On-site Construction Versus Prefabrication

by

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Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of

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Abstract

The question this thesis tries to answer is "How does one decide whether or not to use prefabrication in a project?" Since this is a broad question, we focus on a more specific topic: "How does one decide whether or not to use prefabricated bathrooms in a project?" The problem is approached with the formation of one case study and with the help of construction industry experts (owners, contractors, architects and academics). The case study is created based on data from a real project. The decision-making methodology used to run our comparison is called "Choosing by Advantages" and is described in detail in the thesis. Three alternatives are investigated: on-site bathroom construction, prefabrication of bathrooms adjacent to the worksite and prefabrication in a factory.

Experts from the construction industry evaluate the solutions available, given the same information and data, in an attempt to understand which of the options they would consider to be more appropriate. They assign weights on each of the advantages in order to decide which solution is preferable.

The primary goal of this thesis is to establish a methodology that can be used to tackle broader problems of the construction industry. Our case study could be used as guidance in addressing wider problems and could help the decision-making process. At the same time, the methodology established can be used to identify where differences in opinions lie, to help project stakeholders focus on these differences and to facilitate them in reaching agreement. A secondary goal for this thesis is to explore the difference in philosophy (if any) between all professionals involved in construction projects. We intend to investigate, for example, if all contractors agree among each other when presented identical information. The results are displayed in chapter 4.

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Furthermore, I wish to dedicate this work to the memory of Georgios Kartsaklis, my mathematics tutor, for setting the foundations of my development. He would be very proud to see that a student of his made it to MIT. I also sincerely thank my thesis advisor during my undergraduate thesis, Professor Ioannis Tegos, for his unconditional help and all the kind words in his letters of recommendation.

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Nikolaos Legmpelos

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1 Introduction

The construction industry is a complicated field full of uncertainties. For many years, people failed to optimize the construction sequence and encountered similar problems to manufacturing plants, such as a high share of non-value adding activities. Lean thinking was a real revolution in the manufacturing industry that originated in the 1950's and was gradually implemented in construction in the 1990's.

Lean thinking helped manufacturing plants become more efficient and profitable by minimizing non-value adding activities and inventories, increasing overall quality and productivity and many more components that are discussed in this thesis. The approach was similar to the construction industry that followed the incorporation of lean methodology. There are of course a series of differences between construction and manufacturing that will be analyzed in detail in chapter 2.

Prefabrication seems to be the next step that the commercial construction industry will attempt to take in the USA, since it is able to combine lean techniques both in a manufacturing and a construction sense. Major construction companies like SKANSKA have attempted to investigate the potential of the field, implementing prefabrication techniques in a series of projects. In addition, companies like Eggrock Modular Solutions that specialize in fabrication of components used in building projects have also been founded.

The sector seems to have a future (bright or not, only time can show) but the big question that arises is "How can one decide whether or not to use prefabrication in a project?" The decision is not an easy one, as a series of potentially interdependent factors influence the process. This thesis attempts to focus on a more specific decision-making question: "How does one decide whether or not to use prefabricated bathrooms in a project?" By focusing on a more specific component, we hope to address the issue better by identifying all factors that influence such a decision.

Others have approached the issue as well. Several attempts have been made to identify value components of the construction process. Tam et al conducted a big survey in 2006, reaching out to the construction industry in order to gather opinions towards prefabrication. The major advantages reported were better supervision, frozen design at an early stage, reduced construction costs and shortened construction time. On the other hand the major disadvantages were inflexibility for design changes, lack of research information and higher initial construction costs. (Tam et al., 2006)

In addition, Olsen and Ralston in 2013 investigated if utilization of prefabrication is based on reasoned decisions or educated guesses. They observed that "prefabrication is a new strategy for most construction professionals" and that "they lack the historical costs and schedule data to make strategic decisions about prefabrication and are relying on their best guesses". (Olsen and Ralston, 2013)

Consequently, the field could definitely benefit from more research and from establishing a decision-making methodology that could be used to avoid relying on educated guesses. Commercial building projects like hospitals, student dormitories or hotels with a big number of identical bathroom units are targeted in our research. After discussing with many companies and visiting several projects, a case study was created based on real data from a hospital constructed in Wilmington, Delaware.

The case study is analyzed based on a decision-making methodology called "Choosing by Advantages" (CBA). We attempt to investigate in depth and identify all factors that influence the decision-making process. Our goal is to build a case study that can be used to test the method in a real project and at the same time, approach several construction industry experts to collect their opinions.

The process of identifying and correctly quantifying all factors related to a case is highly demanding. It is the most important step for using the method and is an iterative process, which is very likely to take quite some time to complete. Tackling a problem from all its perspectives in a short time is not an easy task. Nevertheless, as soon as such a tool is developed, all future decisions in the relevant area can be made faster and more accurately.

