AN INTERNATIONAL COMPARISON OF THE DELIVERY PROCESS OF POWER DISTRIBUTION EQUIPMENT

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ABSTRACT

This paper compares and contrasts the delivery and assembly processes of power distribution equipment on three projects. Included are switchboards, panelboards, and motor control centers. Two projects were from the US and one was from Finland, which also gave an opportunity to compare the American National Electrical Manufacturing Association (NEMA) standard with the European Standard (EN) with respect to power distribution equipment and the delivery process. Data was collected by observation, records analysis, and interviews or workshops with owners, users/operators, architects, electrical engineers, project management firms/ general contractors, electrical contractors, and equipment manufacturers. Identifying and exploring the similarities and differences between projects, has greatly broadened the understanding about the delivery process for this type of engineered-to-order product for both the researchers and industry participants.

24 process performance measures were developed. The causes of the main differences among the measures were investigated. Even though the components of the equipment are acquired mostly from the same manufacturers, there were notable differences in the engineering and manufacturing methodologies in the U.S. and Finland. This had a significant impact on engineering lead time, manufacturing cycle time, and design changes and/or errors. Also the procurement methodology has a large impact on the power distribution equipment delivery lead time. Some of the areas of weaknesses identified are incomplete and uncertain input data, lack of systematically collecting input data throughout the process, lack of knowledge and resources to process information, adversarial process environments, and destructive incentives.

KEY WORDS

Engineered-to-order product, equipment, lead time, standard, lean construction, manufacturing procurement, product specification

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INTRODUCTION

Elfving et al. (2002) argued that radical lead time reduction for the delivery process of engineered-to-order (ETO) products requires consideration of the engineering and procurement methodologies, in addition to the manufacturing practices. One key obstacle has been the lack of data and comparative cases of ETO delivery processes in the construction industry. These issues among others have slowed down the research community's understanding and progression of complex ETO product delivery processes, such as for power distribution equipment (Elfving et al. 2002).

In the case of engineered-to-order (ETO) products, customer orders are processed through engineering, detailing, fabrication, and delivery (see e.g., Wortmann et al. 1997). This difference is driven by the different intersection of customer orders with the entire production process. Other intersections define make-to-order (MTO), assemble-to-order (ATO), and make-to-stock (MTS) products. The ETO delivery process includes five main phases namely the engineering, detailing, procurement, fabrication, and delivery. The authors began by mapping the current state of the processes.

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 systems dynamics (e.g. Forrester 1961, Sterman 2000), in analyzing business strategies (Porter 1985), and in Lean Manufacturing (Ohno 1989, Shingo 1989, Rother and Shook 1998). In recent years, there have been some efforts to map the delivery processes in the construction industry as well (e.g., Tommelein and Weissenberger 1999, Arbulu 2002, Wegelius-Lehtonen and Pahkala 1998, Vrijhoef and Koskela 2000). However, there has been limitation in transferring knowledge between and within the various cases. Besides a generic understanding of the described process maps it has been difficult to compare and understand on a more detailed level why there are differences in the structures of the maps and why certain performance measures differ in the various cases. Therefore, the authors chose three delivery processes of the same type of equipment but in different projects and in different countries, one in Finland and two in the US. This paper focuses on the delivery process and installation of the following power distribution equipment: switchboards, panelboards, and Motor Control Centers (MCC). Other major power distribution equipment is switchgear and transformer.

Next, a brief description of the applied research methodology is followed by a description and comparison of three case studies of the power equipment delivery and installation processes. The case studies highlight differences in the engineering, procurement, and fabrication phases.

