achieving a Lean Design Process". *Proc. 8th Annual Conf. Int'l. Group Lean Constr., IGLC-8*, 17-19 July held in Brighton, UK. http://www.sussex.ac.uk/spru/imichair/news/template.cfm?content=iglc-8.cfm

Frutos, J.D. and Borenstein, D. (2003). "Object-Oriented Model for Customer-Building Company Interaction in Mass Customization Environment". *Journal of Construction Engineering and Management*, ASCE, 129(3), 302-313.

Ganeshan, R., Tayur, S., and Magazine, M. (1999). *Quantitative Methods for Supply Chain Management*. Kluwer Academic Publisher, Boston, MA, 885 pp.

Gil, N. (2001). *Product-Process Development Simulation to Support Specialty Contractor Involvement in Design*. Ph.D. Dissertation, Dept. of Civil & Envir. Engrg., University of California, Berkeley, 220 pp.

Gil, N., Tommelein, I.D., and Kirkendall, R. (2000). "Holistic Product-Process Modeling of a Design-Build System". *Proc. 8th Annual Conf. Int'l. Group Lean Constr. IGLC 8*, 17-19 July held in Brighton, UK. http://www.sussex.ac.uk/spru/imichair/news/template.cfm?content=iglc-8.cfm

Gilbreth, F.B. and Gilbreth, L.M. (1922). "Process Chart and Their Place in Management". *Mechanical Engineering*, January, 38-41.

Grover, V. and Malhotra, M.K. (2003). "Transaction Cost Framework in Operations and Supply Chain Management Research: Theory and Measurement". *Journal of Operations Management*, 11(4), 457-473.

Gunasekaran, A. and Nath, B. (1997). “The Role of Information Technology in Business Process Reengineering”. *International Journal of Production Economics*, 50 (2-3), 91-104.

Hammond, M. (1990). “Reengineering Work: Don’t Automate, Obilirate”. *Harvard Business Review*, July-August, 104-112.

Handfield, R.B. (1995). *Re-Engineering for Time-Based Competition*. Quorum Books, Westport, CT, 224 pp.

Halpin. D. W. (1973). *An Investigation of the Use of Simulation Networks for Modeling Construction Operations*. Ph.D. Dissertation, University of Illinois, Urbana, Il.

Halpin, D.W. (1993). “Process-Based Research to Meet International Challenge”. *Journal of Construction Engineering and Management*, ASCE, 119(3), 417-425.

Hanna, A., Russell, J.S., Gotzin, T.W., and Nordheim, E.V. (1999). ‘‘Impact of Change Orders on the Labor Efficiency for Mechanical Contractors.’’ *Journal of Construction Engineering and Management*, ASCE, 125(3), 176–184.

Harris, R.B. and Ioannou, P.G. (1998). “Scheduling Projects with Repeating Activities”. *Journal of Construction Engineering and Management*, ASCE, 124(4), 269-278.

Hayek, F. (1945). “The Use of Knowledge in Society”. *American Economic Review*, 35(September), 519-630.

Hershauer, J.C., Walsh, K.D., and Tommelein, I.D. (2001). "Issues in Construction Supply Chains." Edited by Blackmon, K., Brown, S., Cousins, P., Graves, A., Harland, C., Lamming, R., and Maylor, H. (2002). *What Really Matters in Operations Management.* Papers from the European Operations Management Association 8th Annual Conference (EurOMA '01), 3-5 June, Bath, UK, pp. 345-355

Hester, W.T., Kuprenas, J.A., and Chang, T.C. (1991). *Construction Changes and Change Orders: Their Magnitude and Impact*. Construction Industry Institute, Austin, TX.

Hinze, J. (2001). *Construction Contracts*. 2nd ed., McGraw-Hill, New York, NY, 489 pp.

Hobbs, J.E. (1996). “A Transaction Cost Approach to Supply Chain Management”. *Supply Chain Management,* 1(2), 15-27.

Holzemer, M., Tommelein, I.D., and Lin, S.L. (2000). “Materials and Information Flows for HVAC Ductwork Fabrication and Site Installation”. *Proc. 8th Annual Conf. Int’l. Group Lean Constr. IGLC 8*, 17-19 July held in Brighton, UK. http://www.sussex.ac.uk/spru/imichair/news/template.cfm?content=iglc-8.cfm

Hong-Minh, S. (2002). *Re-engineering the UK Private House Building Supply Chain*. Ph.D. Dissertation, Cardiff Business School, University of Wales, 310 pp.

Hopp, W., and Spearman, M. (2000). *Factory Physics: Foundation of Manufacturing Management*. 2nd ed., Irwin/McGraw-Hill, Boston, 668 pp.

Houlihan, J.B. (1985). “International Supply Chain Management”. *International Journal of Physical Distribution and Materials Management,* 15(1), 22-38.

Housing Forum (2000). www.housingforum.org.uk.

Howell, G. (1999). “What is Lean Construction”. *Proc. 7th Annual Conf. Int’l. Group Lean Constr. IGLC-7*, 26-28 July held in Berkeley, CA. http://www.ce.berkeley.edu/~tommelein/IGLC-7/index.html

Howell, G., Laufer, A., and Ballard, G. (1993). “Interactions Between Sub-Cycles: One Key to Improved Methods”. *Journal of Construction Engineering and Management*, ASCE, 119(2), 714-728.

Iansiti, M. (1995). “Shooting the Rapids: Managing Product Development in Turbulent Environments”. *California Management Review*, 38(1), 37-58.

Ibbs, C.W. (1986). *Determining the Impact of Various Construction Contract Types and Causes on Product Performance: Volume I and II*. Construction Industry Institute, Austin, TX.

Ibbs, C.W., Kwak, Y.H., Ng, T., and Odabasi, A.M. (2003). "Project Delivery Systems and Project Change: Quantitative Analysis". *Journal of Construction Engineering and Management*, 129(4), 382-387.

Institute of Value Management (2003). www.ivm.uk.org, last visited 11/5/2003.

Jarnbring, J. (1994). (In Swedish) "Byggarbetsplatsens Materialflödeskostanader". [Material Flow Cost on Building Site]. *Lunds Tekniska Högskola, Institutionen för Teknisk Logistik*, Lund Sweden, Rapport 94:1.

Johnson, M.E. and Whang, S.J. (2002). "E-Business and Supply Chain Management: An Overview and Framework". *Production and Operations Management*, 11 (4), 413-423.

Johnston, P. (1995). "Supply Chain Management: The Past, The Present, and The Future. *Manufacturing Engineer*, 213-217.

Juran, J.M. (1974). *Quality Control Handbook*. 3rd ed., Irwin/McGraw-Hill, New York, NY.

Kankainen, J. and Seppänen, O. (2003). "A Line-of-balance Based Schedule Planning and Control System". *Proc. 11th Annual Conf. Int'l. Group Lean Constr. IGLC-11*, July held in Blacksburg, VA. 132-143. http://strobos.cee.vt.edu/IGLC11/

Karmarkar, U.S. (1983). “Lot Sizes, Lead Times & In-Process Inventories”. *Management Science*, 33(3), 409-419.

Kay, N.M (1998). Clusters of Collaboration: “The Firm, Joint Ventures, Alliances, and Clubs”. Edited by Foss, N.J. and Loasby, B.J. *Economics Organization, Capabilities, and Cooperation*, Rutledge, New York, NY, 300 pp.

Koo, B. and Fisher, M.A. (2000). “Feasibility Study of 4D CAD in Commercial Construction”. *Journal of Construction Engineering and Management*, ASCE, 126(4), 251-260.

Koskela, L. (1992). *Application of the New Production Philosophy to Construction*. Technical Report No. 72, Stanford, EUA: CIFE, 75 pp.

Koskela, L (1999). “ Management of Production in Construction: A Theoretical View.” *Proc. 7th Annual Conf. Int’l. Group Lean Constr. IGLC-7*, 26-28 July held in Berkeley, CA. 241-252. http://www.ce.berkeley.edu/~tommelein/IGLC-7/index.html

Koskela, L. (2000). *An Exploration Towards a Production Theory and its Application to Construction*. Ph.D. Dissertation, VTT Publications 408, Espoo, Finland, 296 pp.

Koskela, L., Howell, G., Ballard, G. and Tommelein, I.D. (2002). “The Foundation of Lean Construction”. Edited by Best, T. and de Valence, G. *Design and Construction: Building in Value*. Butterworth-Heinemann, New York, NY, 504 pp.

Krishnan, V., Eppinger, S.D., and Whitney, D.E. (1997). “A Model-Based Framework to Overlap Product Development Activities”. *Management Science*, 43(4), 437-451.

LaLonde, B. (1998). “Supply Chain Management: An Opportunity for Competitive Advantage*”. Department of Transportation and Logistics, The Ohio State University.*

Lambert, D.M. and Cooper, M.C. (2000). “Issues in Supply Chain Management”. *Industrial Marketing Management, 29*, 65-83.

Lamming, R. (1993). *Beyond Partnership – Strategies for Innovation and Lean Supply*. Prentice-Hall, Englewood Cliffs, NJ.

Lancioni, R.A., Smith, M.F., and Olivia, T.A. (2000). “ The Role of Internet in Supply Chain Management”. *Industrial Marketing Management, 29*, 45-56.

Laufer, A. (1987). *Simultaneous Management: Managing Projects in a Dynamic Environment*. Amacom, New York, NY, 313 pp.

Laufer, A. and Tucker, R.L. (1987). “Is Construction Project Planning Really Doing Its Job? A Critical Examination of Focus, Roles, and Process”. *Construction Management and Economics*, 5, 243-266.

Law, A.M. and Kelton, W.D. (2000). *Simulation Modeling and Analysis*. Irwin/McGraw-Hill, New York, NY, 760 pp.

Lee, H.L., Padmanabhan, V., and Whang, S (1997). “The Bullwhip Effect in Supply Chains”. *Sloan Management Review*, Spring, 93-102.

Lin, F-R. and Shaw, M. (1998). “Reengineering the Order Fulfillment Process in Supply Chain”. *The International Journal of Flexible Manufacturing Systems*, 10, 197-229.

Little, J.D.C. (1961). “A Proof for the Queuing Formula: L=λW”. *Operations Research*, 9, 383-387.

Loch, C.H. and Terwiesch, C. (1998). “Communication and Uncertainty in Concurrent Engineering”. *Management Science*, 44(8), 1032-1048.

London, K.A. and Kenley, R. (2001). ”An Industrial Organization Economic Supply Chain Approach for the Construction Industry: a Review”. *Construction Management and Economics*, 19, 777-787.

Love, P.E.D. (2002). “Influence of Project Type and Procurement Method on Rework Costs in Building Construction Projects”. *Journal of Construction Engineering and Management*, ASCE, 128(1), 18-29.

Luhtala, M., Anttila, P., and Kilpinen, E. (1994). *LOGI Managing Make-to-Order Supply Chains*. Helsinki University of Technology, Teta, Report 153.

Macneil, I.R. (1974). “The Many Futures of Contracts”. *Southern California Law Review*, 47(May), 691-816.

Mahaffie, T. (1998). “The Power of Partnering”. *Electrical Contractor*, July.

Mariti, P. and Smiley, R.H. (1996). “Cooperative Agreements and Organization of Industry”. Edited by Buckely, P.J. and Michie, J. *Firms, Organizations, and Contracts*. Oxford University Press, New York, NY, 475 pp.

Martinez, J.C. (1996). STROBOSCOPE: State and Resource Based Simulation of Construction Processes. Ph.D. Dissertation, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, 518 pp.

Mckenzie, J. (2001). “Guide to the Electrical Contracting Market”. *Electrical Contractor*, http://www.ecmag.com/research/guide/2001guide.pdf, last visited 3/19/2001. 24 pp.

Miles, L.D. (1961). *Techniques of Value Analysis and Engineering.* Irwin/McGraw-Hill, New York, NY.

Monden, Y. (1994). *Toyota Production System*. 2nd ed., Chapman & Hall, London, UK, 423 pp.

Nishiguchi, T. (1994). *Strategic Industrial Sourcing*. Oxford Univ. Press, Oxford, UK, 319 pp.

Nonaka, I., Toyama, R., and Konno, N. (2000) “SECI, BA and Leadership: A Unified Model of Dynamic Knowledge Creation”. *Long Range Planning*, 33(1), 5-34.

Nunally, S.W. (2002). *Construction Methods and Management*. 5th ed., Prentice Hall, Upper Saddle River, NJ, 549 pp.

O'Brien, W. J. and Fischer, M. A. (1993). "Construction Supply-Chain Management: a Research Framework." *Proceedings of CIVIL-COMP-'93, Information Technology for Civil and Structural Engineers, The Third International Conference on the Application of Artificial Intelligence to Civil and Structural Engineers*, Edinburgh, Scotland, August 17-19, 61-64.

Ohno, T. (1988a). *Toyota Production System: Beyond Large-Scale Production.* Productivity Press, Cambridge, Massachusetts, 143 pp.

Ohno, T. (1988b). *Just-In-Time for Today and Tomorrow.* Productivity Press, Cambridge, Massachusetts, 145 pp.

Oliver, R.K. and Webber, M.D. (1982). " Logistics Catches Up with Strategy". Edited by Christopher, M.G. (1992). *Logistics: The Strategic Issues*. Chapman and Hall, London, UK.

Paulson, B.C.Jr., Chan, W.T., and Koo, C.C. (1987)."Construction Operations Simulation by Microcomputer". *Journal of Construction Engineering and Management*, ASCE, 113 (2), 302-314.

Penrose, E. (1959). *The Theory of Growth of the Firm*. John Wiley & Sons, New York, NY.

Porter, M.E. (1985). *Competitive Advantage*. The Free Press, New York, NY, 557 pp.

Prahalad, C.K. and Hamel, G. (1990). “The core Competence of a Company”. *Harvard Business Review*, 68, May-June, 79-90.

Riggs, D.A. and Robbins, S.L. (1998). *The Executive’s Guide to Supply Management Strategies: Building Supply Chain Thinking to All Business Processes*. AMACOM, New York, NY, 245 pp.

Richardson, G.B. (1960). *Information and Investment: A Study in the Working of the Competitive Economy*. Oxford University Press, Oxford, UK, 226 pp.

Richardson, G.B. (1996). “The Organization of Industry”. Edited by Buckely, P.J. and Michie, J. *Firms, Organizations, and Contracts*. Oxford University Press, New York, NY, 475 pp.

Robson, C. (2002). *Real World Research*. 2nd ed, Blackwell Publishers Ltd, Oxford, UK, 510 pp.

Ross, D.F. (1998). *Competing through Supply Chain Management*. International Thomson Publishing, New York, NY, 365 pp.

Rother, M. and Harris, M. (2001). *Creating Continues Flow: An Action Guide for Managers, Engineers and Production Associates.* The Lean Enterprise Institute, Brookline, MA, 103 pp.

Rother, M. and Shook, J. (1998). *Learning to See: Value Stream Mapping to Add Value and Eliminate Waste*. The Lean Enterprise Institute, Brookline, MA, 94 pp.

R.S. Means (2001). "Change Orders." from *Building Construction Cost Data*, 59th ed., Kingston, MA: R.S. Means Co.

Russell, R.S. and Taylor, B.W.III. (1999). *Operations Management: Multimedia Version*. Prentice Hall, Upper Saddle River, N.J, 879 pp.

Sacks, R., Akinci, B., and Ergen, E. (2003). "3D Modeling and Real-Time Monitoring in Support of Lean Production of Engineered-to-Order Precast Concrete Buildings". *Proc. 11th Annual Conf. Int'l. Group Lean Constr. IGLC-11*, July held in Blacksburg, VA. 398-410. http://strobos.cee.vt.edu/IGLC11/

Santech Industries (2003). *The Airplane Game*. www.santech.com

Santos dos, A., (1999). *Application of Flow Principles in the Production Management of Construction Sites*. Ph.D. Thesis, School of Construction and Property Management, University of Salford, England, 463 pp.

Shewhart, W.A. (1939). *Statistical Method from the Viewpoint of Quality Control*. Lancaster Press, Lancaster, DC,155 pp.

Schmenner, R.W. (1993). *Production/Operations Management*. Prentice Hall, New Jersey, NJ, 825 pp.

Schonberger, R.J. (1996). *World Class Manufacturing: The Next Decade*. The Free Press, NewYork, NY, 275 pp.

Schruben, D.A. and Schruben, L.W. (1999). *Event Graph Modeling Using SIGMA*. Custom Simulations, http://www.customsimulations.com

Senge, P.M. and Sterman, J.D. (1994). “Systems Thinking and Organizational Learning: Acting Locally and Thinking Globally in the Organization of the Future”. Edited by Morecroft, J.D.W. and Sterman, J.D. *Modeling for Learning Organizations*. Productivity Press, Portland, OR, 400 pp.

Shingo, S. (1988). *Non-Stock Production*. Productivity Press, Cambridge, MA, USA, 454 pp.

Shingo, S. (1992). *The Shingo Production Management System: Improving Process Functions*. Productivity Press, Cambridge, MA, USA, 215 pp.

Simon, H.A. (1961). *Administrative Behavior*. 2nd ed., Macmillan, New York, NY, 259 pp.

Smeaton, R.B. (1987). *Switchgear Control Handbook.* 2nd ed., Irwin/McGraw-Hill, New York, NY, 1040 pp.

Smith, R.P. and Eppinger, S.D. (1997). “Identifying Controlling Features for Engineering Design Iteration”. *Management Science*, 43(3), 276-293.

Smith, P.G. and Reinertsen, D.G. (1991). *Developing Products in Half the Time*. Van Nostrand Reinhold, New York, NY, 298 pp.

Sobek, D.K.III. (1996). “A Set-Based Model of Design”. *Mechanical Engineering*, 118(7), 78-81.

Sobek, D.K.II,, Ward, A.C., and Liker, J.K. (1999). “Toyota's Principles of Set-Based Concurrent Engineering”. *Sloan Management Review*, 40(2), 67-83.

Society of American Value Engineers (1998). *Value Methodology Standard*. SAVE International, Dayton, OH. www.value-eng.org/

Songer, A.D. and Molenaar, K.R. (1996). “Selecting Design-Build: Public and Private Sector Owner Attitudes“. *Journal of Management in Engineering,* 12(6), 47-53.

Stadler, H. and Kilger, C. (ed.) (2000). *Supply Chain Management and Advanced Planning: Concepts, Models, Software, and Case Studies*. Springer-Verlag, Berlin, Germany, 371 pp.

Stalk, G.H.Jr. and Hout, T.M. (1990). *Competing against Time: How Time Based Competition Is Reshaping Global Markets.* Free Press, New York, NY, 285 pp.

Sterman, J.D. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin McGraw-Hill, Boston, MA, 982 pp.

Stevens, G.C. (1989). “Integrating the Supply Chain”. *International Journal of Physical Distribution and Materials Management*, 19(3), 3-8.

Steward, D. (1981). “The Design Structure System: A Method for Managing the Design of Complex Systems”. *IIIE Trans. Engineering Management,* (3), 71-74.

Stigler, G.J. (1946). *The Theory of Price*. Macmillan, New York, NY.

Stuckhart, G. (1995). *Construction Materials Management.* Marcel Dekker Inc., New York, NY. 328 pp.

Supply Chain Council (2003). http://www.supply-chain.org

Tanhuanpää, V-P., Koskela, L., Lahdenperä, P. (1999). (In Finnish) *Rakennushankkeen Toteutuksen Tehostaminen: Mahdollisuudet ja Keinaot Hankkeen Eri Vaiheissa*. [Improving the Performance in Construction Projects: Means and Possibilities in Different Project Phases]. VTT Building Technology, Espoo, 90 pp.

Takeuchi, H. and Nonaka, I. (1986). “The New York Product Development Game” *Harvard Business Review*, January-February, 137-146.

Tavistock Institute (1966). *Independence and Uncertainty*. Tavistock Publications, London, UK, 83 pp.

Teece, D. (1996). “Firm Organization, Industrial Structure, and Technological Innovation”. *Journal of Economic Behavior and Organization*, 31, 193-224.

Thomas, P.R. (1990). *Competitiveness through Total Cycle Time*. Irwin/McGraw-Hill, New York, NY.

Thomson, D.S., Austin, S.A., Devine-Wright, H., and Mills, G.R. (2003). “Managing value and quality in design”. *Building Research and Information* 31(5), 334–345.

Toikkanen, S. (1995). (In Finnish) “JOT Toistuvassa Rakentamisessa”. [JOT in Repetitive Construction]. Helsinki University of Technology, Unit of Construction Economics and Management, No 132, 93 pp.