The alternatives investigated in terms of bathroom construction are three:

- On-site (Stick-built) construction
- Prefabrication in a warehouse adjacent to the worksite
- Prefabrication in a factory

The first two are options where the general contractor is in charge of construction whereas in the third option, a third party undertakes the responsibility to construct the bathrooms, ship them and install them in the building. The prefabricator of this option is usually a company exclusively concentrated in the area. In order to develop a good understanding of each alternative, the author visited in person construction sites and a manufacturing firm of prefabricated bathroom units and observed the process followed in each of them.

As mentioned, the author spent a significant amount of time corresponding with experts from the construction industry in an attempt to identify as many value components as possible. Each expert has his/her own perceptions of these values and we wanted to include all of them in our analysis. In order to be as objective as possible, we reached out to experts in all three areas asking them to list their major advantages.

After the case study of the hospital in Wilmington, Delaware was created, experts of the construction industry were called on to evaluate it and provide their opinions. The second part of this thesis focuses on studying those opinions to see what the experts agree and disagree on. We want to determine whether professionals of the same field will agree with each other.

Our hypothesis is that owners and architects will agree with each other, while contractors will hold a different ground. As a result, we expect to see some cohesion amongst people from the same profession. At the same time though, it will be interesting to see their stance towards prefabrication. Some companies react more positively than others towards this solution, and since everyone was invited to participate, we aim to see where their differences (if any) will lie. The case study consists of 19 factors and we want to see how they will be evaluated in order to reflect opinions in favor or against prefabrication.

The second chapter informs the reader about the history of lean thinking and the steps towards optimization of manufacturing and construction techniques. The Toyota Production System is also presented, which was the first step towards this direction. Lean manufacturing follows and finally lean construction, the concept that we focus more on.

The “Choosing by Advantages” method used in our case study is described in detail in chapter 3 and is another step in the improvement process. It is usually used in tandem with lean thinking, since it requires all project stakeholders to be involved at an early stage.

Chapter 4 presents the results of our case study, which proved to be uniformly supportive towards prefabrication in a factory for this particular case. The sponsors of the case study supported their opinion with interesting arguments, which will hopefully help the reader develop a clear understanding. However, another case could very well produce different opinions. On-site construction that was very far from being selected using the CBA for our case could easily be used for another type of project. In addition, cohesion was observed among contractors and owners but not among architects.

Chapters 5 and 6 include our conclusions and discussion on the results. Chapter 6 also includes a critical interpretation of the CBA as well as a list of potential future steps for research in the area suggested by the author.

2 Relevant concepts in construction

This chapter presents two major concepts of construction that we focus on: the lean thinking and the prefabrication. Lean thinking is a broad concept that is applied both in manufacturing and construction activities. It originated by Toyota, the big automobile company, which created the Toyota Production System that is described in section 2.1.1. Lean manufacturing is based on the fundamental ideas of the Toyota system and is used widely across the manufacturing industry nowadays. Section 2.1.4 deals with its application in construction, where the reader will get a chance to see similarities and differences between manufacturing and construction as well as where lean thinking is applied in project management.

The second part of the chapter presents prefabrication, which is connected to lean thinking because it combines both manufacturing and construction components, since off-site construction is a procedure that can be similar to manufacturing. Some construction companies attempt to use prefabrication in tandem with lean techniques pursuing a certain set of potential advantages. Those advantages (and disadvantages) alongside with two example projects are presented in section 2.2.

The ultimate goal of the second chapter is to prepare the ground for presenting the "Choosing by Advantages" methodology. The method is presented in chapter 3 and is also combined with lean thinking, since it requires project stakeholders to work together well in advance to lay out a detailed plan for the project. Important decisions need to be made during that stage and this is the area that CBA attempts to assist.

2.1 Lean thinking

This section presents the lean philosophy that shifted the manufacturing industry during the last century. It also provides the reader with the background of "Choosing by Advantages" methodology that is going to be used later on in this thesis in order to evaluate the question we attempt to answer.

To begin with, the effort originated in Japan after World War II and was initiated by the Toyota Automobile Corporation. The main goal behind the development of the method was to eliminate waste from the manufacturing process and avoid fixing defects in cars. What Toyota aimed for, was constructing cars as efficiently as possible, minimizing defects, providing big variety to the customers and eventually maximizing profits. (Womack and Jones, 2003)

But what is defined as waste? All kinds of activities that do not contribute directly to the value generation process are considered waste. In other words (following the lean vocabulary), waste is defined as all kinds of non-value adding activities. (Womack and Jones, 2003)

The means to this goal was the famous Toyota Production System, which is described in detail in the next section. The Toyota Production System was the "ancestor" of Lean Manufacturing and Lean Construction that will also be described later on. All this "Lean" movement led eventually to the conception of the CBA method, a decision-making tool that can help people make better decisions.