METHODOLOGY

A hybrid exploratory-explanatory case study approach (Robson 1993) was applied. The exploration aimed to gain insight into the current processes and identify improvement opportunities. The explanation aimed to understand why there were differences between the case studies. The authors were given access to data from three large construction projects, which had recently been completed or were under construction. The data gathering took place between August 2002 and April 2003. Data was collected by observation, records analysis, and interviews or workshops with owners, users/operators, architects, electrical engineers, project management firms/ general contractors, electrical contractors, and equipment manufacturers. 92 interviews were conducted, some part of the six workshops that were facilitated. The purpose of the workshops was to bring all the members from each supply chain tier to the same place at the same time. This helped the members to better understand the issues beyond their own narrow niche specialization and to identify improvement opportunities that could enhance the whole process instead of a single member of the process. It also helped the authors to validate the findings. In the first workshops, the participants mapped the current state map, in the second workshops, the current state map was verified and problems were identified, and in the third workshops, improvement opportunities were identified and a future state map was generated. Data was analyzed with the help of process maps, performance measures, and simulations.

CASE STUDIES

DESCRIPTION OF CASES

The first case study, 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, 9restaurants 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. It has 6 main switchboards, 8 motor control centers, and 150 panelboards.

The second case study, Novo, is a 300,000 square foot office building for a large IT-company, in Helsinki, Finland. The building has 10 floors of which 3 were subsurface. The office space is around 234,000 square foot and provides workspace for about 1,000 employees; the rest is subsurface parking structure. There are 2 main switchboards, 10 motor control centers, and 60 panelboards.

The third case study, 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 rest shops, restaurants, and maintenance facilities. Along with the vertical construction[4] Disney also developed and built the electrical infrastructure, including two switching stations for the resort. The local utility company normally handles electrical infrastructure, thus it was not included in this study. Paradise Pier had 10 main switchboards, 12 motor control centers, and 200 panelboards.

SWITCHBOARD, PANELBOARD, AND MCC

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 power distribution equipment 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 where the power is further distributed with feeders to motor control centers, which

[4] Vertical constructions refers buildings that houses indoor power distribution equipment and horizontal construction refers to subsurface electrical infrastructure and outdoor power distribution equipment.

supply mechanical equipment (chill water systems, pumps, fans, etc.), and local panelboards. Besides switches, the switchboard may include instruments such as voltmeter, ammeter, wattmeter, and varmeter.

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 switchboard stand on a floor and panelboard is attached on a wall.

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).

COMPARISON OF THE THREE CASES

Though the various components that go into the switchboards, MCCs, and panelboards are about the same in all the cases, and even fabricated by the same manufacturers, there were some fundamental differences in the engineering, procurement, and fabrication phases between Finland and the US. Due to the space limitation, this paper highlights only some of the main findings and compares four (engineering hours, engineering changes, manufacturer's cycle time and lead time (Table 1)) of 24 performance measures. The case studies are described in detail, including the performance measures, and current and future state maps, in three technical reports (Elfving et al. 2003a, Elfving 2003, Elfving et al. 2003b).

Table 1: Comparison of some performance measures

Performance measure	Bay Street, US	Novo, Finland	Paradise Pier, US
Engineering hours	350	501	1639
Engineering changes	30 (10)	300	40
Manufacturing cycle time	1-2 days	12 days	2-4 days
Manufacturing lead time	5 weeks	5 weeks	6 weeks

Differences in the engineering methodologies between the US and Finland

The engineering hours per switchboard were significantly higher in the Finnish case than in the US cases. Switchboard engineering can be divided roughly into systems engineering and detailed level engineering. In the systems level engineering, the logic and loads for the power distribution is defined, and in the detailed level, the structure and components of each board are specified. It is the latter that causes major differences in the engineering hours, and particularly one drawing, the 3-line diagram,. The 3-line-diagram (Figure 1) defines the electrical wiring of the boards. One main switchboard can have over 100 CAD-pages of 3-

line diagrams, and the cases that were investigated had thousands of pages of 3-line-diagrams. Thus, the way they are generated has a major impact on the engineering time.

The Finnish case, the 3-line diagram consumed one third of the total engineering time, whereas in the US cases at most a tenth of this time was needed. The Finnish case, also had significantly more design changes with respect to the boards than the US cases. The reason for the tedious detailed engineering and for a significant part of the changes lies in equipment standards and configuration software. In the US, several standard setting bodies especially the National Electrical Manufacturer Association (NEMA) and the large board 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. 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.