Tommelein, I.D. (1997). "Discrete-event Simulation of Lean Construction Processes." *Proc. 5th Annual Conference of the International Group for Lean Construction, IGLC-5, 16-17 July at Griffith University-Gold Coast Campus*, Gold Coast, Queensland, Australia, 121-135. http://web.bham.ac.uk/d.j.crook/lean/iglc5/abstract.htm

Tommelein, I.D. (1998). “Pull-Driven Scheduling for Pipe-Spool Installation: Simulation of Lean Construction Technique”. *Journal of Construction Engineering and Management*, ASCE, 124(4), 279-288.

Tommelein, I.D. and Ballard, G. (1997). *Coordinating Specialists*. Technical Report No. 97-8, Construction Engineering and Management Program, Civil and Environmental Engineering Department, University of California, Berkeley, CA

Tommelein, I.D. and Li, A.E.Y. (1999). “Just-in Time Concrete Delivery: Mapping Alternatives for Vertical Supply Chain Integration. *Proc. 7th Annual Conf. Int'l. Group Lean Constr. IGLC-7*, 26-28 July held in Berkeley, USA. 97-108. http://www.ce.berkeley.edu/~tommelein/IGLC-7/index.html

Tommelein, I.D., Riley, D., Howell, G.A. (1999). " Parade Game: Impact of Work Flow Variability on Trade Performance". *Journal of Construction Engineering and Management*, ASCE, 125(5), 304-310.

Tommelein, I.D., Walsh, K.D., and Hershauer, J.C. (2003). *Improving Capital Projects Supply Chain Performance.* Research Report PT172-11, Construction Industry Institute, 241 pp.

Tommelein, I.D. and Weissenberger, M. (1999). "More Just-In-Time: Location of Buffers in Structural Steel Supply and Construction Processes". *Proc. 7th Annual Conf. Int'l. Group Lean Constr. IGLC-7*, 26-28 July held in Berkeley, USA. 12 pp. http://www.ce.berkeley.edu/~tommelein/IGLC-7/index.html

Towill, D.R. (1996). "Time Compression and Supply Chain Management – A Guided Tour". *Supply Chain Management*, 1(1), 15-27.

Tsao, C.C.Y., Tommelein, I.D., Swanlund, E., and Howell, G. (2000). "Case Study for Work Structuring: Installation of Metal Door Frames". *Proc. 8th Annual Conf. Int'l. Group Lean Constr. IGLC 8*, 17-19 July held in Brighton, UK. http://www.sussex.ac.uk/spru/imichair/news/template.cfm?content=iglc-8.cfm

Ulrich, K.T. and Eppinger, S.D. (1999). *Product Design and Development.* 2nd ed., Irwin/McGraw-Hill, New York, NY.

US Census Bureau (2001). *Switchgear, Switchboard Apparatus, Relays, and Industrial Controls: 2000*. US Department of Commerce. 13 pp. www.census.gov /industry/1/ma335a01.pdf

Vaart van der, J.T., Vries de, J., and Wijngaard, J. (1996). "Complexity and Uncertainty of Materials Procurement in Assembly Situation". *International Journal of Production Economics,* 46-47, 137-152.

Vaidyanathan K. (2003). "Value of Visibility and Planning an Engineer-to-Order Environment". *Proc.11th Annual Conf. Int'l. Group Lean Constr. IGLC-11*, July held in Blacksburg, VA. 332-344. http://strobos.cee.vt.edu/IGLC11/

Vonderembse, M.A. and Tracey, M. (1999). "The Impact of Supplier Selection Criteria and Supplier Involvement on Manufacturing Performance". *The Journal of Supply Chain Management*, 35(3), 33-39.

Vrijhoef, R. and Koskela, L. (1999). "Roles of Supply Chain Management in Construction". *Proc. 7th Annual Conf. Int'l. Group Lean Constr. IGLC-7*, 26-28 July held in Berkeley, USA. 133-146. http://www.ce.berkeley.edu/~tommelein/IGLC-7/index.html

Vrijhoef, R. and Koskela, L. (2000). "The Four Roles of Supply Chain Management in Construction". *European Journal of Purchasing & Supply Management*, 6, 169-178.

Vrijhoef, R., Koskela, L., and Voordijk, H. (2003). "Understanding Construction Supply Chains: A Multiple Theoretical Approach to Inter-Organizational

Relationships in Construction”. *Proc. 11th Annual Conf. Int'l. Group Lean Constr. IGLC-11*, July held in Blacksburg, VA. 280-292. http://strobos.cee.vt.edu/IGLC11/

Walsh, K.D. , Hershauer, J.C., Walsh, T.A., Tommelein, I.D., and Sawhney, A. (2002). “Lead Time Reduction via Pre-Positioning of Inventory in an Industrial Construction Supply Chain”. *Proc. Winter Sim. Conf.* (WSC02), San Diego, CA,1752-1758. http://www.cpgec.ufrgs.br/norie/iglc10/

Walsh, K.D., Sawhney, A., and Bashford, H.H. (2003). “Cycle-Time Contributions of Hyper-Specialization and Time-Gating Strategies in US Residential Construction”. *Proc. 11th Annual Conf. Int'l. Group Lean Constr. IGLC-11*, July held in Blacksburg, VA. 390-397. http://strobos.cee.vt.edu/IGLC11/

Ward, A., Liker, J.K., Cristiano, J.J., and Sobek, D.K.III. (1995). “The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster”. *Sloan Management Review*, 36(3), 43-61.

Weber, M.M. (2000). “Calculating the Cost of Variance in the Supply Chain”. *Industrial Marketing Management*, 29, 57-64.

Wegelius-Lehtonen, T. and Pahkala, S. (1998). “Developing Material Delivery Processes in Cooperation: An Application Example of the Construction Industry”. *International Journal of Production Economics*, 56-57, 689-698.

Williamson, O. E. (1975). *Markets and Hierarchies: Analysis and Antitrust Implications*. Free Press, New York, NY.

Williamson, O.E. (1985). *The Economic Institutions of Capitalism*. Free Press, New York, NY, 450 pp.

Williamson, O.E. (2000). “The New Economic Institution: Taking Stock, Looking Ahead”. *Journal of Economic Literature*, 38(September), 595-613.

Winch, G.M. (1989). “The Construction Firm and Construction Project: A Transaction Cost Approach”. *Construction Management and Economics*, 7(4), 331-345.

Winner, R.I., Pennell, J.P., Bertrend, H.E., and Slusarczuk, M.M.G. (1988). *The Role of Concurrent Engineering in Weapons Systems Acquisition*. IDA Report R-338, Institute for Defense Analysis, Alexandria, VA.

Womack, J.P. and Jones, D.T. (1996). *Lean Thinking*. Simon & Schuster, New York, NY, 350 pp.

Womack, J.P., Jones, D.T., and Roos, D. (1990). *The Machine That Changed the World*. Harper Collins, New York, NY, 323 pp.

Wortmann, J.C., Muntslag, D.R., and Timmermans, P.J.M. (1997). *Customer Driven Manufacturing*. Chapman & Hall, London, UK, 464 pp.

Yazdani, B. and Holmes, C. (1999). “Four Models of Design Definition; Sequential, Design Centered, Concurrent and Dynamic”. *Journal of Engineering Design*, 10(1), 25-37.

Yin, R.K. (2003). *Case Study Research: Design and Methods*. 3rd ed., SAGE Publications, London, UK, 170 pp.

Zeitoun, A.A. and Oberlander, G.D. (1993). *Early Warning Signs of Project Changes*. Source Document 91, Construction Industry Institute, Austin, TX.

Zipkin, P.H. (1986). “Models for Design and Control of Stochastic Multi Item Batch Production System”. *Operations Research*, 34, 91-104.

APPENDICES

APPENDIX 1

Current state process map of Bay Street

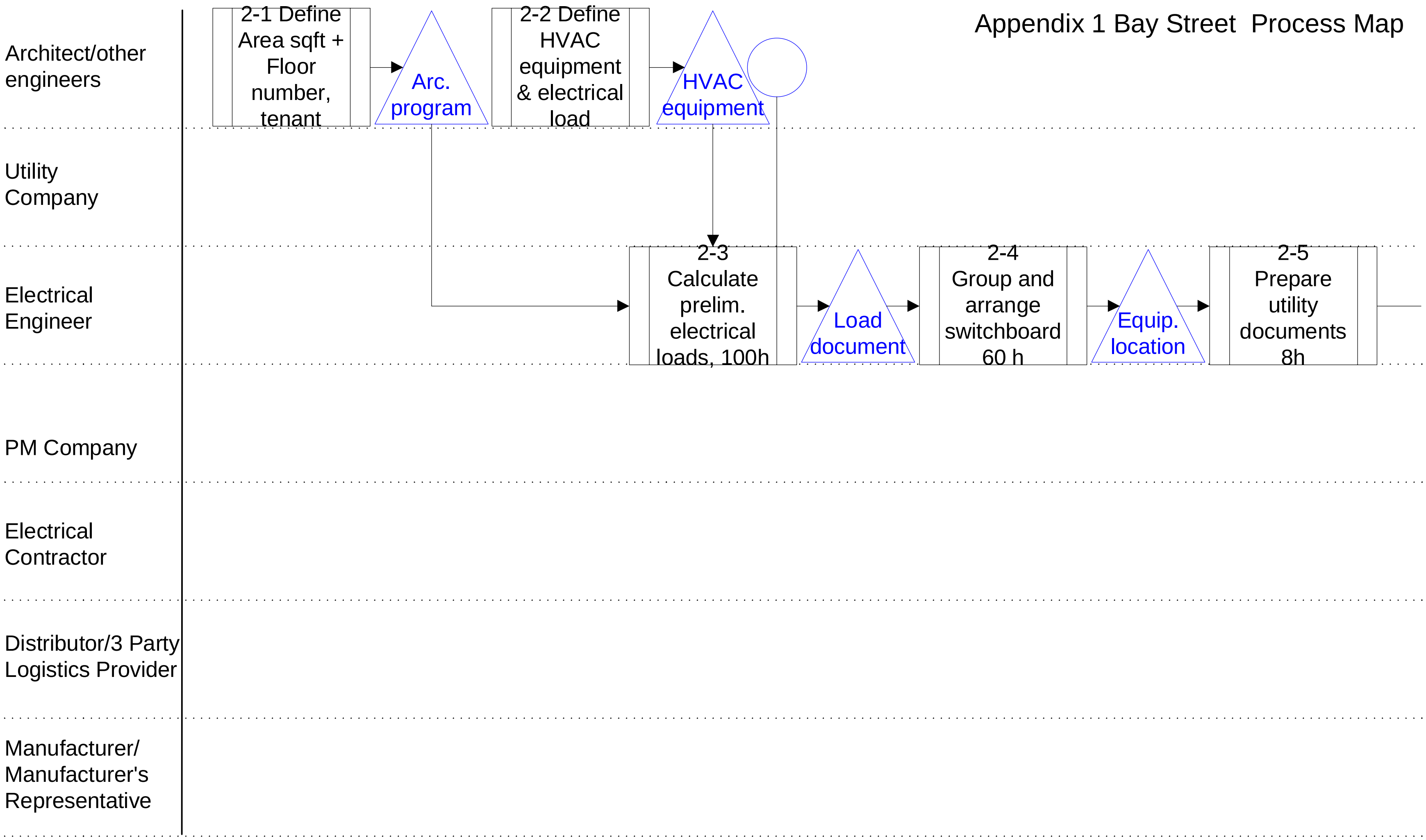
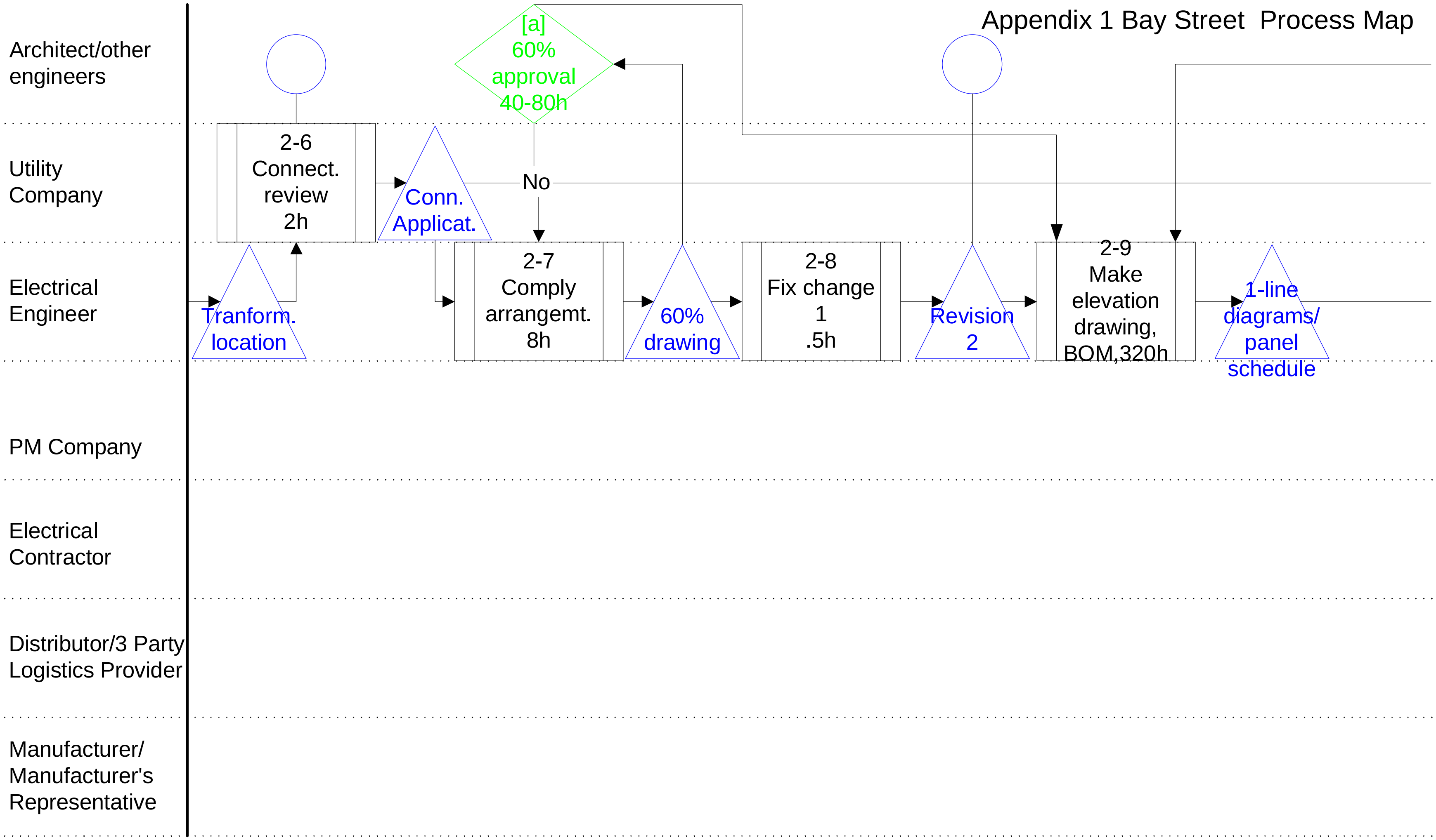
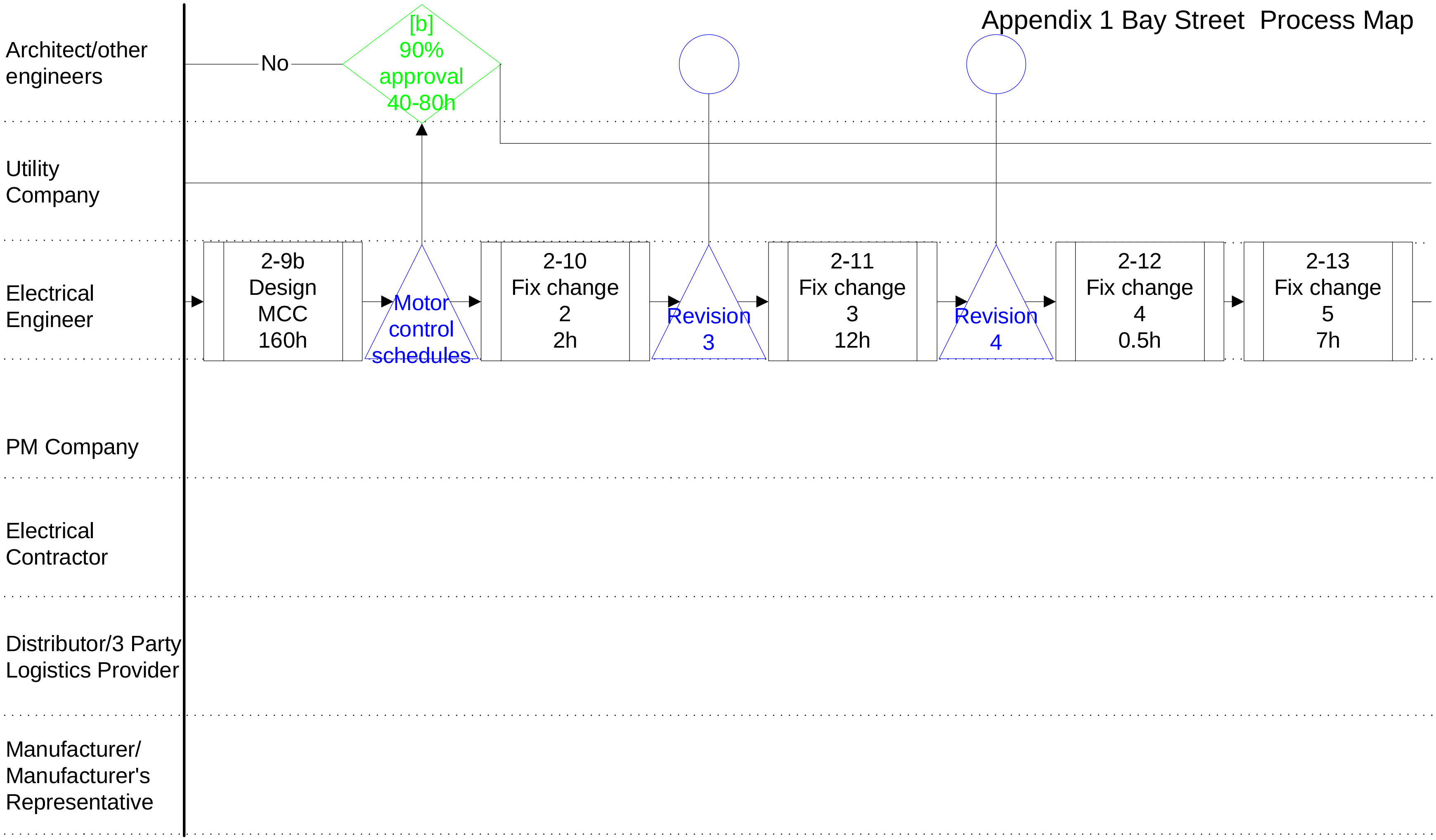


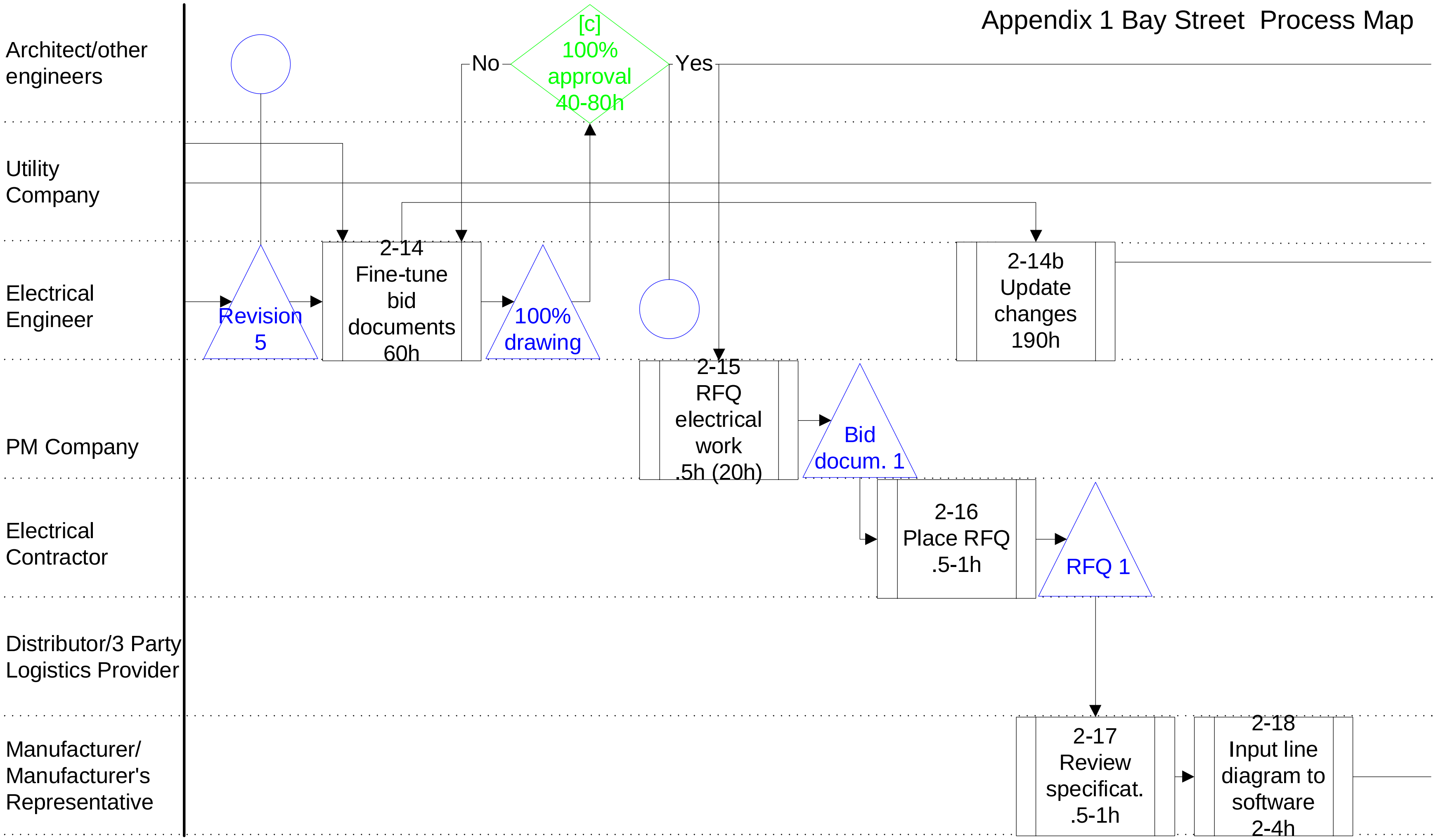
Figure 44: Current state process map-Bay Street

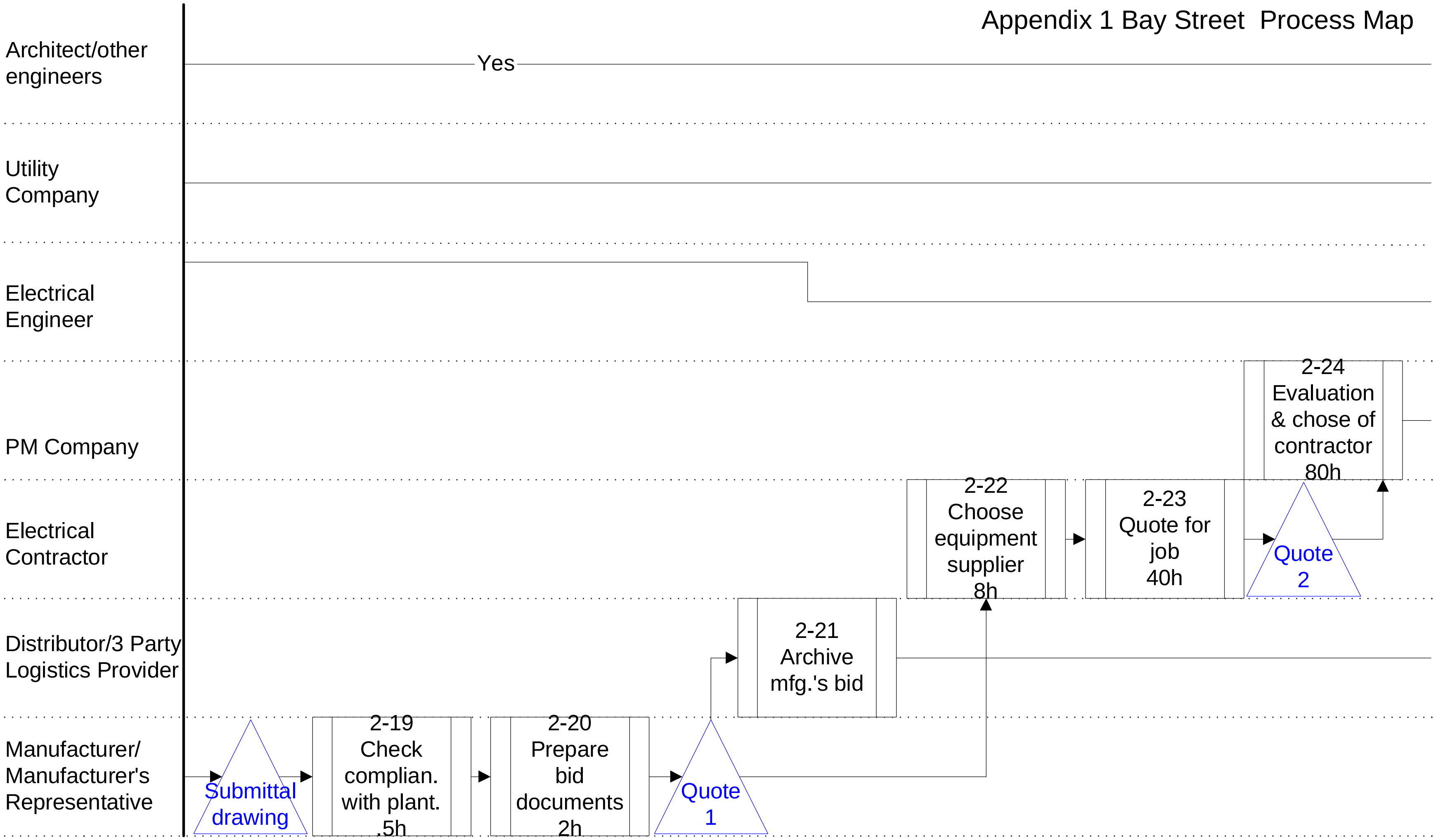

Architect/other engineers
Utility Company
Electrical Engineer
PM Company
Electrical Contractor
Distributor/3 Party Logistics Provider
Manufacturer/ Manufacturer's Representative
2-6 Connect. review 2h
[a] 60% approval 40-80h
Conn. Applicat.
No
Tranform. location
2-7 Comply arrangemt. 8h
60% drawing
2-8 Fix change 1 .5h
Revision 2
2-9 Make elevation drawing, BOM,320h
1-line diagrams/ panel schedule

Appendix 1 Bay Street Process Map

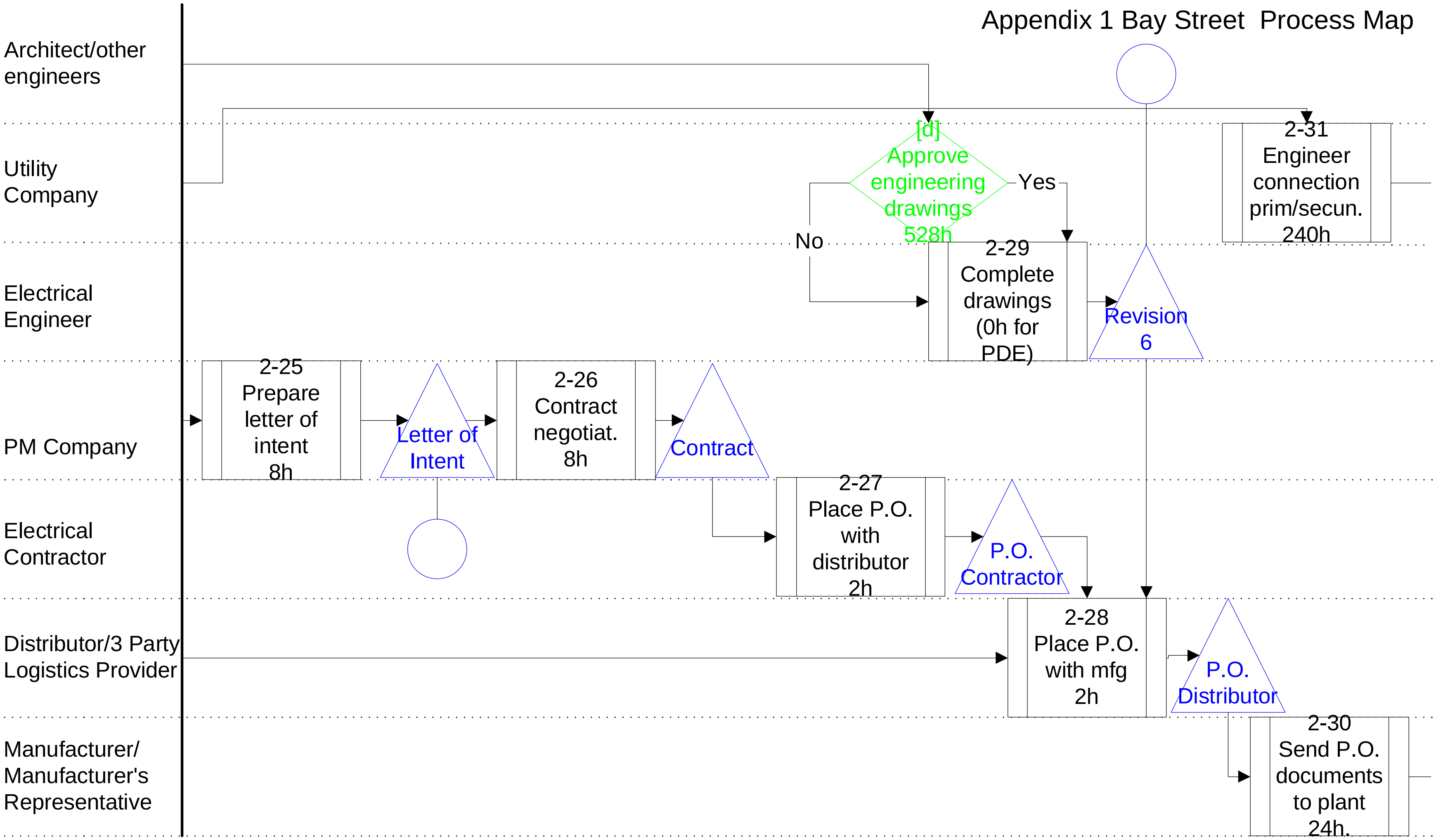


Appendix 1 Bay Street Process Map



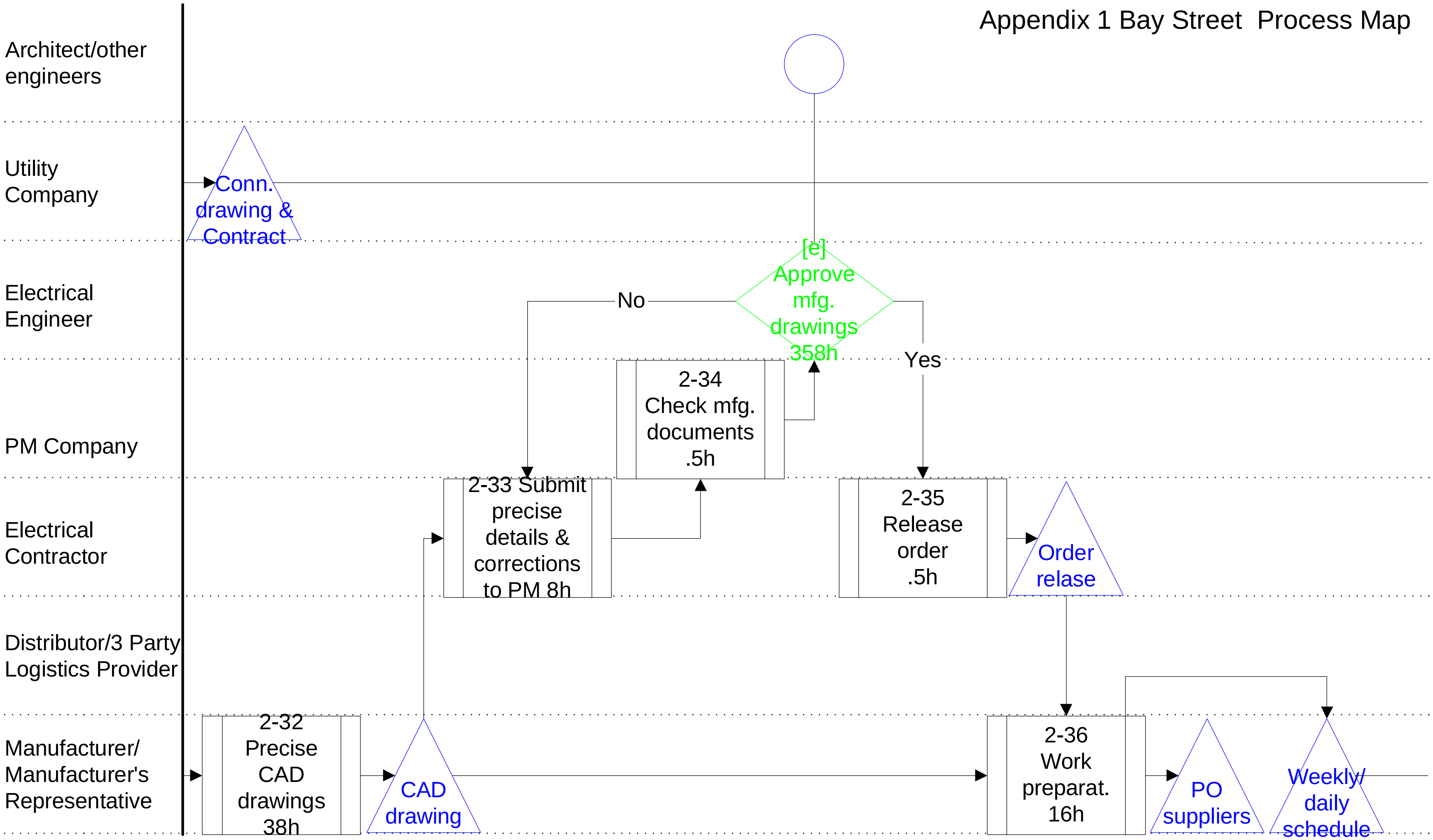

Architect/other engineers
Yes
Utility Company
Electrical Engineer
PM Company
Electrical Contractor
Distributor/3 Party Logistics Provider
Manufacturer/ Manufacturer's Representative
Submittal drawing
2-19 Check complian. with plant. .5h
2-20 Prepare bid documents 2h
Quote 1
2-21 Archive mfg.'s bid
2-22 Choose equipment supplier 8h
2-23 Quote for job 40h
Quote 2
2-24 Evaluation & chose of contractor 80h