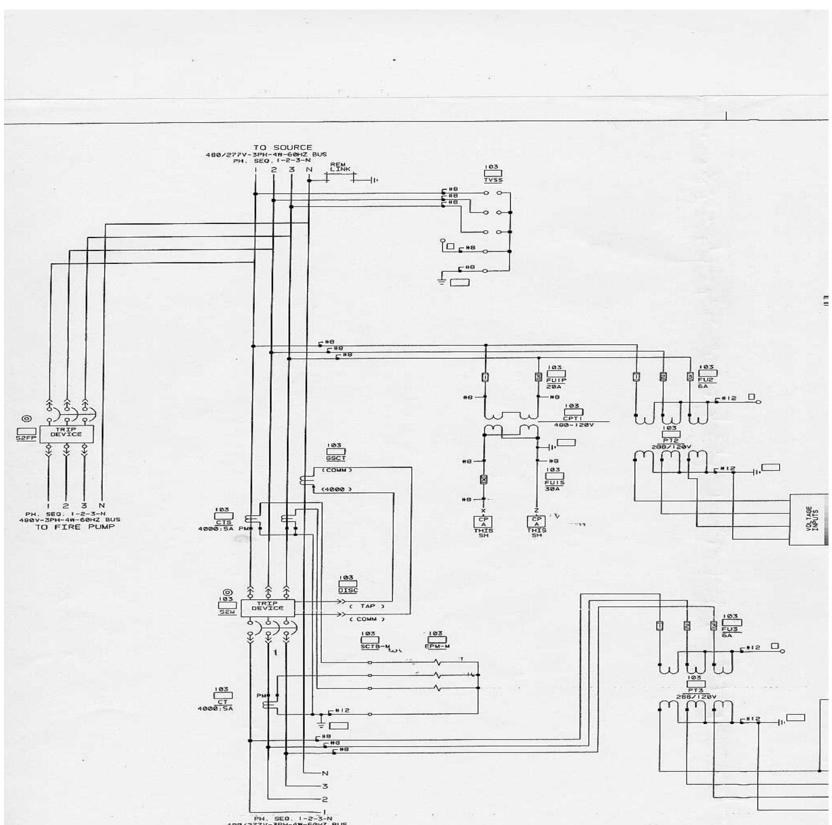

Figure 1: An Example of a 3-line diagram of one section of a main switchboard

In the US cases, the main power equipment manufacturers have advanced software that automatically identifies which 3-line-diagram has to be used in the ordered board. The development and implementation of such configuration software is expensive and takes many years, which may explain why the relatively small Finnish equipment manufacturer does not yet have one. Moreover, in US cases, the manufacturers generate the diagrams, and not the electrical engineer of the record or electrical contactor as in Finland. This has further helped the manufacturers to standardize the diagrams and also the assembly on the shop floor. Through the high degree of standardization, the large US manufacturers have been able to integrate the detailed engineering to their pricing and configuration software. In other words, at the same time as the Bill-of-Material (BOM) for the quotation is fed into the pricing software, the shop drawings, including the 3-line diagram, are generated, sometime without a single human's intervention. 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. As a result, the time savings in detailed engineering are several months and errors in the drawings are rare. Smeaton (1987) did similar findings of the European and the US standards. The disadvantage of a high level of product standardization is that it reduces the incentive for product innovation, which was one the reasons why the standard in Finland was changed from a product to a performance based standard.