Appendix 1 Bay Street Process Map



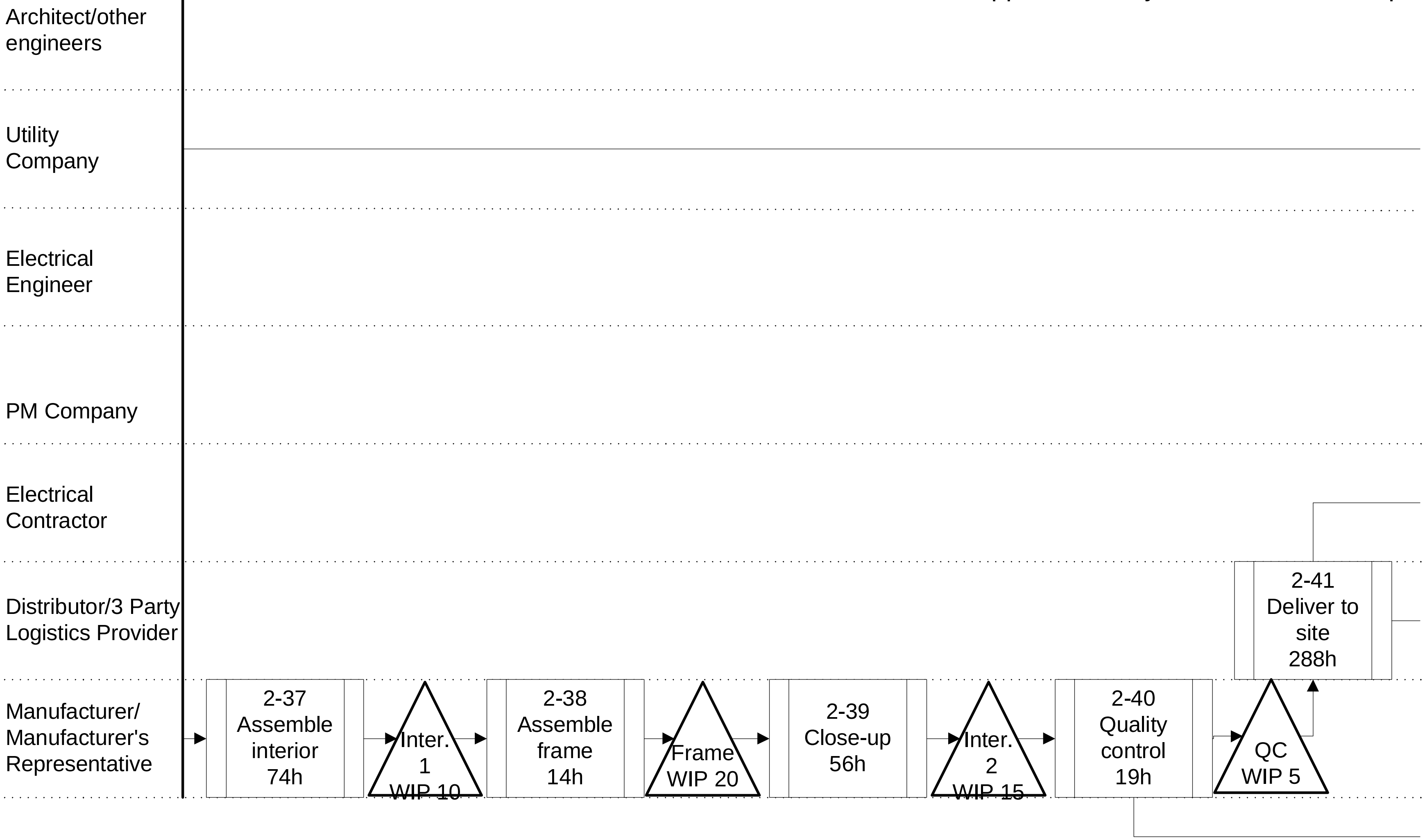
289

Appendix 1 Bay Street Process Map

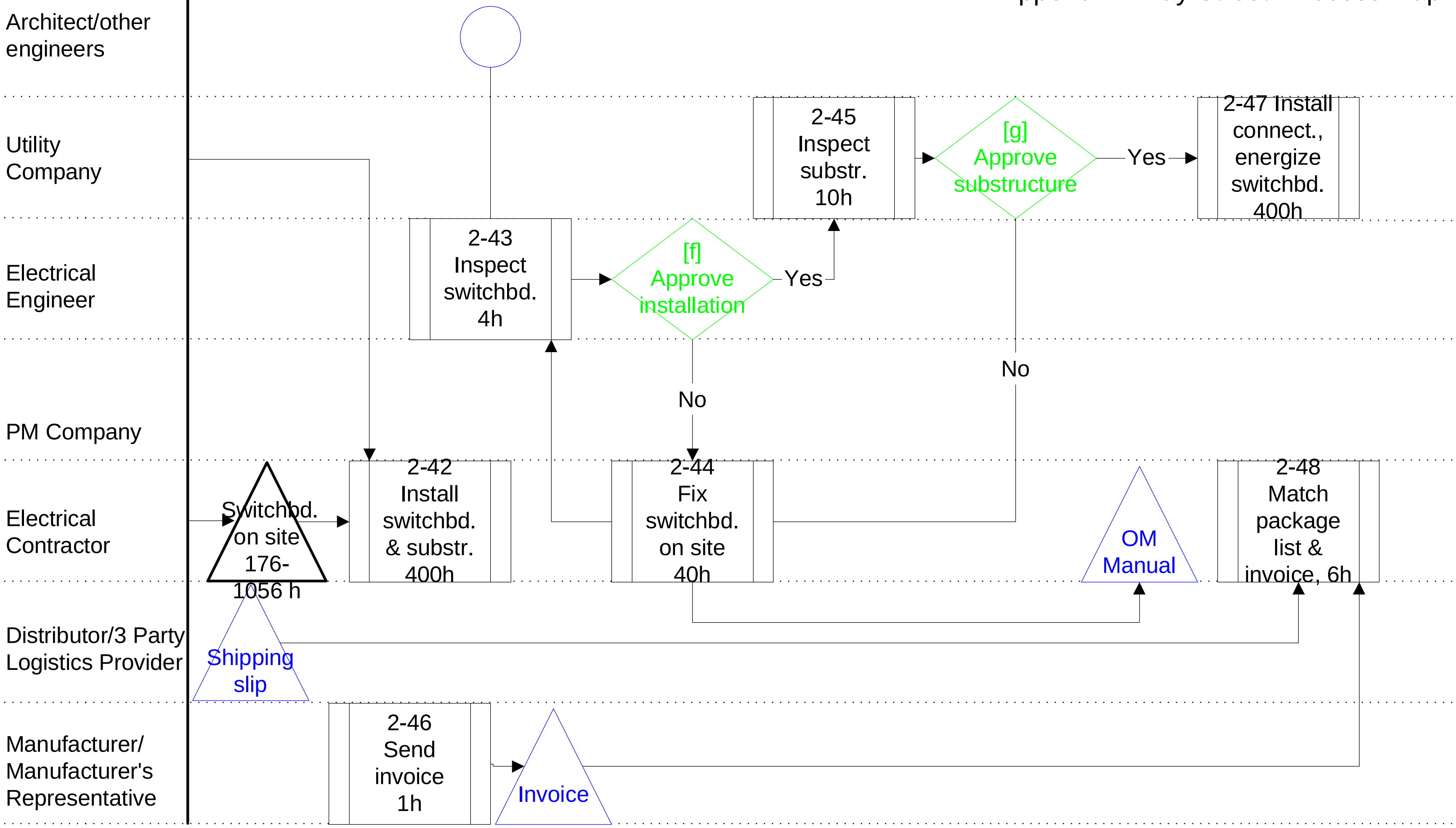


291

Appendix 1 Bay Street Process Map



Appendix 1 Bay Street Process Map



APPENDIX 2

Current state process map of Novo

Appendix 2 Novo Process Map

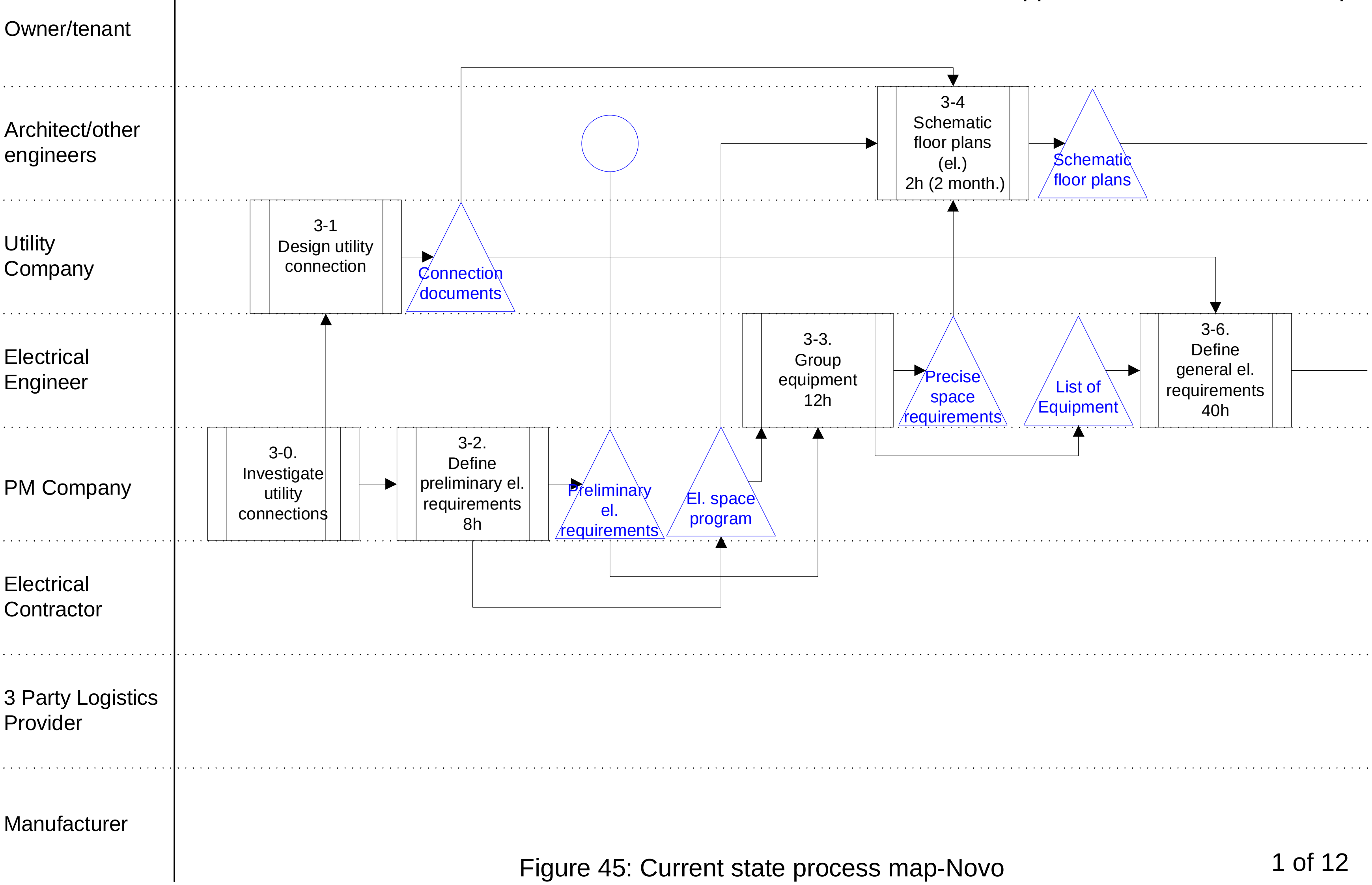
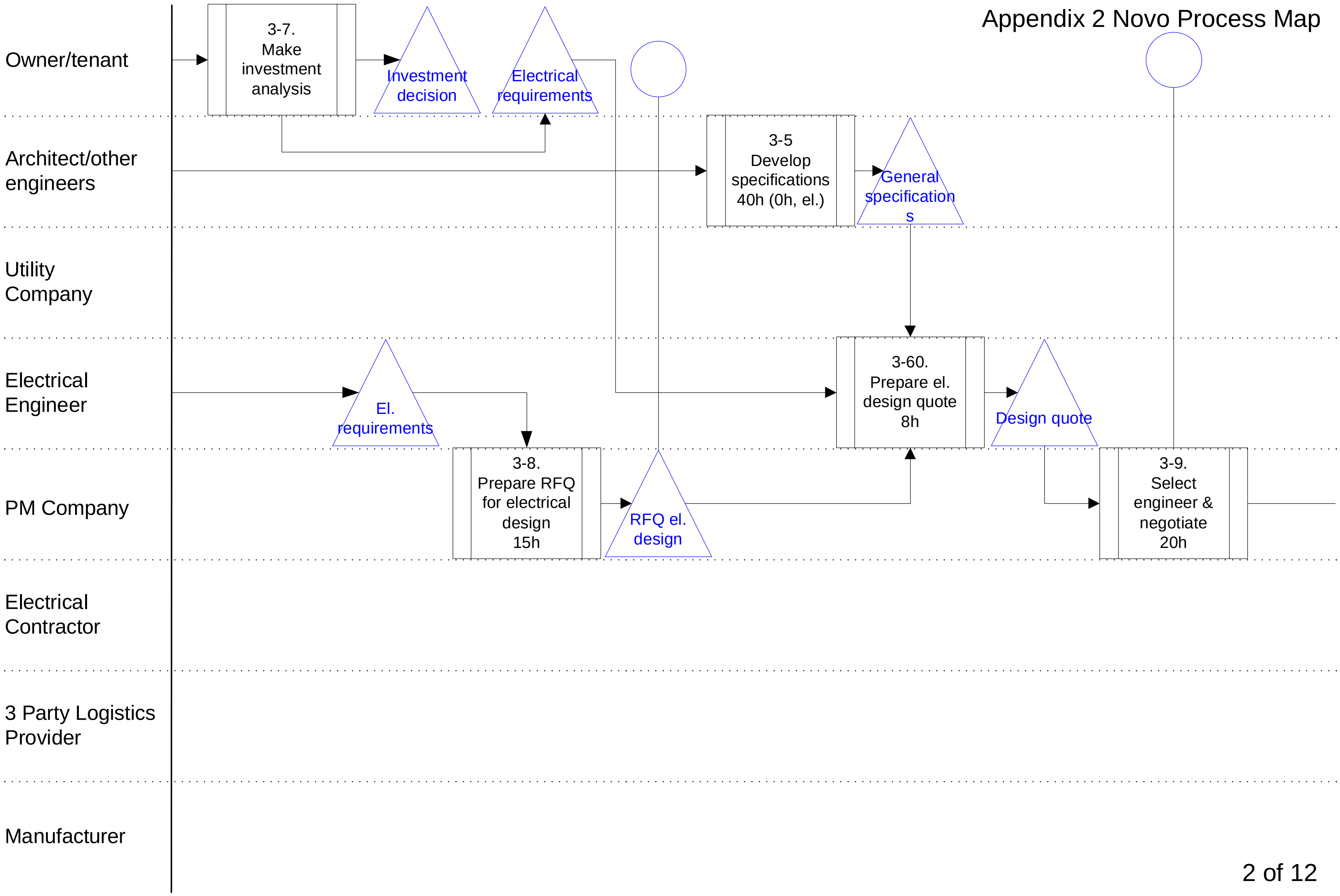
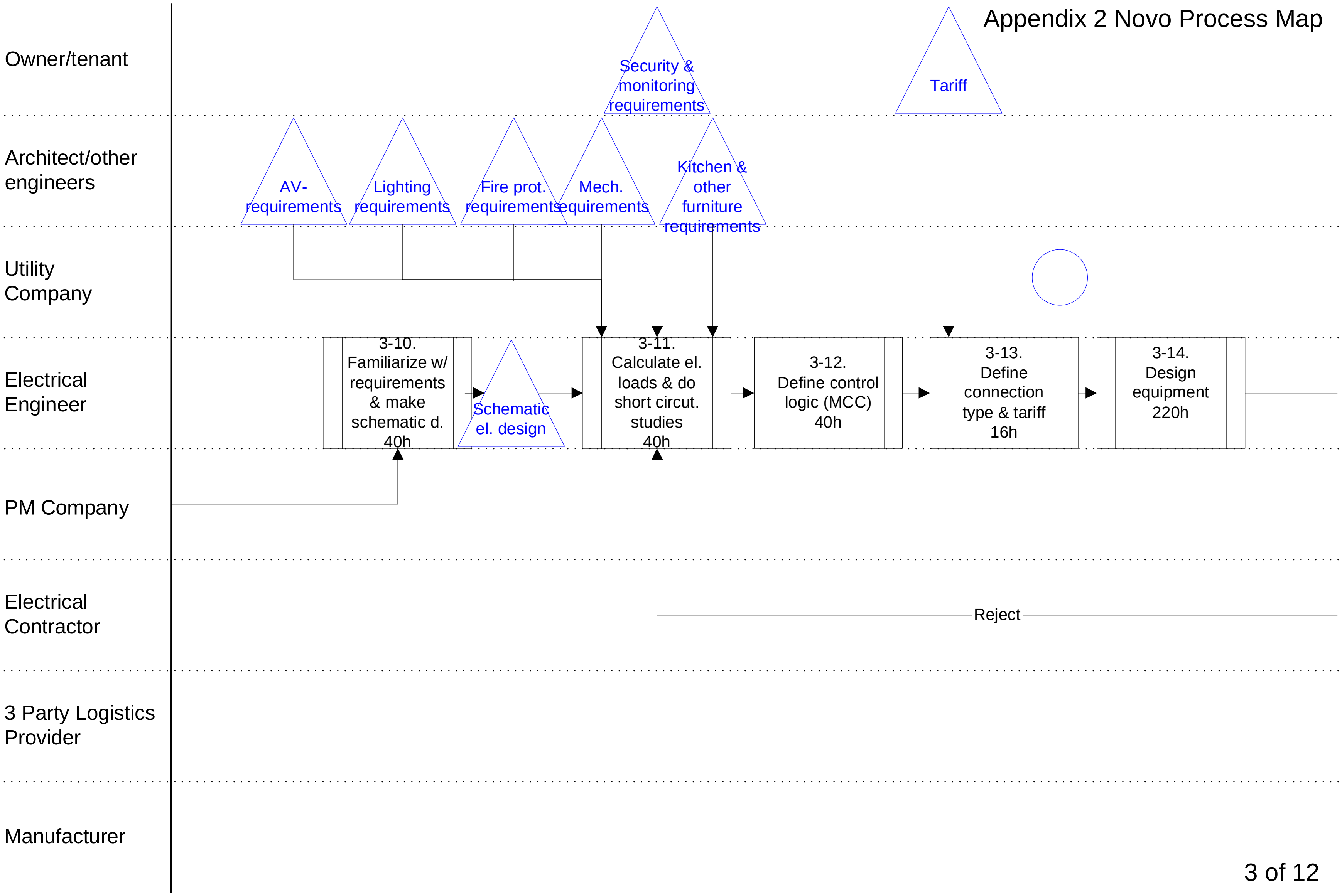


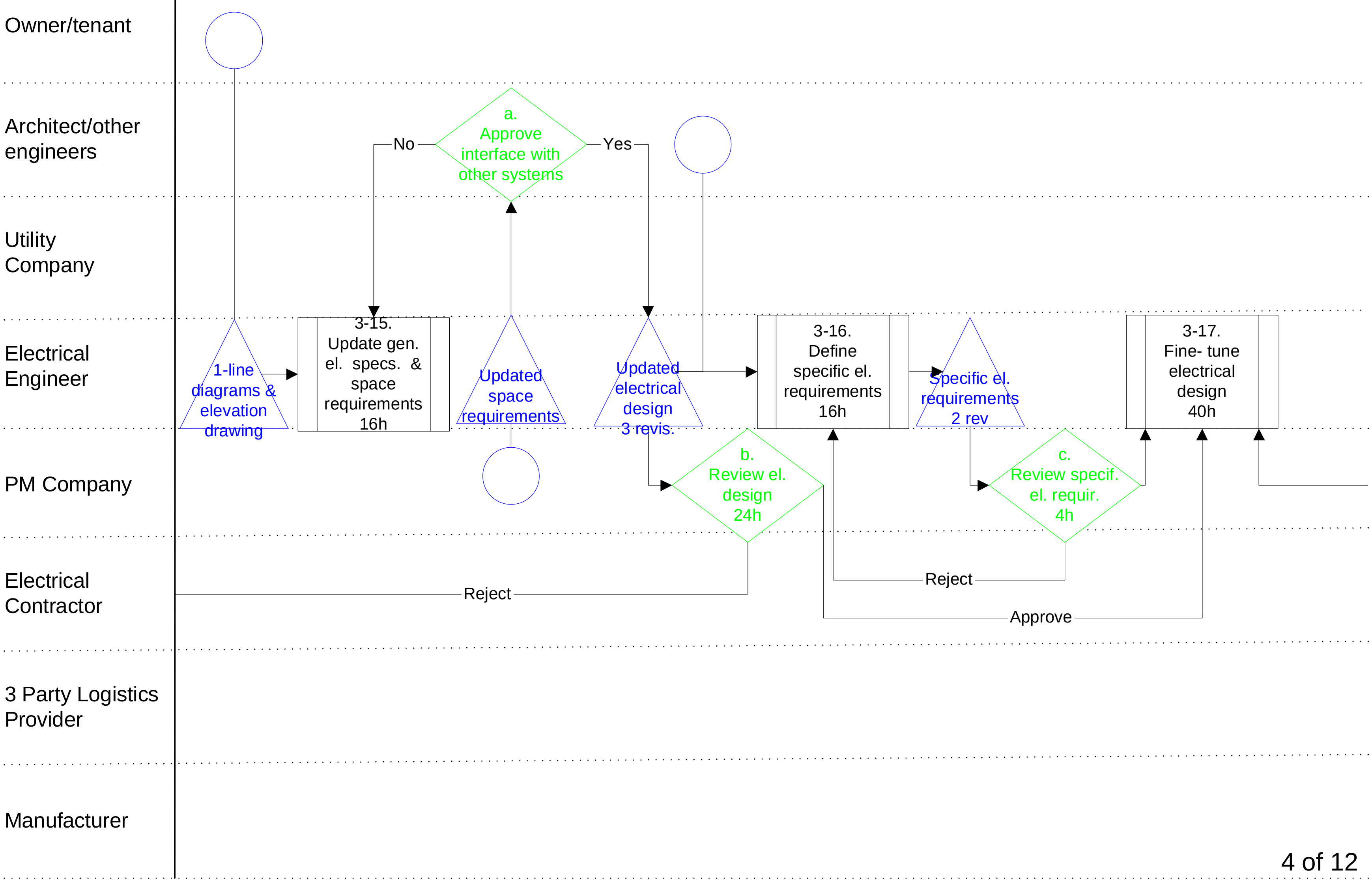
Figure 45: Current state process map-Novo

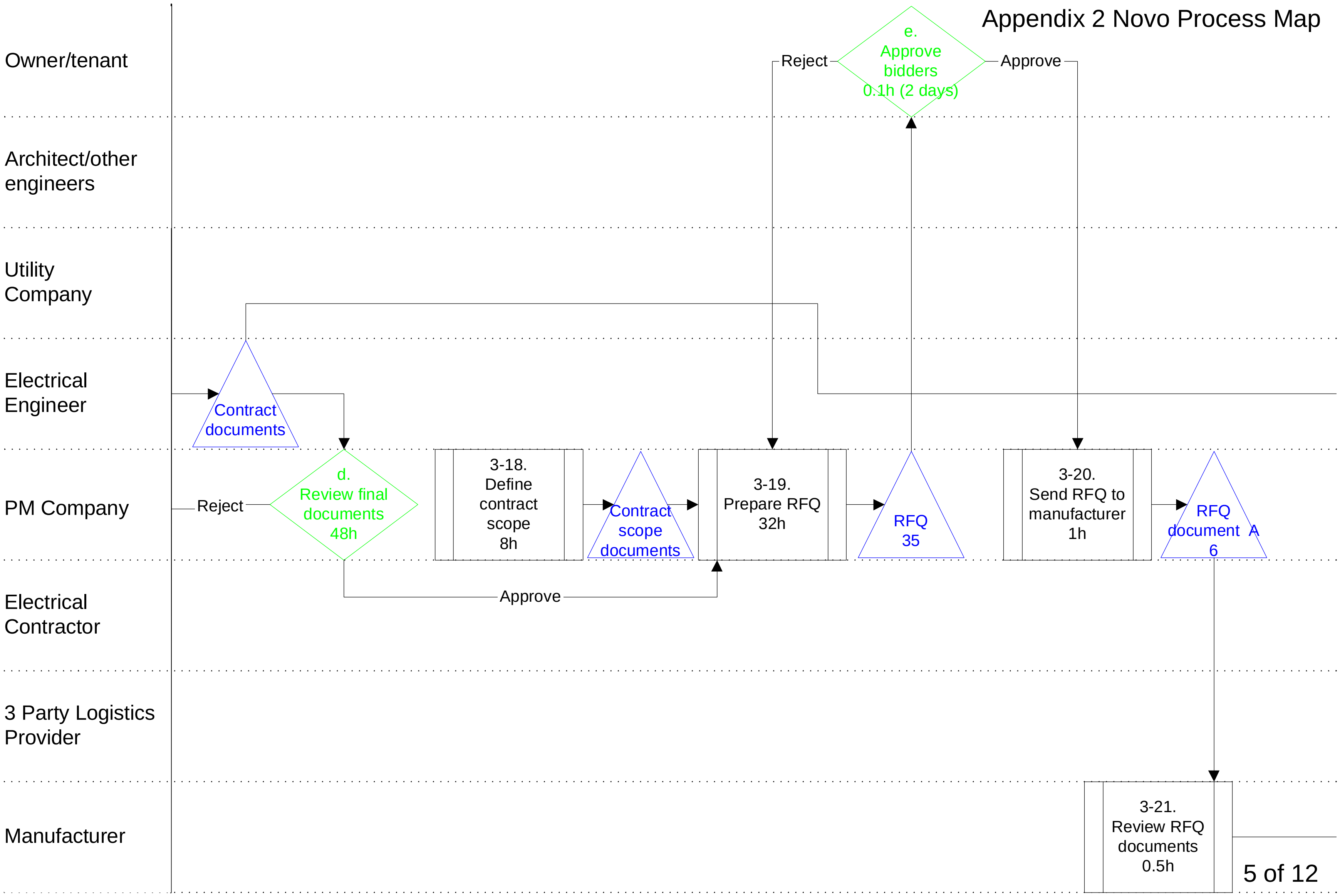
Appendix 2 Novo Process Map



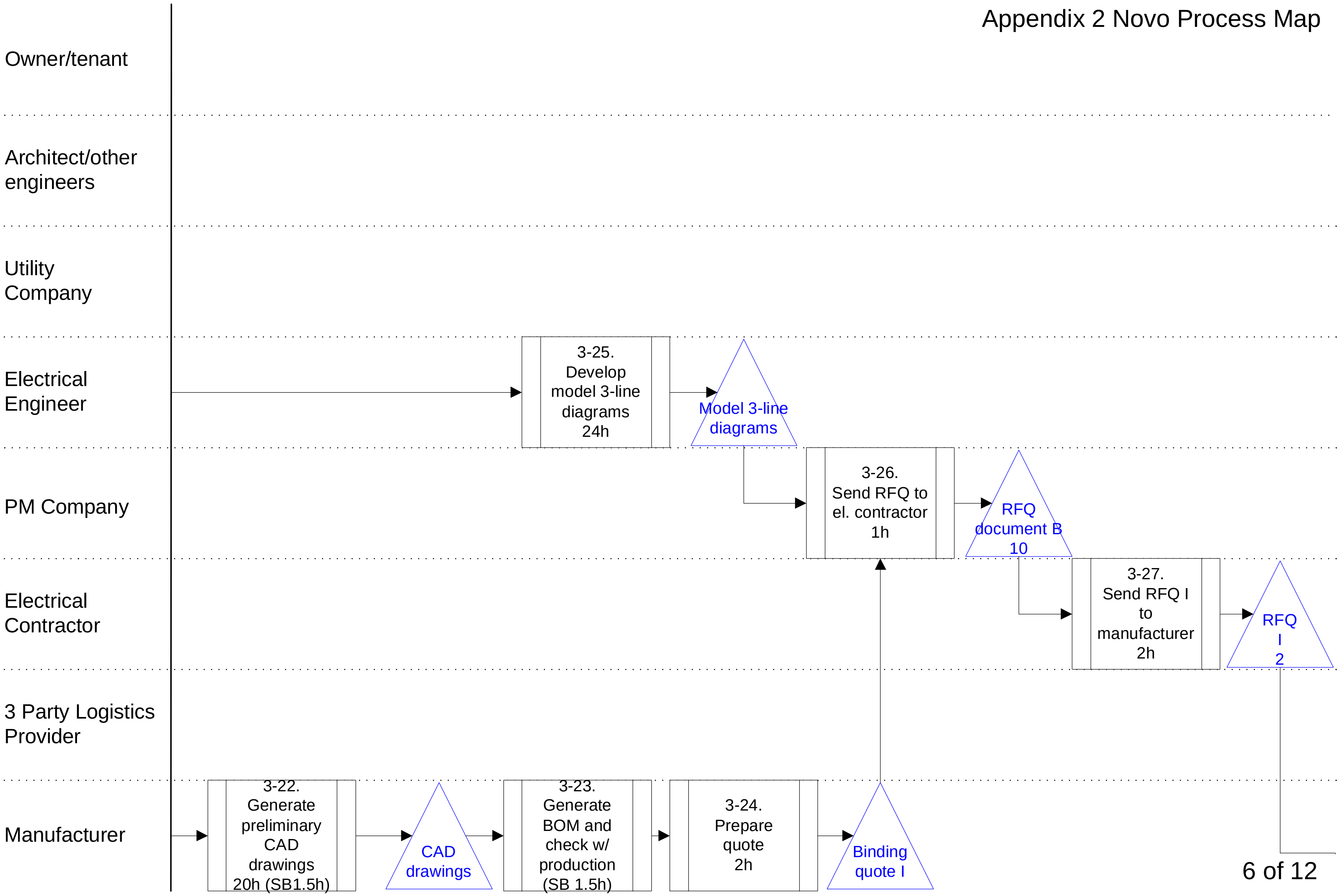
Appendix 2 Novo Process Map



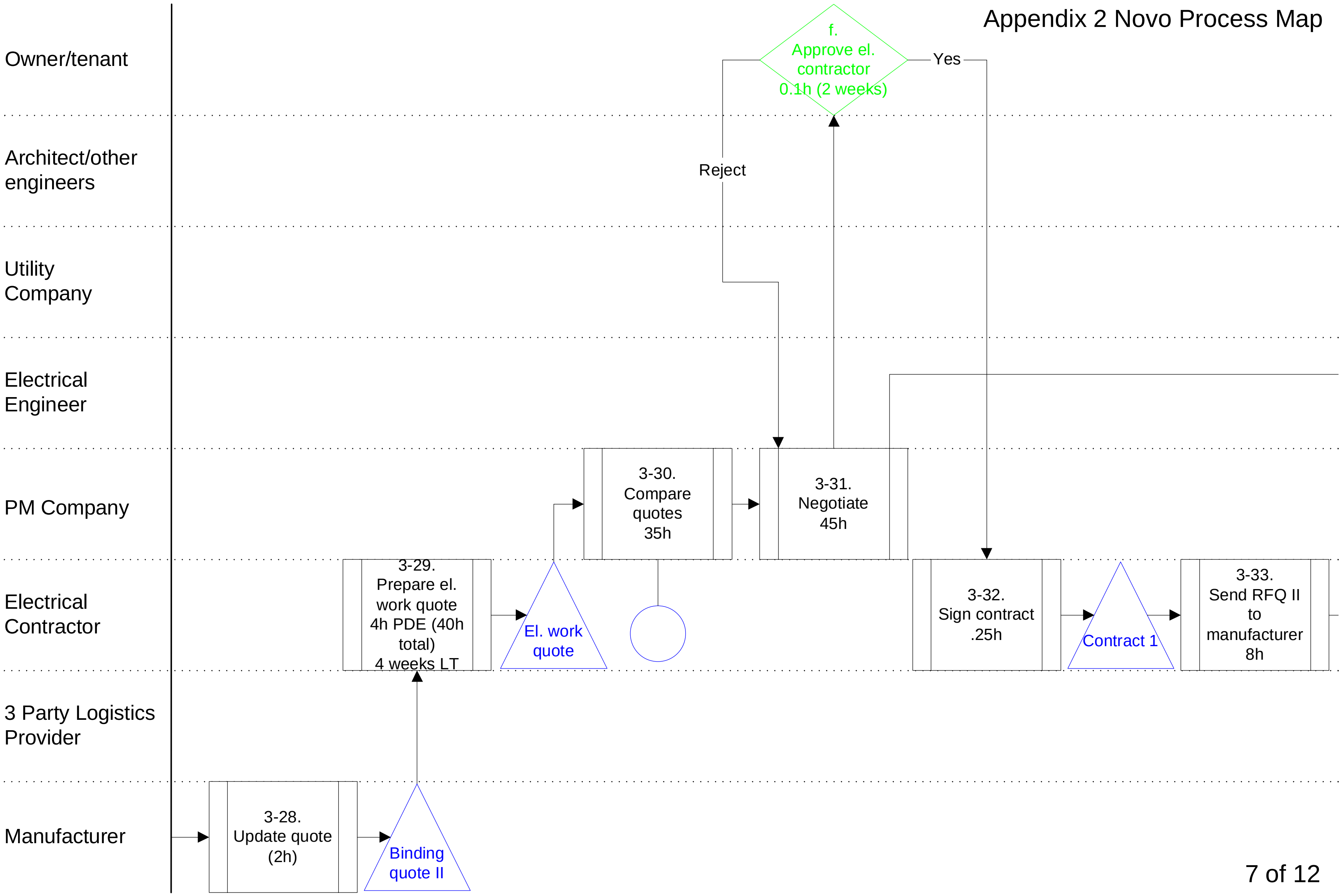

Owner/tenant
Architect/other engineers
Utility Company
Electrical Engineer
PM Company
Electrical Contractor
3 Party Logistics Provider
Manufacturer
1-line diagrams & elevation drawing
3-15. Update gen. el. specs. & space requirements 16h
Updated space requirements
a. Approve interface with other systems
No
Yes
Updated electrical design 3 revis.
b. Review el. design 24h
Reject
3-16. Define specific el. requirements 16h
Specific el. requirements 2 rev
c. Review specif. el. requir. 4h
Reject
Approve
3-17. Fine- tune electrical design 40h


Appendix 2 Novo Process Map
Owner/tenant
Architect/other engineers
Utility Company
Electrical Engineer
PM Company
Electrical Contractor
3 Party Logistics Provider
Manufacturer
e. Approve bidders 0.1h (2 days)
Reject
Approve
Contract documents
d. Review final documents 48h
Reject
Approve
3-18. Define contract scope 8h
Contract scope documents
3-19. Prepare RFQ 32h
RFQ 35
3-20. Send RFQ to manufacturer 1h
RFQ document A 6
3-21. Review RFQ documents 0.5h
5 of 12

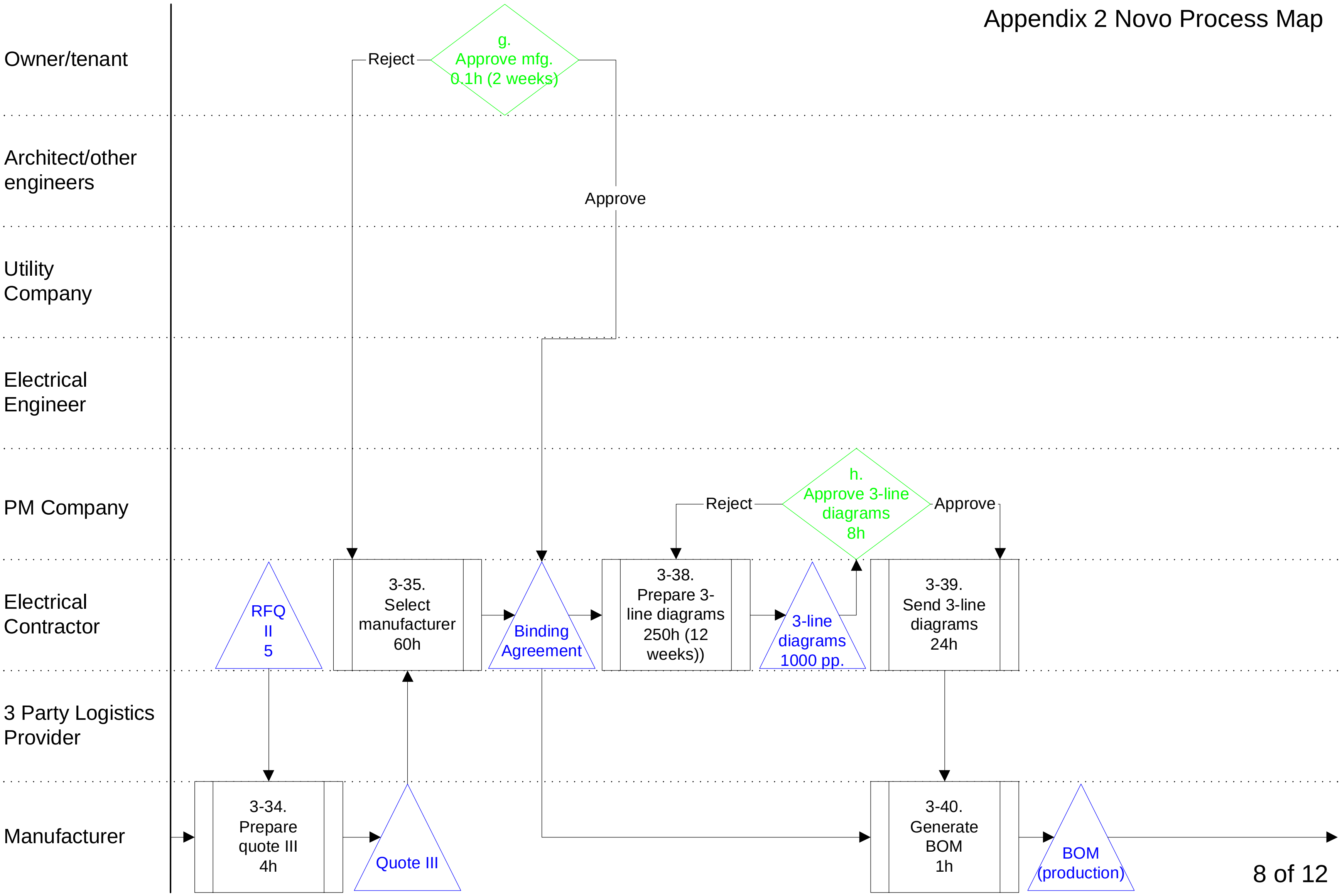
298



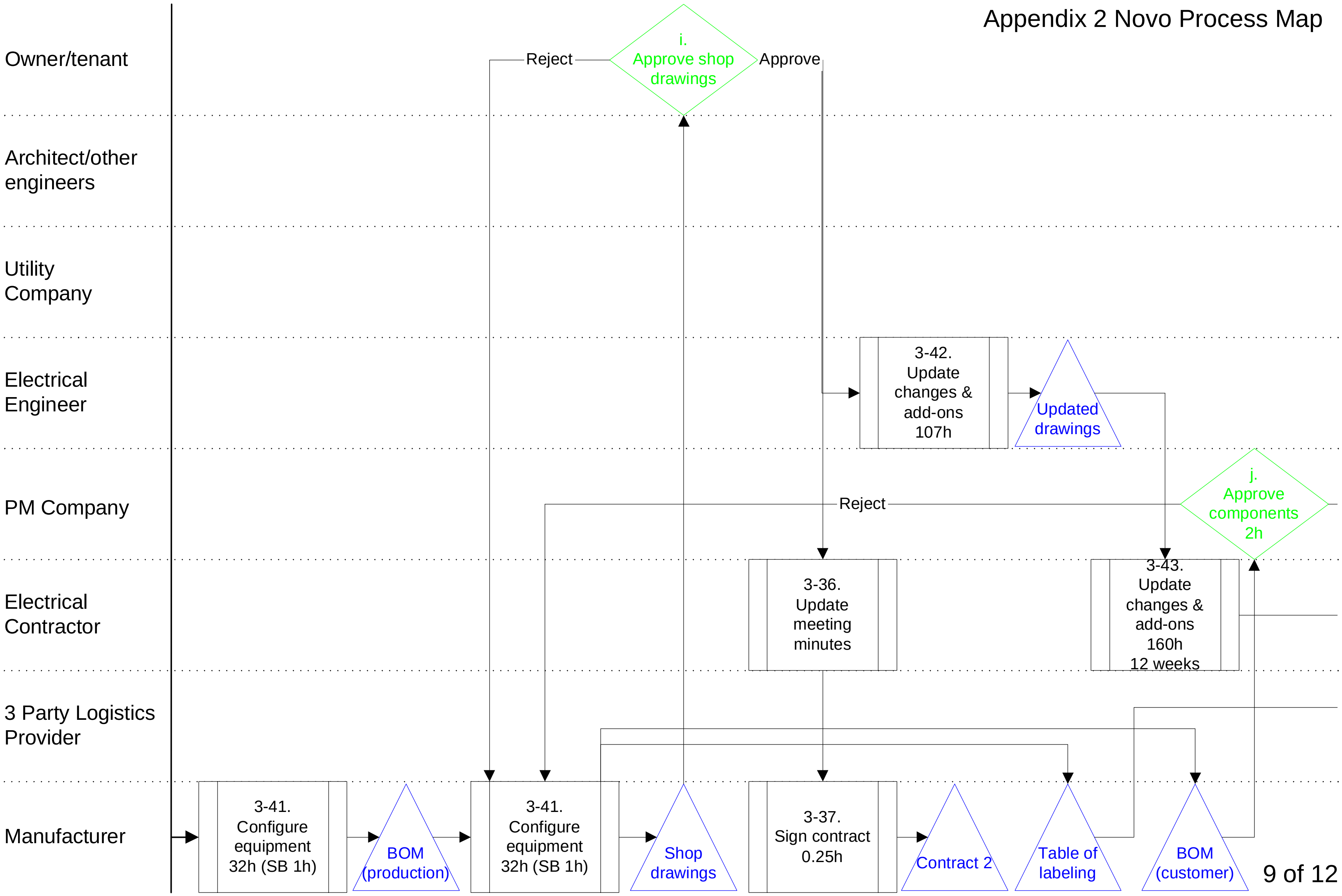
Appendix 2 Novo Process Map
Owner/tenant
Architect/other engineers
Utility Company
Electrical Engineer
PM Company
Electrical Contractor
3 Party Logistics Provider
Manufacturer
3-25. Develop model 3-line diagrams 24h
Model 3-line diagrams
3-26. Send RFQ to el. contractor 1h
RFQ document B 10
3-27. Send RFQ I to manufacturer 2h
RFQ I 2
3-22. Generate preliminary CAD drawings 20h (SB1.5h)
CAD drawings
3-23. Generate BOM and check w/ production (SB 1.5h)
3-24. Prepare quote 2h
Binding quote I


Owner/tenant
Architect/other engineers
Utility Company
Electrical Engineer
PM Company
Electrical Contractor
3 Party Logistics Provider
Manufacturer
f. Approve el. contractor 0.1h (2 weeks)
Yes
Reject
3-28. Update quote (2h)
Binding quote II
3-29. Prepare el. work quote 4h PDE (40h total) 4 weeks LT
El. work quote
3-30. Compare quotes 35h
3-31. Negotiate 45h
3-32. Sign contract .25h
Contract 1
3-33. Send RFQ II to manufacturer 8h