Differences in procurement methodologies between the US and Finland

In all three cases, traditional competitive bidding was employed as the procurement method and the contracts were awarded to the lowest bidder. However, the bid documents differed somewhat as did the material take-off. Also, in the US cases, the electrical contractor placed the request-for-quote (RFQ) and the purchase order (P.O.) to a distributor, who then placed the documents to the sales manufacturer's representative who then placed the documents to the manufacturing plant. In Finland, the electrical contractor placed the RFQ and P.O. directly to the manufacturer. In both countries the observed document flow was the predominant practice. The US practice added about a month to the whole delivery process, because the manufacturer needed some additional information from the customer and it easily took a month before the information had traveled back and forth from the manufacturer to the customer through the two middlemen. On the Paradise Pier project, the owner fixed a price cap for the power distribution equipment by a pre-bid. That is, the owner placed RFQs during the feasibility phase, when there were only rough schemes about the design. Then the manufacturer's sales representatives gave the quote as a reduction percentage of their list prices. This gave the electrical contractor an upper boundary that he could try to get lower through competitive bids from their distributors.

Another major difference between Finland and the 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 with the US practice is that the sales representative has access to all the project drawings, so that if there are some obscure definitions in the power equipment documents the sales representative is able to make better adjustments than in Finland where the manufacturer has to rely on the documents he receives from the electrical contractor. In Finland, the manufacturer for example 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 with 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.

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 breaker sizes, and a panel schedule, is the main RFQ document. In Finland, in addition to the one-line diagram, a detailed board design that 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 the control over the 3-line-diagram, which greatly impacts the structure of the boards.

Differences in manufacturing methodologies between the US and Finland

In manufacturing, the most significant difference was in the cycle time, which is defined as the time for an individual job to traverse a routing on the shop floor. In the US the cycle time for the main switchboard was between one and four days and in Finland the cycle time for the main switchboard was about 12 days[5]. The main switchboard normally consists of six to 12 sections, which vary between 18 inches and 50 inches in width. Because, it is too large to get moved as one piece onto the site, the electrical contactor requests the manufacturer to assemble the switchboard in two or more pieces, which the electrical contractor connects together when the switchboard is in its final location in the building.

The reason for the dramatically shorter cycle time is the batch size. In the US, the frame, the installation of equipment and wiring are made separately for each section and first in the end of the assembly, based on customer requirements, the sections are connected together to line-up. In Finland, the frame, the installation of equipment and wiring of the whole line-up is built together straight from the beginning (Figure 2).

The advantage with US manufacturing practice is the smaller batch sizes and one-section-flow. When the sections are build separately, one electrician can work with each of the sections and the sections can be build simultaneously. If the sections are joined together straight from the beginning only one or two electricians can assemble the switchboard due to space constraint. 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 there are discontinuities the higher the probability is for error. In the US cases, about 1% of the connections have problems. 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. Finally, due to the high level of product standardization in the US, the installation of equipment and wiring is also on average faster. However, the order delivery or customer lead time, which is defined as the time

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

between customer order and order fulfillment, was about the same, in Finland about five weeks whereas in the US cases it was five and six weeks respectively.