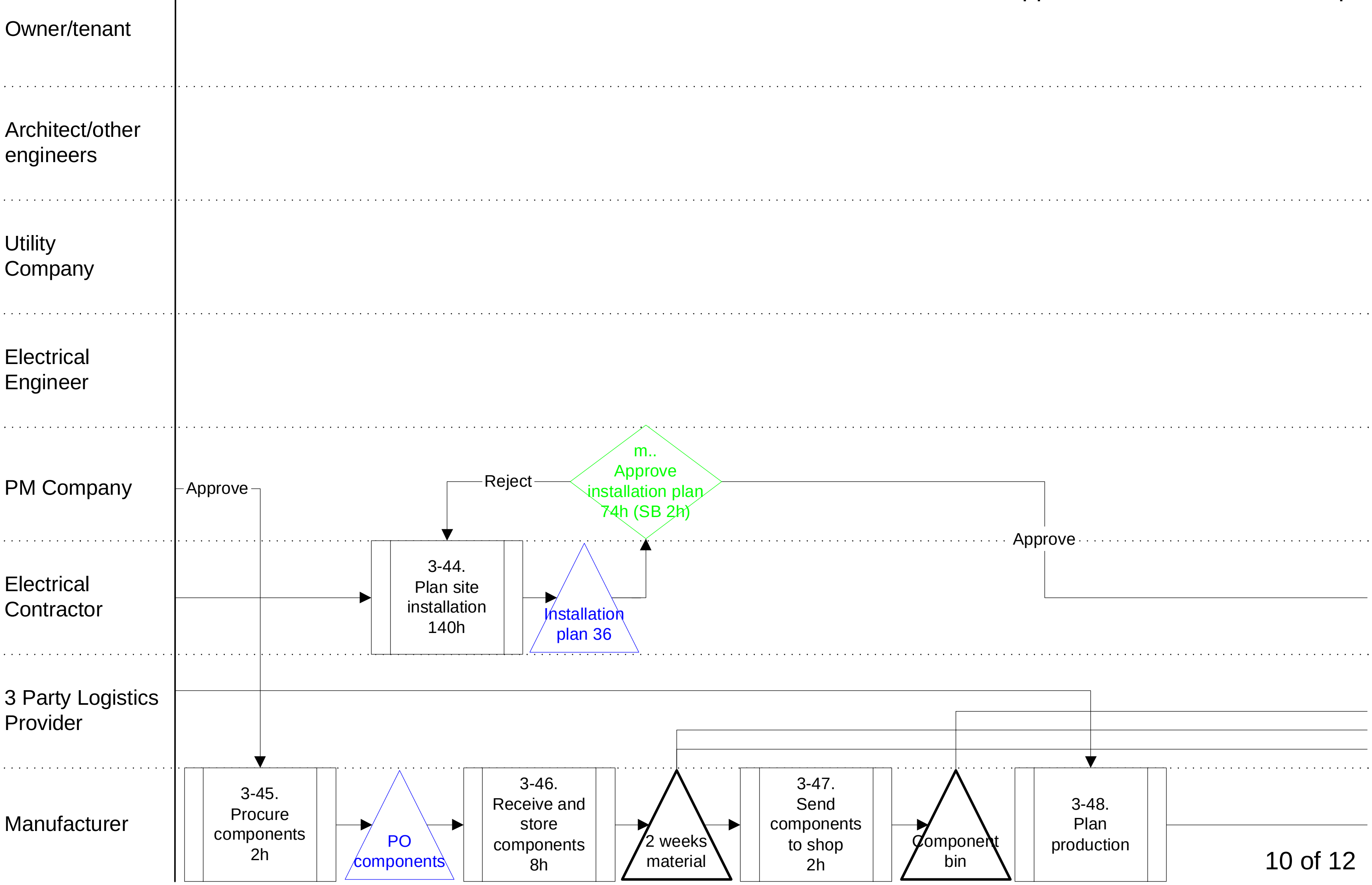
Appendix 2 Novo Process Map

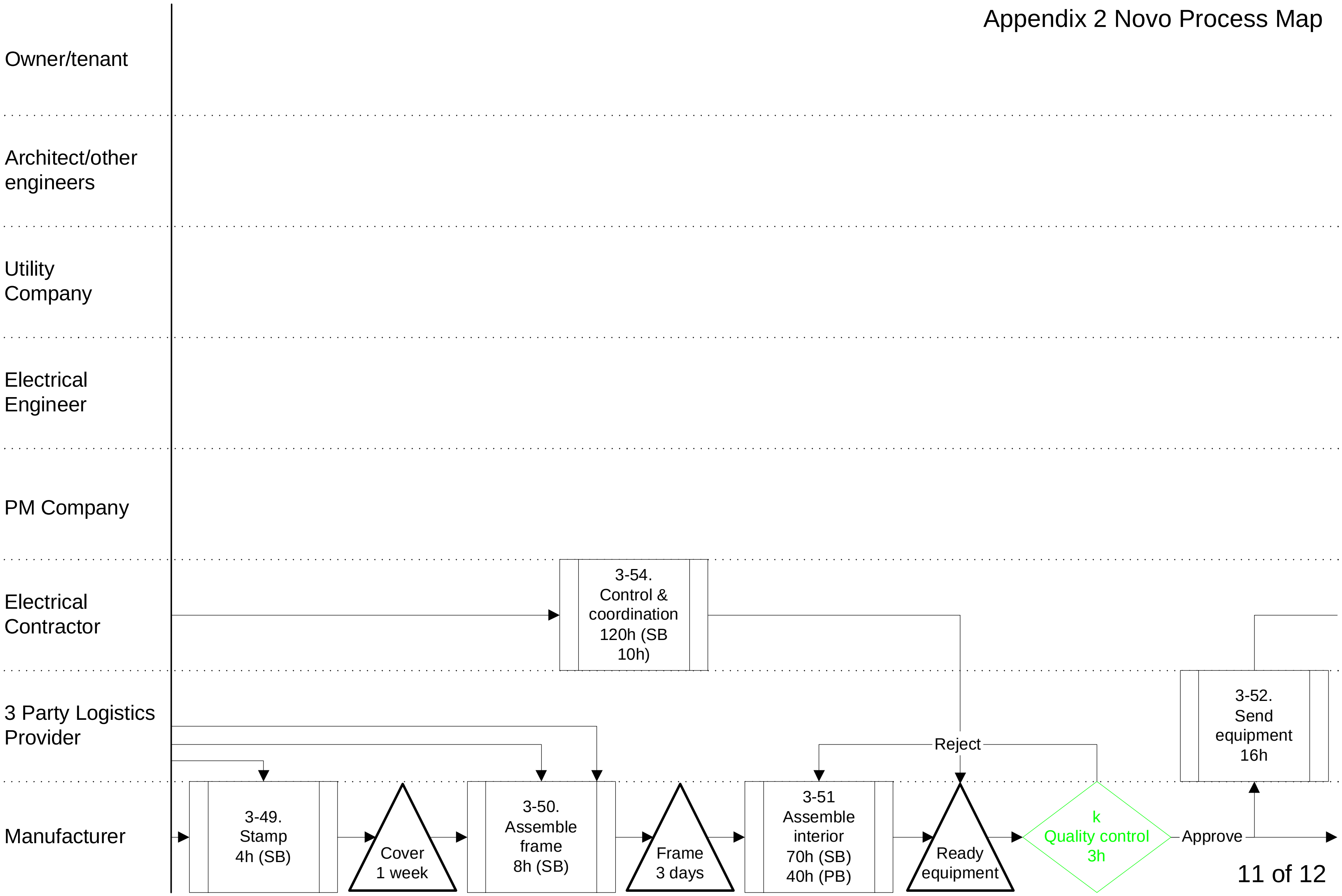


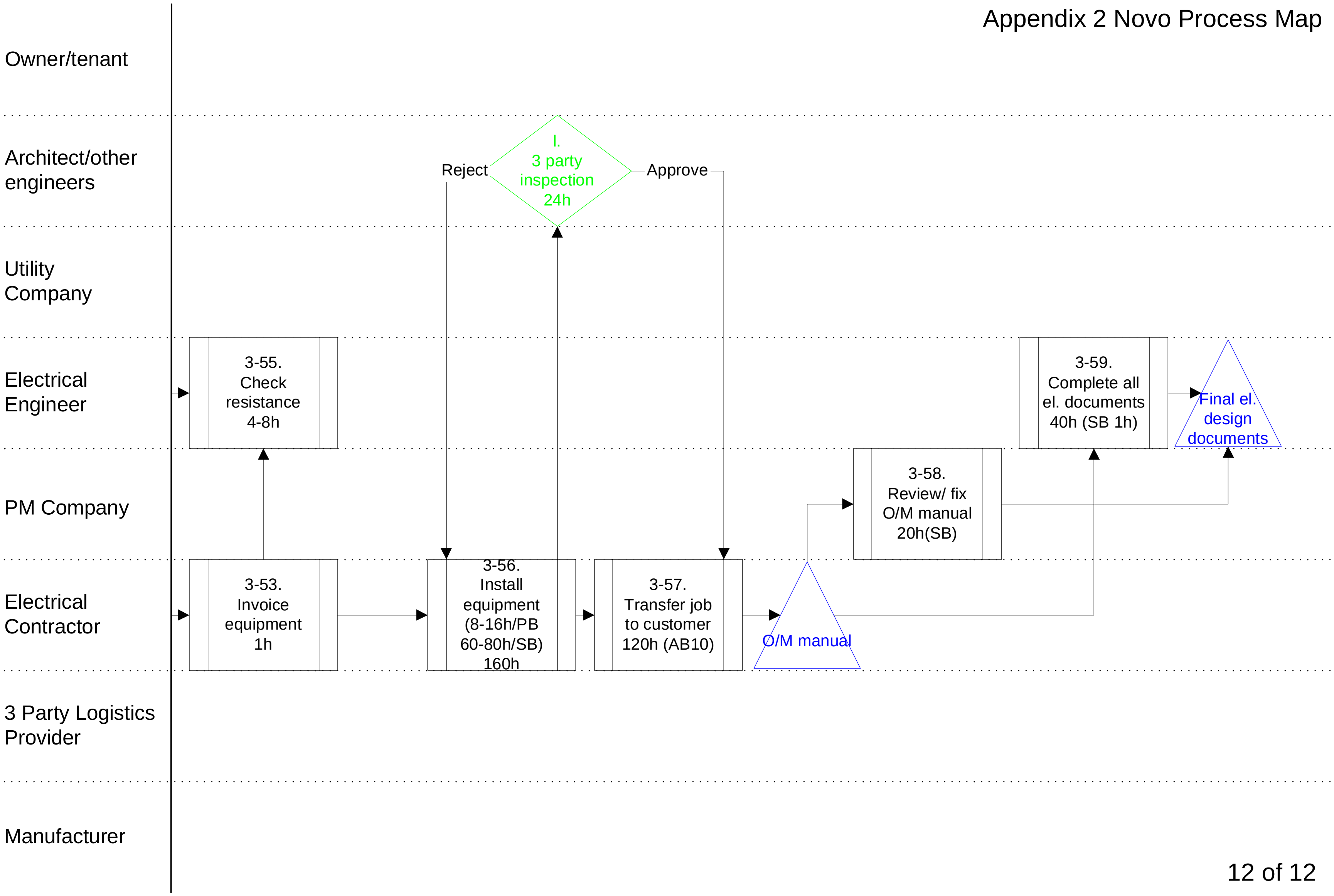
Appendix 2 Novo Process Map



Appendix 2 Novo Process Map




Owner/tenant
Architect/other engineers
Utility Company
Electrical Engineer
PM Company
Electrical Contractor
3 Party Logistics Provider
Manufacturer
3-54. Control & coordination 120h (SB 10h)
3-52. Send equipment 16h
3-49. Stamp 4h (SB)
Cover 1 week
3-50. Assemble frame 8h (SB)
Frame 3 days
3-51 Assemble interior 70h (SB) 40h (PB)
Ready equipment
Reject
k Quality control 3h
Approve


Owner/tenant
Architect/other engineers
Utility Company
Electrical Engineer
PM Company
Electrical Contractor
3 Party Logistics Provider
Manufacturer
I. 3 party inspection 24h
Reject
Approve
3-55. Check resistance 4-8h
3-59. Complete all el. documents 40h (SB 1h)
Final el. design documents
3-58. Review/ fix O/M manual 20h(SB)
3-53. Invoice equipment 1h
3-56. Install equipment (8-16h/PB 60-80h/SB) 160h
3-57. Transfer job to customer 120h (AB10)
O/M manual

APPENDIX 3

Current state process map of Paradise Pier

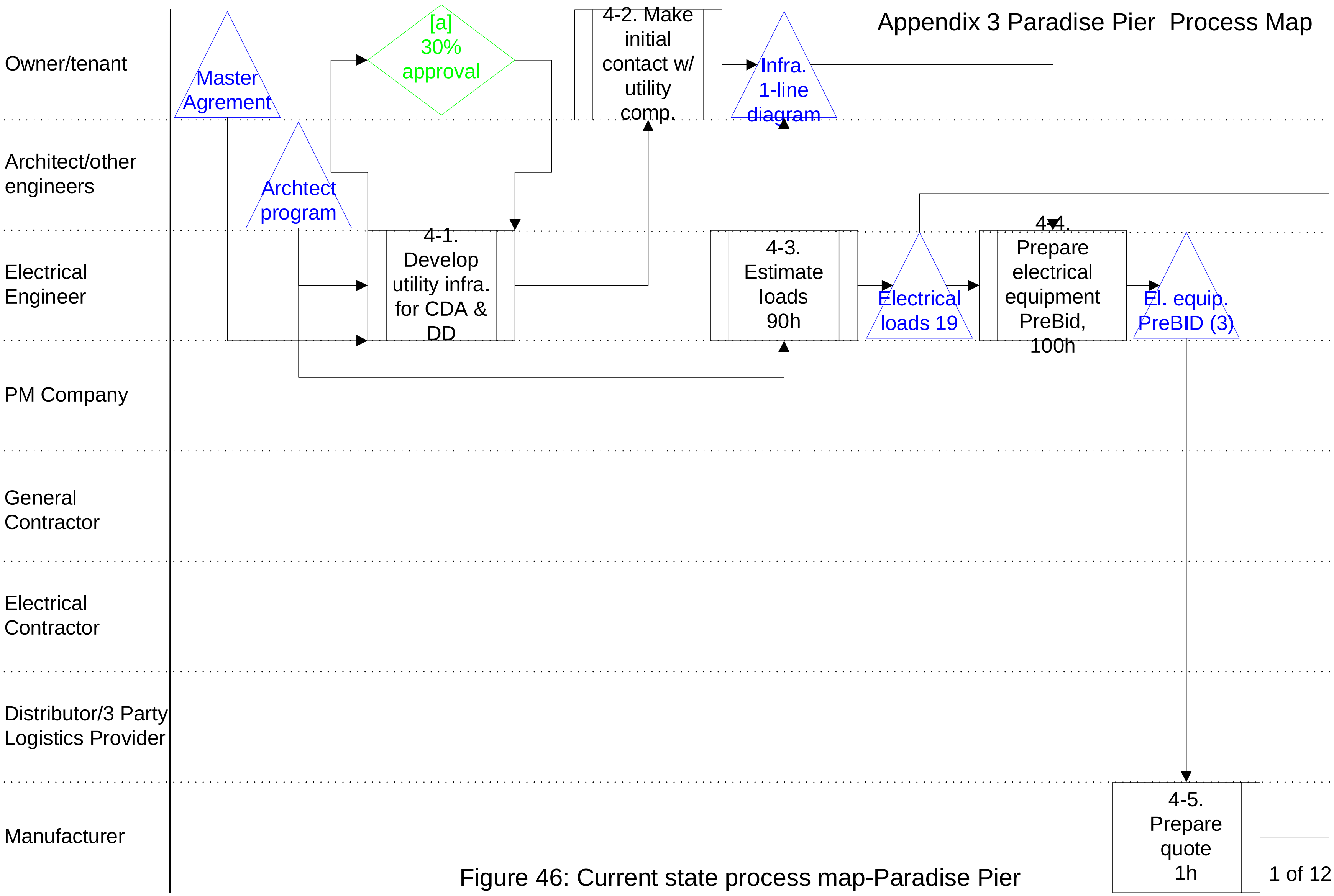
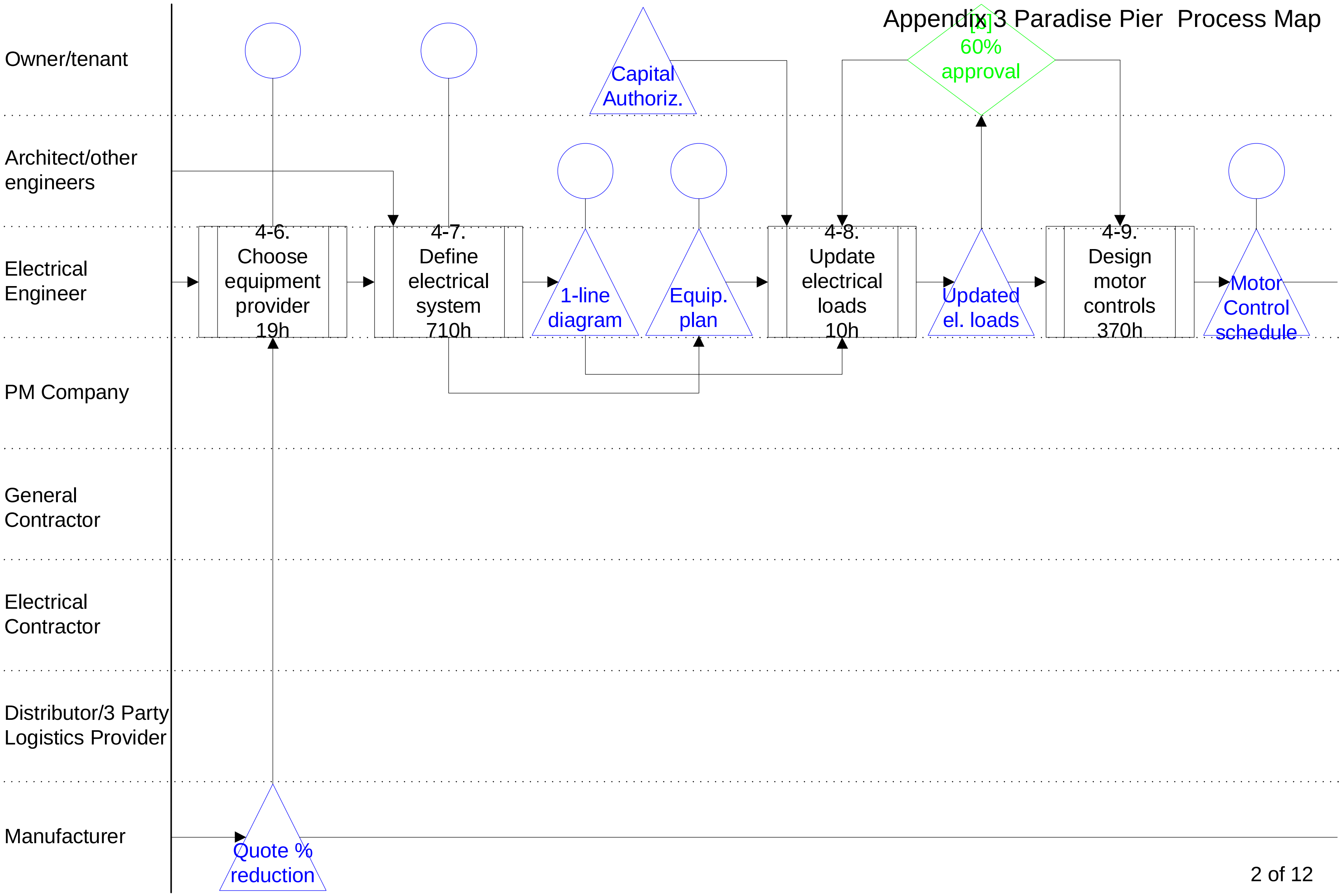
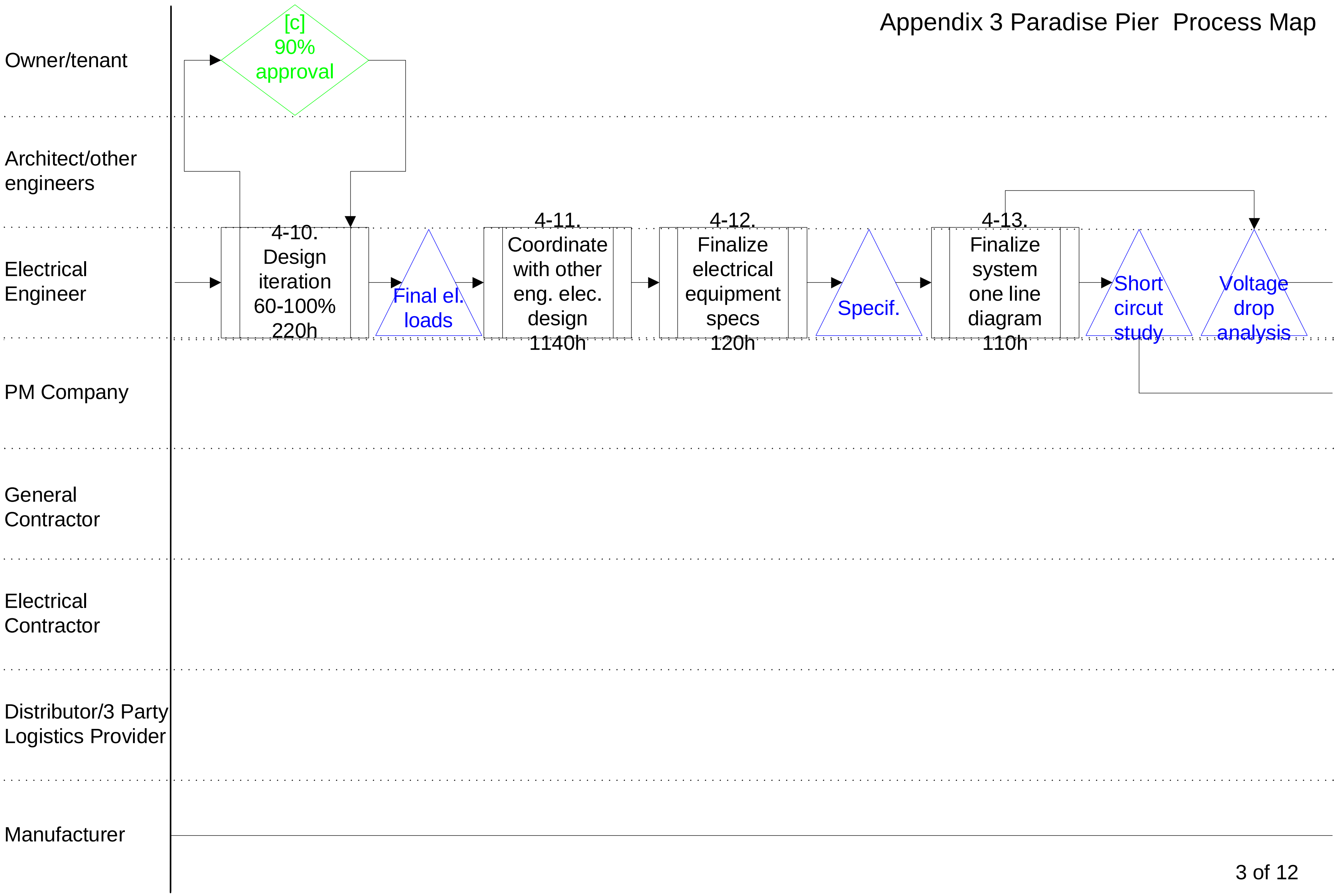