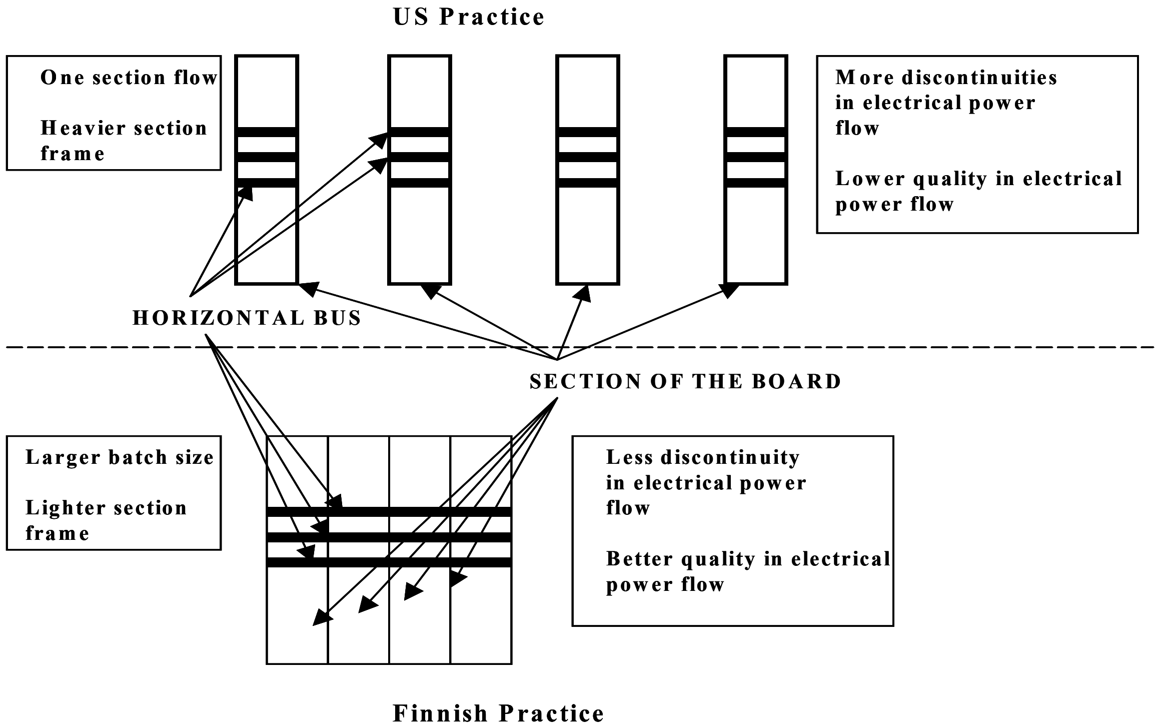

Figure 2: Differences in US and Finnish manufacturing practice.

SUMMARY OF ADDITIONAL FINDINGS

The authors and the industry partners identified several problems in the power equipment delivery process. Some of the problems were lack of considering the flow view; not considering process cost in procurement; numerous misconceptions; uncertainty of input values and their tedious collection, and lack of performance measures. (Elfving 2003, Elfving et al. 2003a, Elfving et. al 2003b). Besides wasted resources, such as rework, waiting, and changes in planned work sequence, the problems increased the lead time of the delivery process. In one case, the electrical engineer had to wait six months before the owner was able to decide if he needed an emergency generator. In another case, due to the tight project schedule, the electrical engineer had to place his connection application with the utility company based on incomplete drawings and project information. This caused changes and rework and increased the application and connection process to over one year from the standard 6-7 months. One of the most questionable issues in all three cases was the true value of procuring power distribution equipment through competitive bidding.

PROCUREMENT THROUGH COMPETITIVE BIDDING EXPENSIVE: AN OBSTACLE FOR IMPROVEMENT

The current practice of procuring power distribution equipment through "serial" competitive bidding has many disadvantages and does not guarantee the lowest process cost though the product cost may be the lowest. Also, the competitive bidding increased fragmentation of the process and increased batch sizes. Moreover, competitive bidding reinforced adverse goals, which led to local optimization instead of global, systems optimization. Participants have little incentive to improve the current process if relations among the participant are set up through competitive bids.

The authors and the industry partners were even more surprised at the negative impact competitive bidding had on delivery time and labor time. In the Novo case, when the participants multiplied the hours with an estimated average cost of an employee per hour, 40 euros/h, it turned out that the bidding practice cost 10% of the value of all the power distribution equipment required in the building. Since the range of the low bids was within 3-4%, the bidding process consumed more money than was gained. The impact on delivery lead time was 2-3 months, but more importantly the procurement may have significant variability (Elfving and Tommelein 2003), which generates numerous problems for the project participants downstream in the supply chain.

EMPHASIZE ON TRANSFORMATION VIEW AND LACK OF FLOW VIEW

Earlier improvement efforts have merely concentrated on transformation of inputs to outputs, e.g. automating the shop drawing phase. Even though there have been some notable improvements for the particular stakeholder who introduced the improvement, the overall delivery process has not benefited in the same magnitude. Very little attention has been paid to the flow view, especially with respect to document flow. Batch sizes were larger than necessary and were not always sequenced. Document batch sizes have a major impact on the process lead time, e.g. 90% of the waiting time of shop drawing approvals can be eliminated if the batch size is reduced to one piece of equipment instead of all the equipment in the project. Also, if one building were engineered from systems design to shop drawings at a time, the lead time per equipment would dramatically shrink. Thus, reducing document batch sizes and the need for approvals would generate the largest lead time reduction in the whole delivery process. In one of the cases, it was estimated that by better managing and streamlining document flow, a year of the 2.5 years could be cut from process delivery time.