Figure 46: Current state process map-Paradise Pier

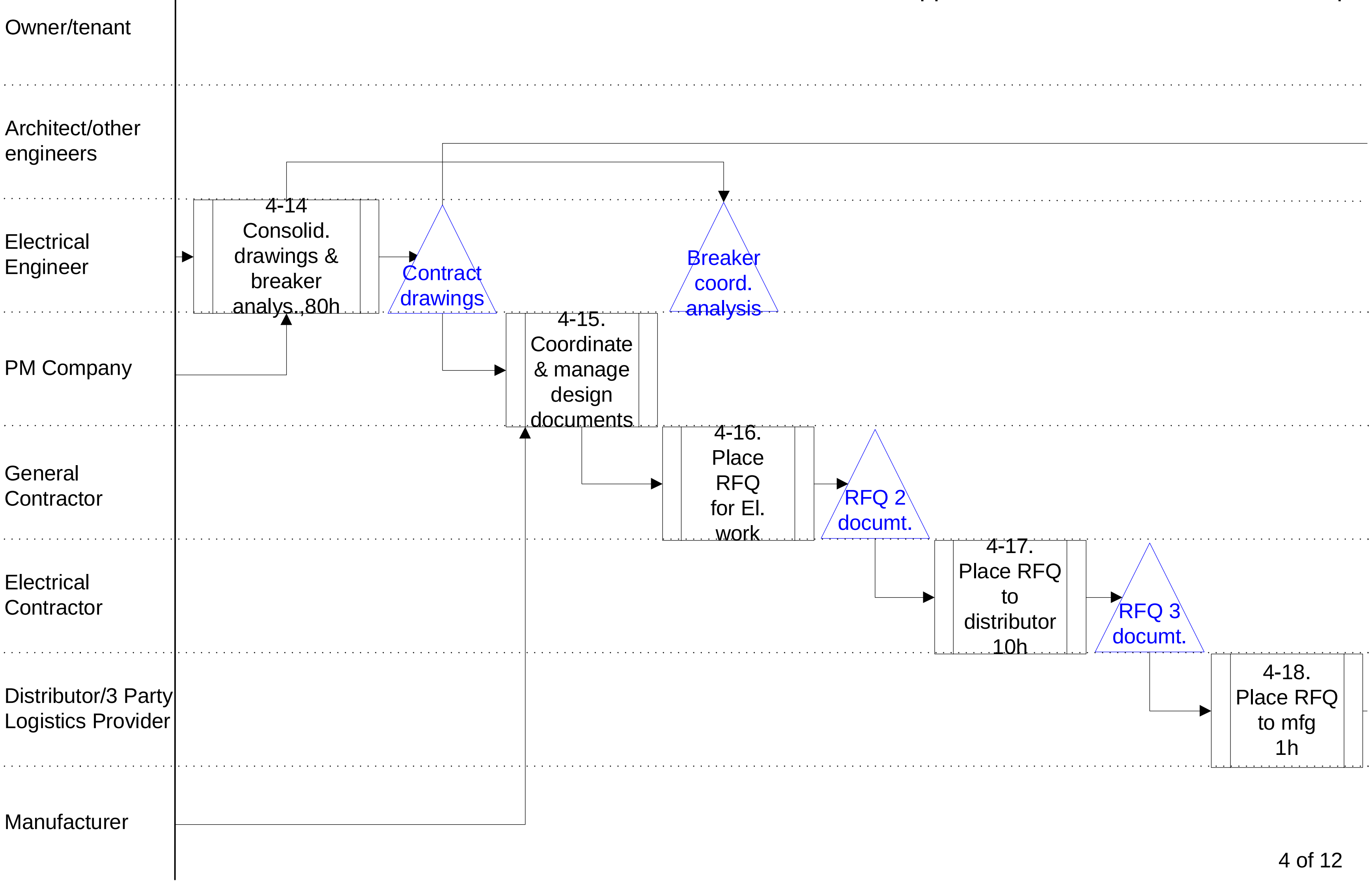
Appendix 3 Paradise Pier Process Map

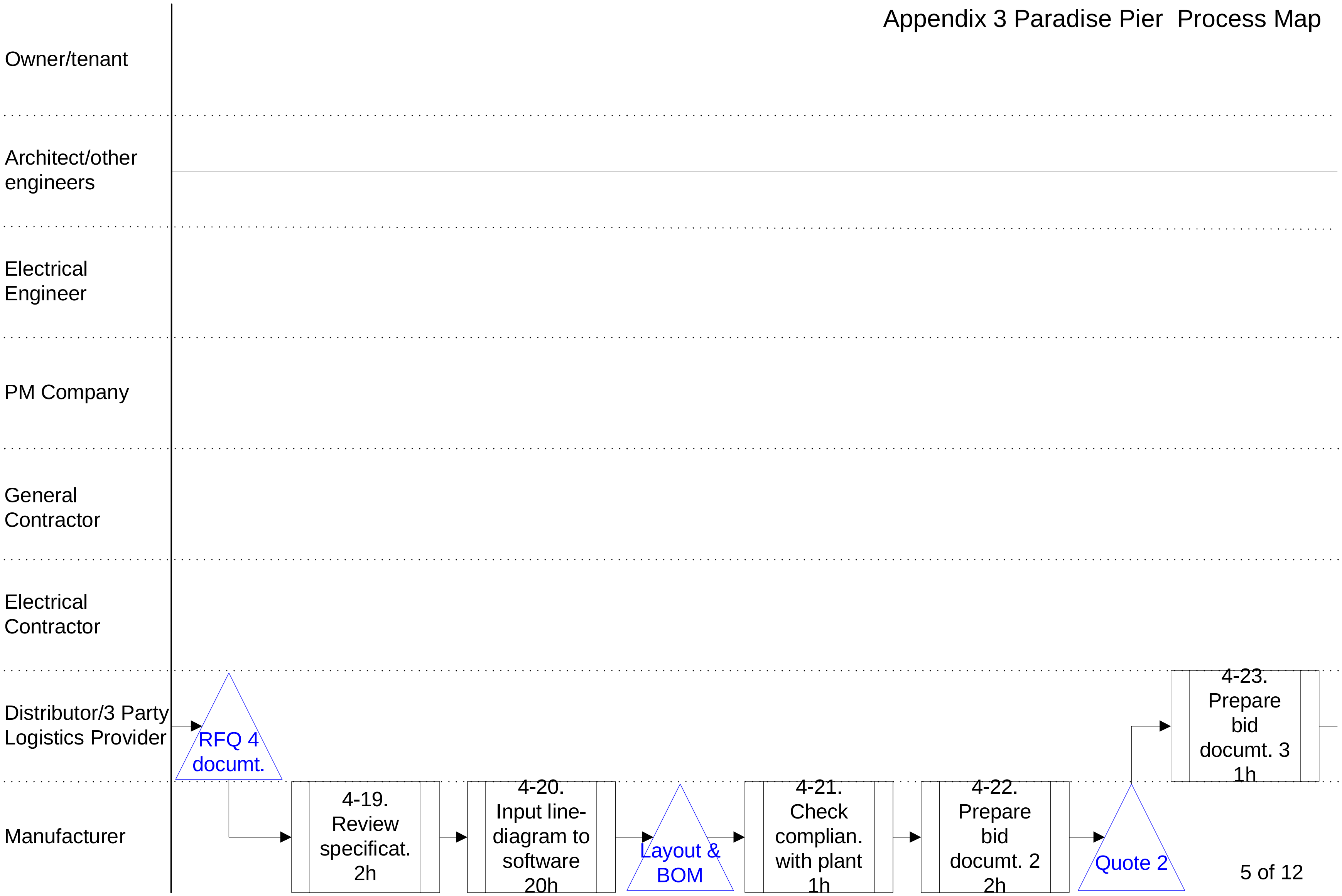


Appendix 3 Paradise Pier Process Map

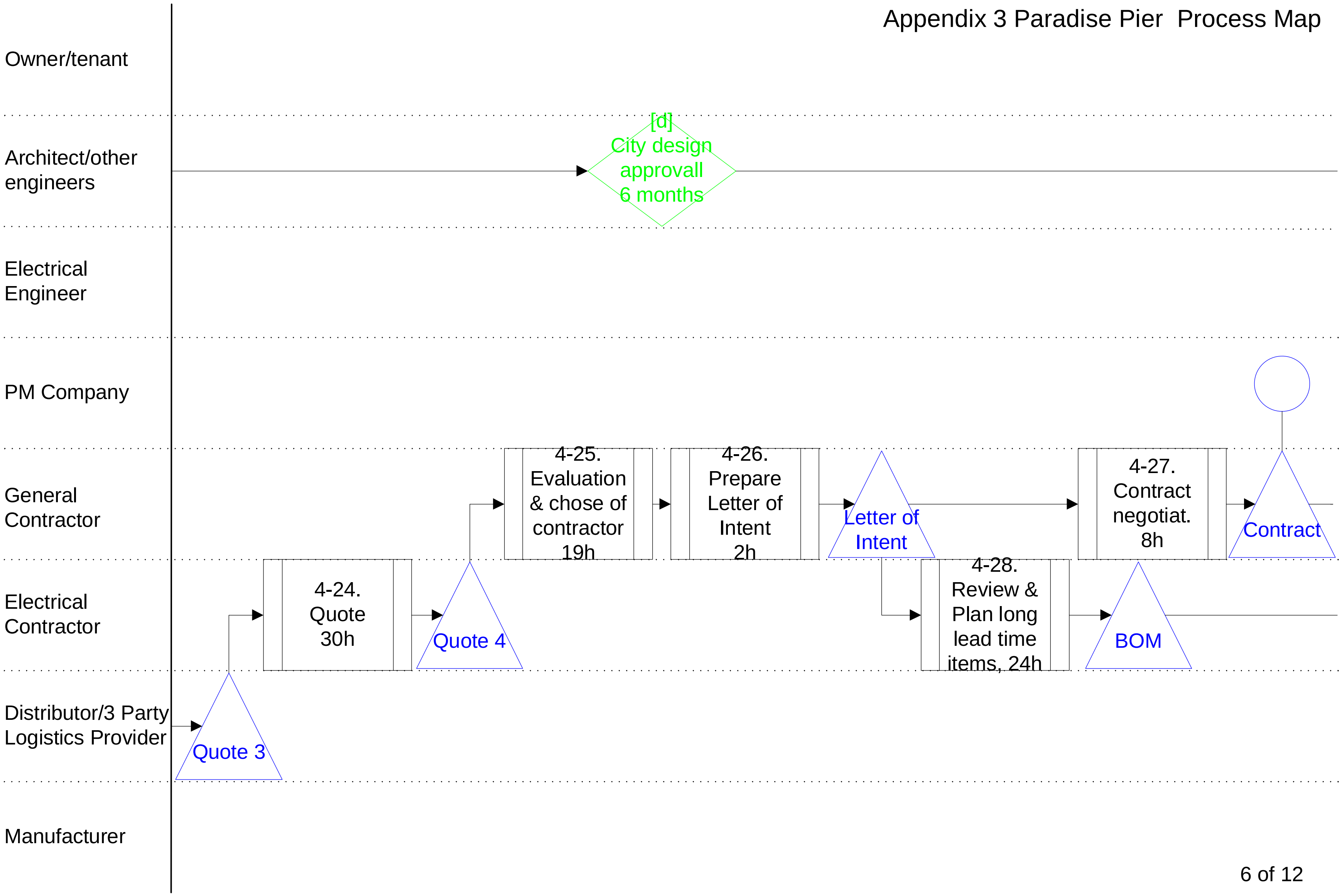


Appendix 3 Paradise Pier Process Map

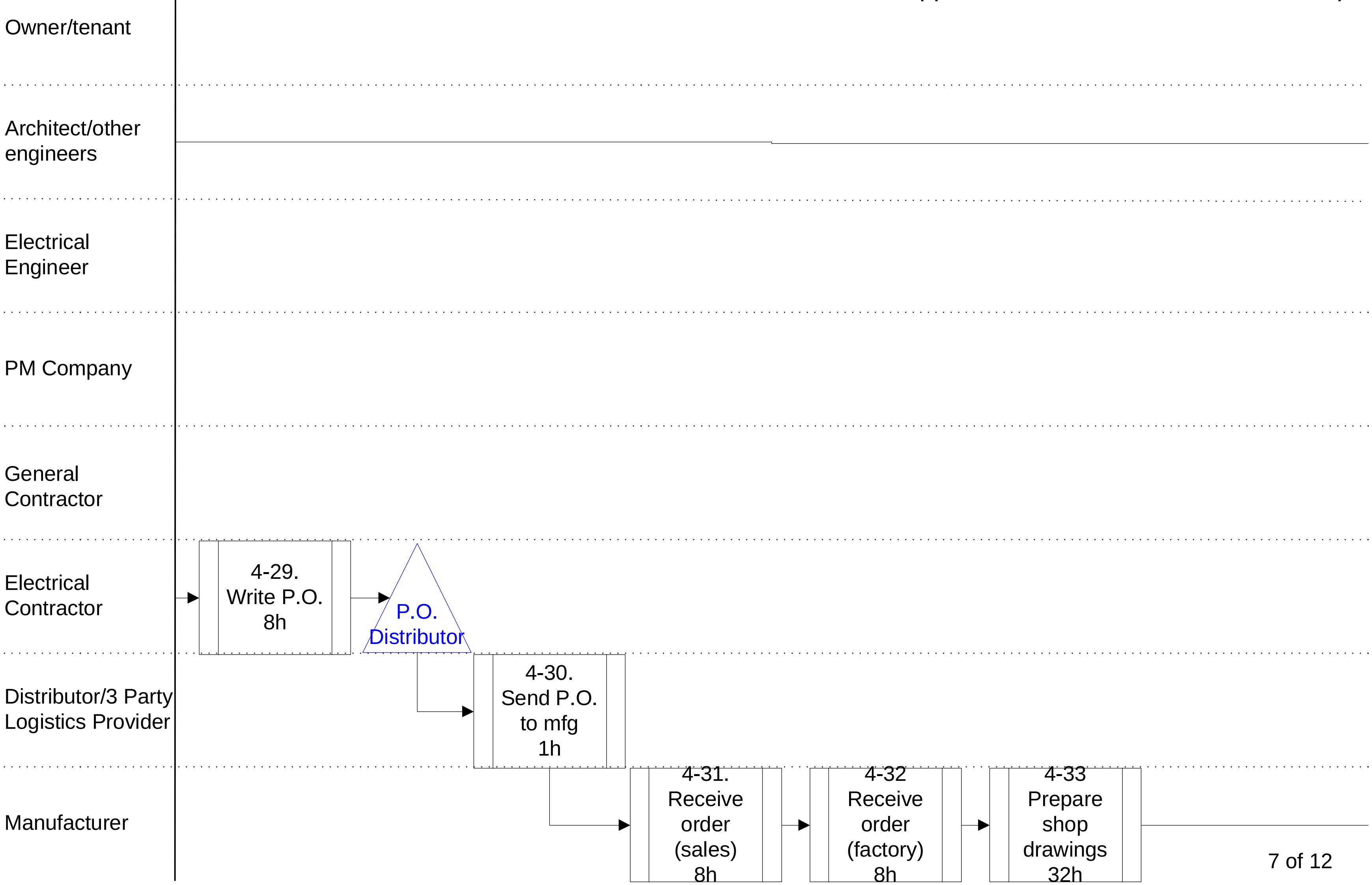



Appendix 3 Paradise Pier Process Map
Owner/tenant
Architect/other engineers
Electrical Engineer
PM Company
General Contractor
Electrical Contractor
Distributor/3 Party Logistics Provider
Manufacturer
RFQ 4 documt.
4-19. Review specificat. 2h
4-20. Input line-diagram to software 20h
Layout & BOM
4-21. Check complian. with plant 1h
4-22. Prepare bid documt. 2 2h
Quote 2
4-23. Prepare bid documt. 3 1h