COGNITIVE CHALLENGES

In the beginning of the case studies, most of the participants did not think significant problems in the process existed but towards the end of the study they realized that there was room for major improvement. One reason for not realizing the opportunities may be the "deep rooted" practices that have not been challenged for decades. It was surprising that even if the US cases were very different in scope and owner capabilities, the current state maps are very similar. This indicates that there are strong practices and clear roles among the stakeholders in the procurement of power distribution equipment, which may be an obstacle to improving the delivery process. Also another reason for paying little attention to the delivery process may be that the cost of design iteration, change orders and add-ons is generally underestimated because only direct costs are considered. The direct cost of change orders and add-ons, which include design and material cost, are about 10% of the contract prices. The indirect cost, managing the change-order process, is not currently measured but the authors estimate that the order of the magnitude is the same as the direct cost. Other cognitive challenges include: participants were not aware of the whole process structure and of each other's capabilities, particularly the manufacturer's capabilities were underestimated; terminology and performance measures were frequently misused, though misunderstandings in terminology did not lead to major confusions.

IMPROVEMENT OPPORTUNITIES

The current delivery process design is partly outdated. The owners and architects, particularly, consider the project environment as dynamic; where it is evident and natural that constant project development, design iterations, and changes take place. However, the delivery process of power distribution equipment is still very bureaucratic and hierarchical, which responds poorly to dynamic needs.

The value adding times in the delivery processes are less than 10%, which indicate that there is notable room for improvement. Together with industry partners the authors developed future state maps, where the lead time of the delivery process of the power distribution equipment was reduced up to 40%. Also, the redesign of the process could save at least 15-20% of labor hours throughout the process. However, if the impact of reduced need for information exchange, changes, and add-ons are included, the labor hour savings are much higher. In identifying improvement opportunities, in addition to the strong involvement of the industry partners, the TFV-theory framework (Koskela 2000) played a fundamental role. The future state maps will be presented in future publications.

CONCLUSIONS

Even though industry partners were initially skeptical, several opportunities for improvement were identified throughout the delivery process. Some of the findings such as the need for organizational and contractual changes; poor information flow; and system simplification and component standardization have also been identified in other studies (e.g. Handfield 1995, Sobek et al. 1999, Wegelius-Lehtonen and Pahkala 1998, Tommelein and Weissenberger 1999, Lambert and Cooper 2000, Arbulu 2002). However, the following findings have not been explicitly addressed in previous case studies in the construction supply chain literature:

- the cost of competitive bidding
- the impact of competitive bidding and document batch sizes on lead time
- the role standards play in detailed engineering
- the largest opportunity for reducing ETO delivery lead time actually lies in improved document flow and not in reducing manufacturing lead times.

Assessing the suitability of competitive bidding for various types of products requires more attention. The purpose of competitive bidding is to obtain the current market price for a product. However, the current market price does not include the cost of procuring the product. This cost can be significant, especially for more complex products such as power distribution equipment.

Furthermore, the current delivery processes for power distribution equipment in the US and Finland have long been unchanged, but comparison revealed some fundamental differences between those processes in all major phases, engineering, procurement, and manufacturing. These opportunities for improvement encouraged the industry participants and the authors to radically redesign the current state maps. The fact that the industry partners were strongly involved in assessing the current state and redesigning the process and the ability to link the findings to the TFV-theory provides strong support both for the findings and the usefulness of the TFV-theory.

Finally, the cases may carry valuable insights about other types of engineered-to-order products as well, where the engineering, procurement, and fabrication methods may have significant impact on the delivery process lead time, product and process cost, and quality.

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