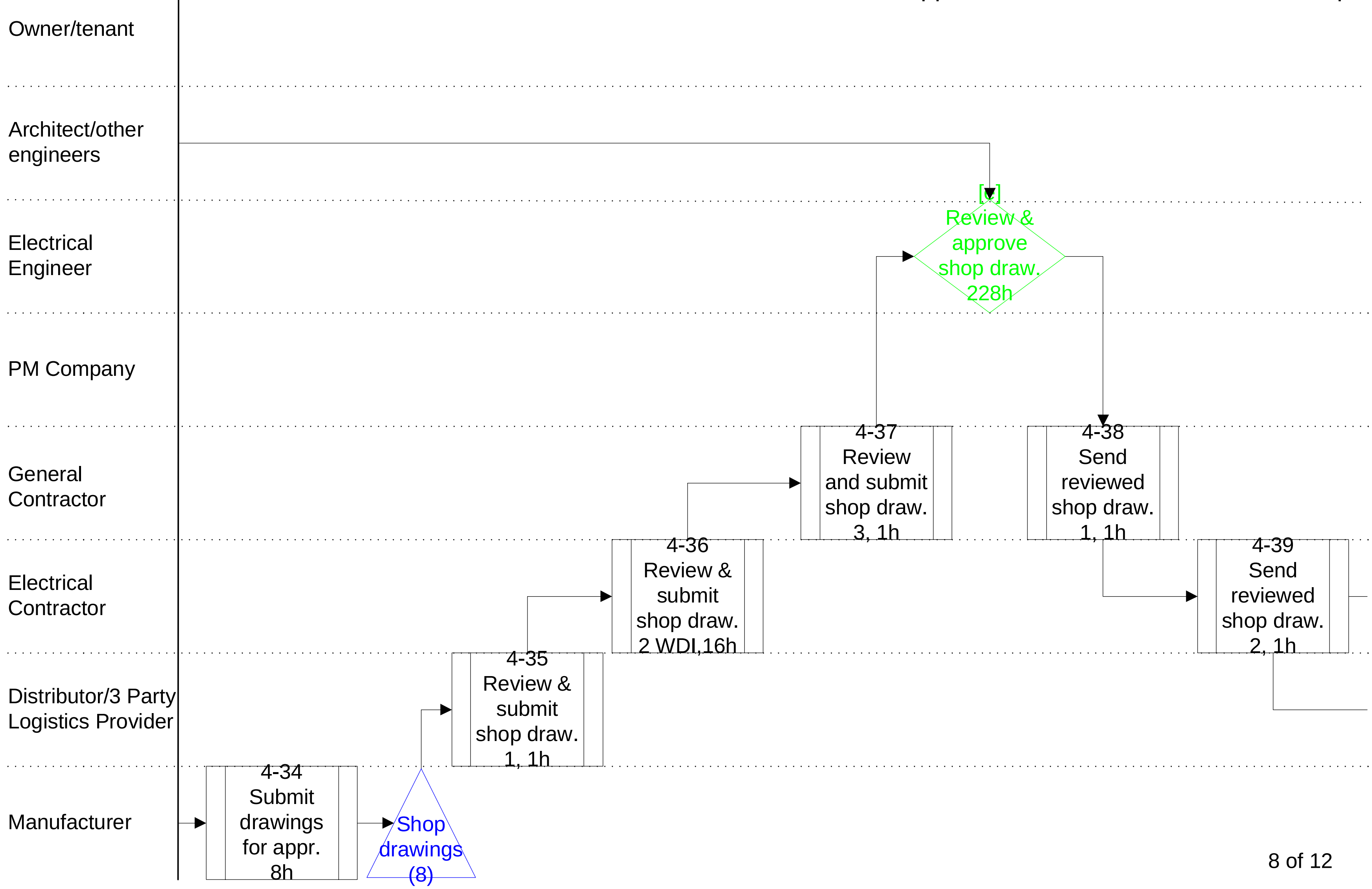
Appendix 3 Paradise Pier Process Map



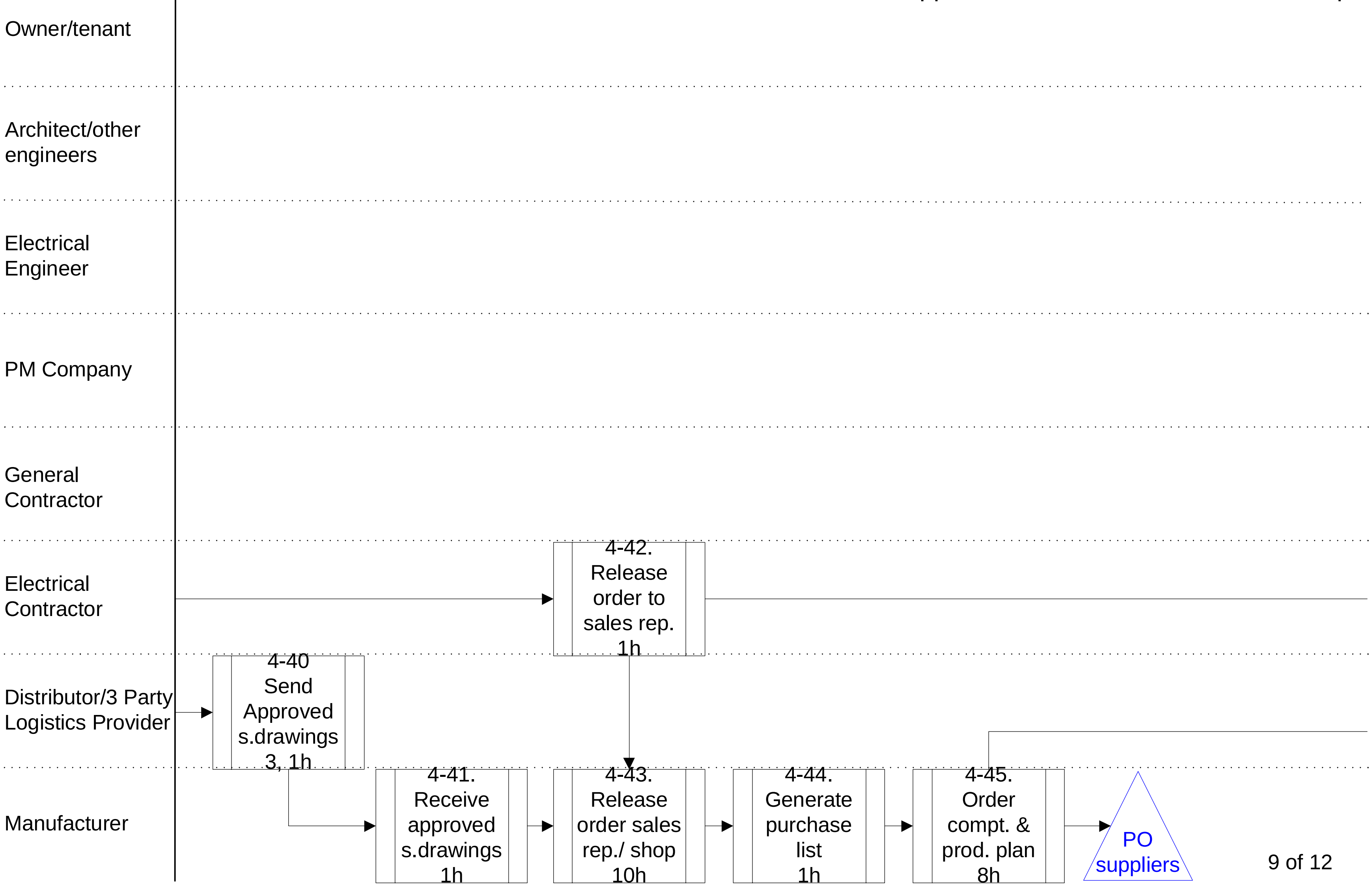
Appendix 3 Paradise Pier Process Map



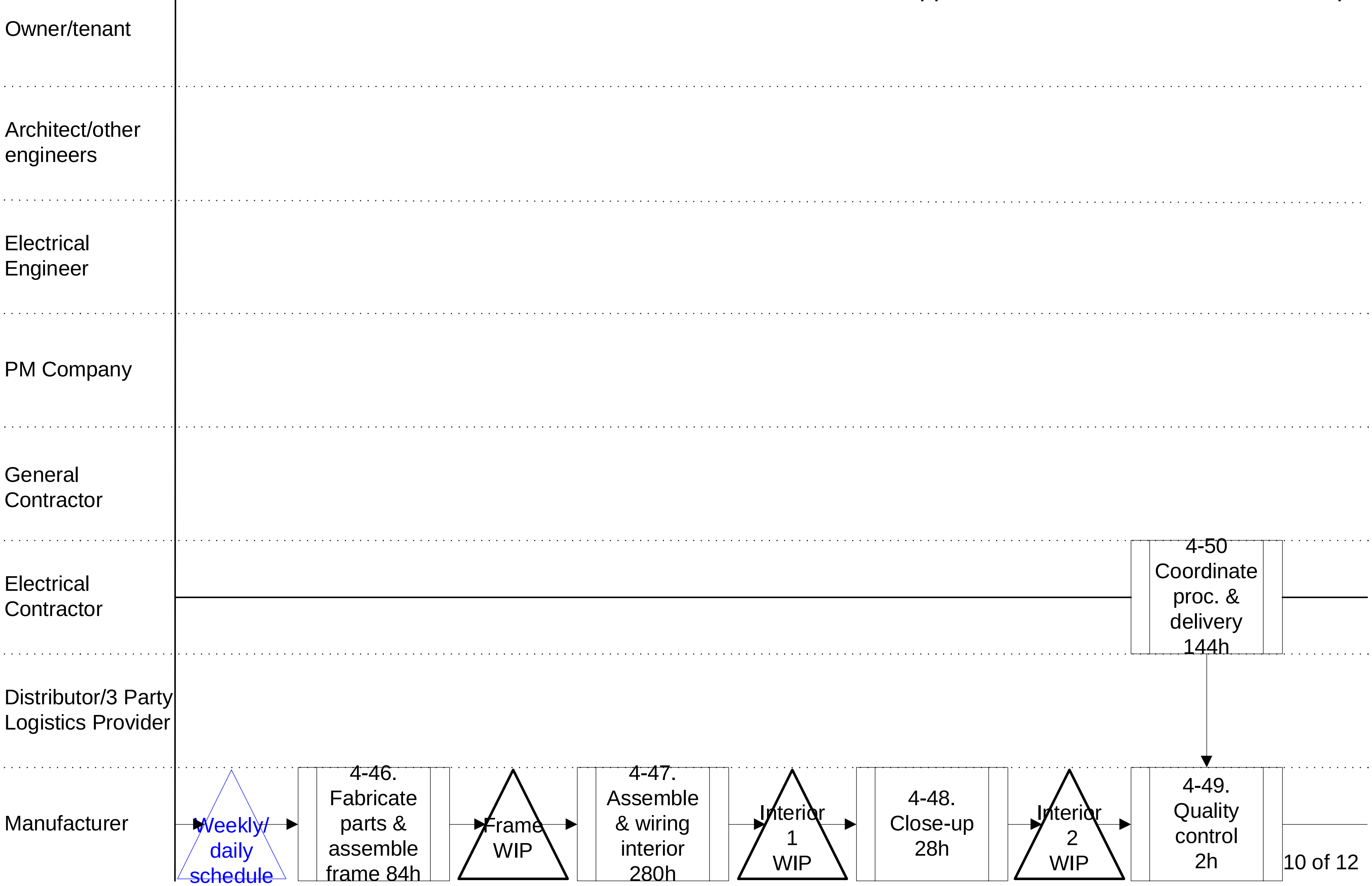
Appendix 3 Paradise Pier Process Map



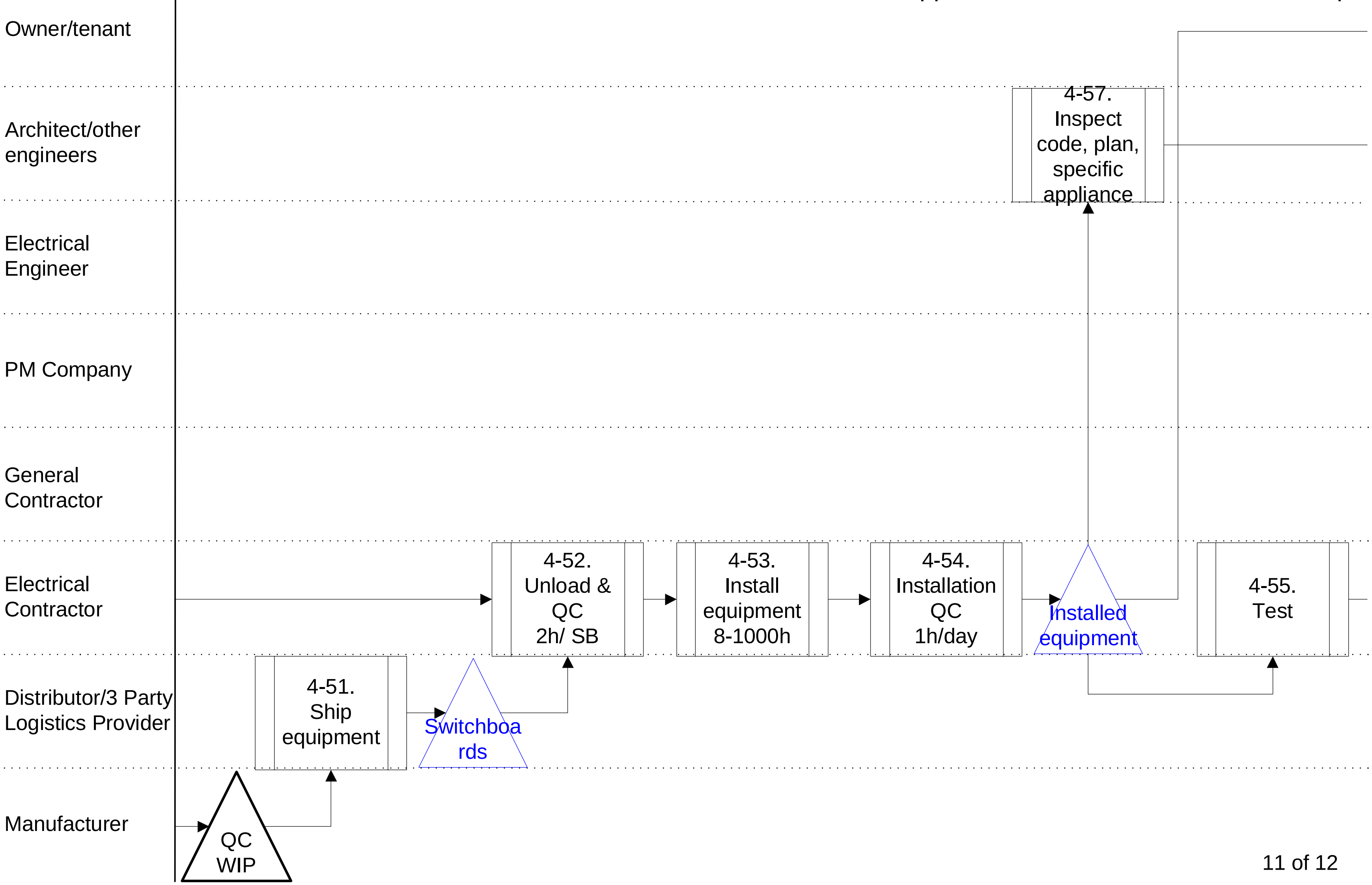
Appendix 3 Paradise Pier Process Map



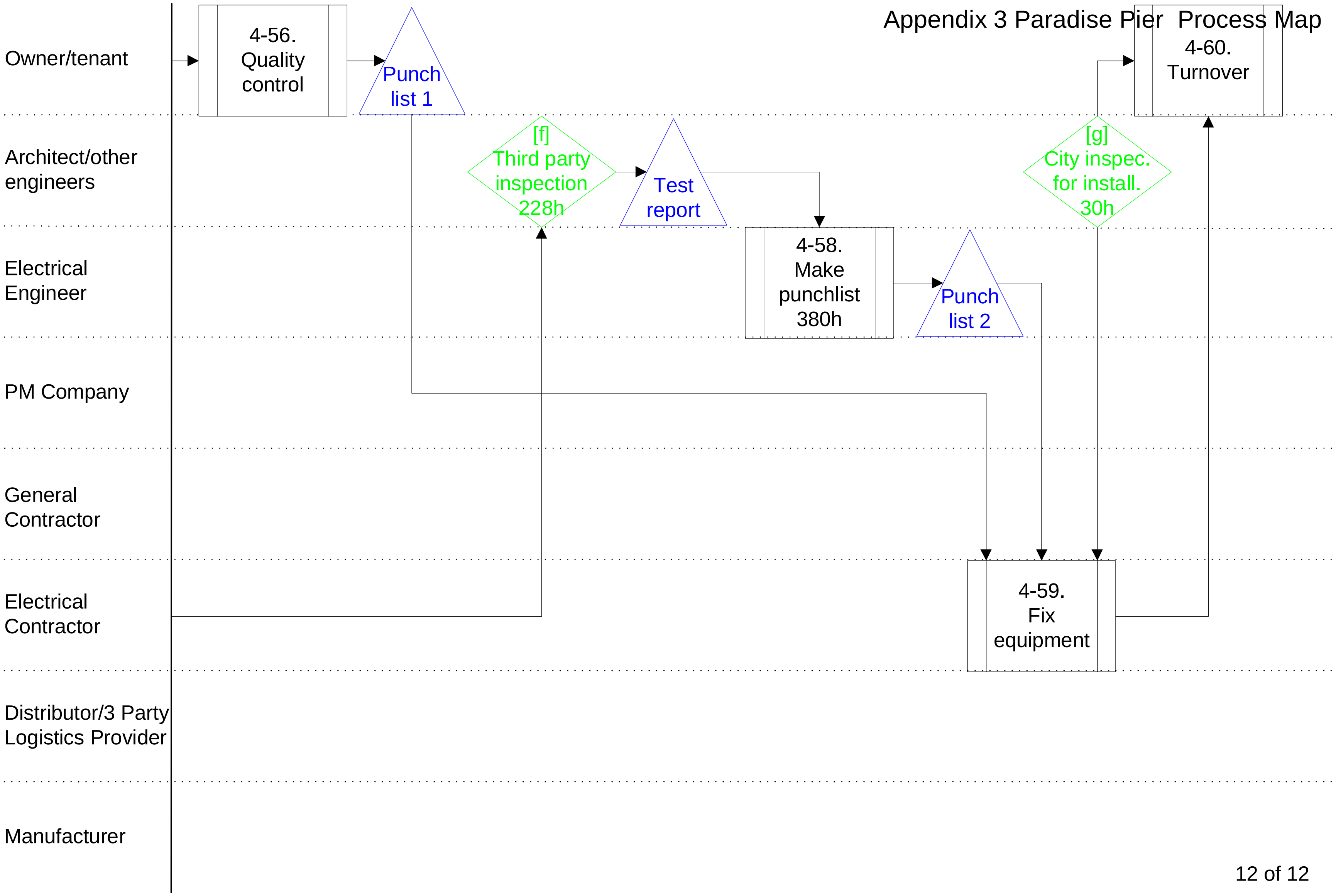
Appendix 3 Paradise Pier Process Map



Appendix 3 Paradise Pier Process Map



Appendix 3 Paradise Pier Process Map



APPENDIX 4

Simulation model documentation

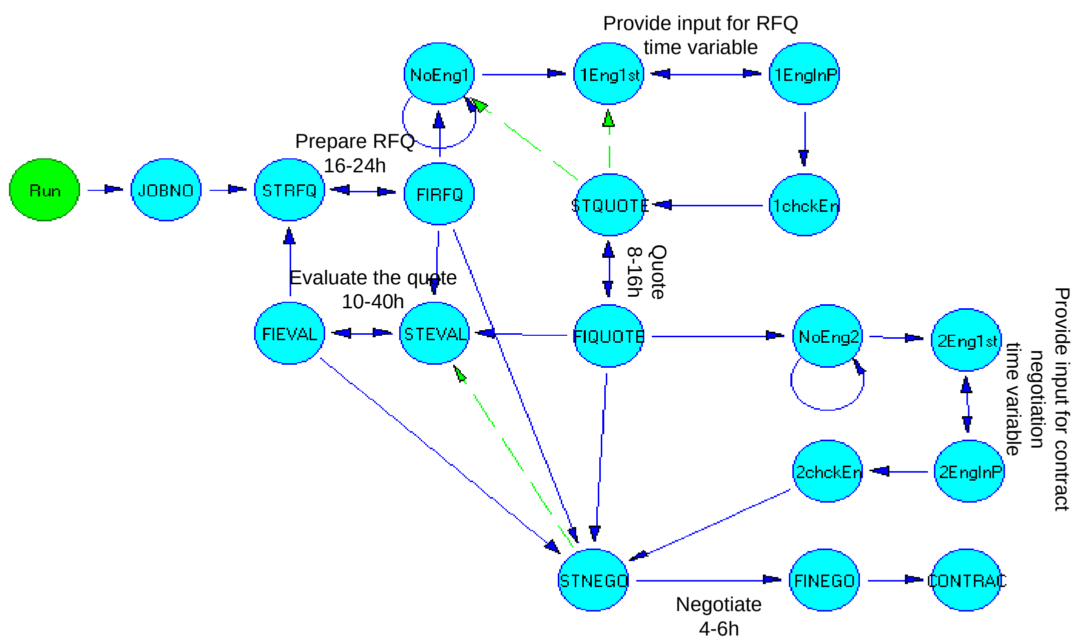


Figure 47: Even graph model of the procurement process

State variables

Table 32 presents all the state variables in the simulation model.

Table 32: State variables

State variable	Description
PM	Number of Project Managers
MFG	Number of Manufacturers
ENG	Number of experts that need to provide input
ENG1	Number of experts assessing the RFQ
ENG2	Number of experts evaluating the quote
W	Is the clock that measures the duration of the simulation run.
JOB	Number of task the Project Manager has waiting to be processed.
RFQ	Request-for-Quotations that the Project Managers generates.
Q	Number of quotes the Manufacturer has waiting to be processed.
Q1	Number of jobs waiting to be negotiated.
Q2	Number of jobs waiting to be evaluated.
FINISH	Number of completed procurement transactions.
PMMT	Number of RFQs the Project Manager process simultaneously.
MMT	Number of QUOTEs the Manufacturer process simultaneously.
R	Probability that Project Manager starts to prepare the new RFQ after FIRFQ.
R1	Probability that Project Manager starts to evaluate a new quote after FIEVAL.
RE1	Probability that ENG2 is available to evaluate a quote. This is the same as ENG/h, the expert's commitment level to the focus job [% of their workweek]
I	Counter; number ENG2 that have to start to evaluate a quote.
J	Counter; number ENG1 that have to start to asses a RFQ.
TOTENG	Counter; number of ENG1 that have finished to assess RFQ.
TOTENG2	Counter; number of ENG2 that have finished to assess quote.
BOOL	Boolean variable, true if ENG1>=I
BOOL2	Boolean variable, true if ENG2>=J

State changes

Table 33 summarizes the state changes that takes place in the model.

Table 33: State changes

Event	State change(s)
Run	JOB=200
JOBNO	W=CLK, JOB=JOB+1
STRFQ	PM=PM-1, JOB=JOB-1
FIRFQ	PM=PM+1, RFQ=RFQ+1
NoEng1	J=J+1, ENG1[J]=1, BOOL=1
1Eng1st	ENG1[J]=ENG1[J]-1
1EngInP	ENG1[J]=ENG1[J]+1, RE1=RND
1chckEn	TOTENG=TOTENG+1
STQUOTE	MFG=MFG-1
FIQUOTE	Q2=Q2+1, MFG=MFG+1, Q=Q+1, R=RND
NoEng2	I=I+1, ENG2[I]=1, BOOL2=1
2Eng1st	ENG2[I]=ENG2[I]-1
STEVAL	PM=PM-1
FIEVAL	PM=PM+1, Q1=Q1+1, R1=RND
2EngInP	ENG2[I]=ENG2[I]+1, RE1=RND
2chckEn	TOTENG2=TOTENG2+1
STNEGO	PM=PM-1, MFG=MFG-1, Q1=Q1-1
FINEGO	PM=PM+1, MFG=MFG+1
CONTRAC	W=CLK, FINISH=1

Simulation conditions

Table 34 presents all the conditions on edges (arrows) in the simulation model. The number refers to numbers in Figure 47, the numbers above the arrow refers to an arrow that points to the right, the numbers below the arrow refer to an arrow that points to the left, the numbers on the left hand side of the arrow refers to an arrow that points up, and the numbers on right hand side of the arrow refers to an arrow that points down.

Table 34: Edge conditions

Number	Condition(s)
1	1==1
2	JOB>0, PM>0
3	1==1
4	1==1
5	J<=ENG
6	1==1
7	1==1
8	RE1<=0.9 (0.9, is variable and refers to commitment percentage)
9	RE1>0.9 (0.9, is variable and refers to commitment percentage)
10	TOTENG>=ENG, RFQ>0, MFG>0
11	1==1, canceling edge
12	1==1, canceling edge
13	1==1
14	MFG>0, Q>0, Q1==0
15	Q2>=MMT, BOOL2==0
16	I<=ENG
17	1==1
18	1==1
19	RE1<=0.9 (0.9, is variable and refers to commitment percentage)
20	RE1>0.9 (0.9, is variable and refers to commitment percentage)
21	TOTENG2>=ENG, Q1>0, PM>0, MFG>0
22	JOB>1, Q1<1, Q2=<10, PM>0
23	Q2>MMT, Q1<1, PM>0
24	Q1>0&Q2<=0, PM>0, MFG>0
25	Q2>=MMT, PM>0
26	Q1>0, R>0.5, PM>0, MFG>0, TOTENG2>=ENG
27	1==1
28	R1>0.33, R1<=0.67, Q2>0, PM>0, Q1<=0
29	R1<=0.33, JOB>0, PM>0
30	PM>0, MFG>0, Q1>0, R1>0.67, Q1>0, TOTENG2>=ENG
31	1==1, canceling edge
32	1==1
33	1==1