2.1.1 Toyota Production System (TPS)

After the end of World War II, Toyota's president Eiji Toyoda spent three months in the USA at Ford' Rouge plant. He was amazed by the total output but thought that the plant generated lots of waste. (Gann, 1996) With the help of Taiichi Ohno, a highly ranked Toyota executive, Toyoda aimed to create a flawless manufacturing procedure, eliminate waste, minimize inventories and all kinds of errors. Taichi Ohno is described as *"the most ferocious foe of waste human history has produced"*. (Womack and Jones, 2003)

The TPS was a real revolution and rendered Toyota the leader of the automobile industry. The first step Toyota had to take though, in order to create this system was to define all sources of waste (or *muda* in Japanese). Those factors of waste are seven: (Womack and Jones, 2003)

1. Transport
2. Inventory
3. Motion
4. Waiting
5. Overproduction
6. Over Processing
7. Defects

However, it must be noted that there are two kinds of waste (muda): (Womack and Jones, 2003)

- Type one muda: Non-value adding, yet unavoidable activities.
- Type two muda: Non-value adding activities that must eliminated immediately.

So, the first step was to identify the sources of waste and locate them in the manufacturing process. The next step was to improve quality of the final product by eliminating defects.

But how were these defects eliminated? Toyota conceived another revolutionary method in order to identify the root causes of each problem and make it disappear forever, the **“**5 whys system**”**. When seeking to solve a problem with the 5 whys, one needs to begin from the final result, figure out what caused what by asking “why?” five times. A simple example of implementing the method is:

1. Why did your car stop? - Because it ran out of gas.

2. Why did it run out of gas? - Because I didn’t buy any gas on my way to work.

3. Why didn’t you buy any gas this morning? - Because I didn’t have any money.

4. Why didn’t you have any money? - Because I forgot my wallet in the pants I was wearing yesterday

5. Why did you forget your wallet in the pants you were wearing yesterday? - Because I usually leave it in my pocket.

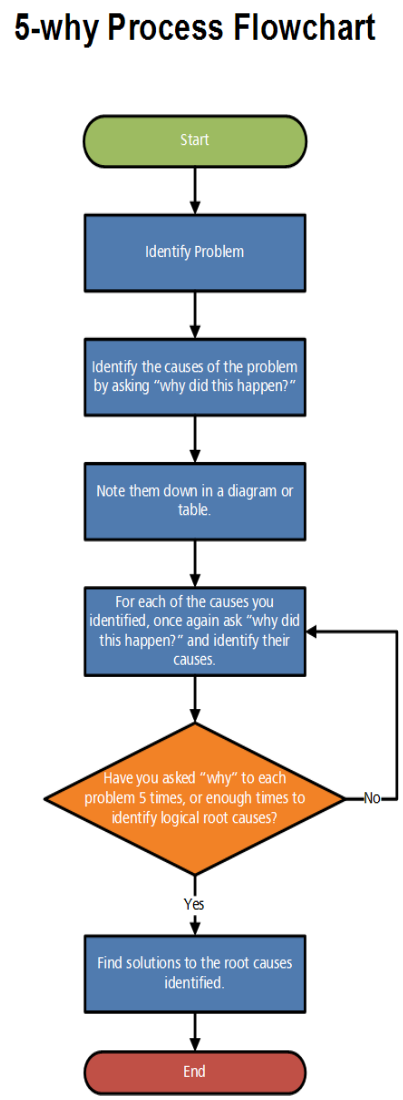


Figure 2.1-1: The 5 why process flowchart (Bulsuk, 2009)

Root cause of the problem: Not removing the wallet when you get home. Since the root cause has been established, it is easy from now on to pay more attention and remove the wallet from the pants in order not to experience such a problem again. That was a very simplistic example in order to give a quick understanding to the reader about the 5 whys technique.

Obviously, the method was applied to more complicated problems that arose within the Toyota manufacturing plants. Driving all problems to their beginning facilitates the solution-seeking process and enables their eternal disappearance.

In the same sense, whenever a problem was spotted within the Toyota factories, the production line was stopped (all workers could stop it) and the item was sent to quality control where it was subjected to the five whys. The procedure resulted in a flawless production line that after a certain point never needed to stop for anything. (Womack et al, 1990)

To sum up, we can accurately summarize the overall idea of the "5 why" system with in the following phrase:

"Το δις εξαμαρτείν ουκ ανδρός σοφού"
"a wise man does not make the same mistake twice"
(Menandros, ancient Greek poet, 4th century B.C.)

In conclusion, Toyota achieved to create a revolutionary production system that allowed the company to enjoy a very successful era. They banished non-value adding activities from the process and developed a flexible production line that provided enormous variety of products. The whole philosophy that Toyota developed served as foundation for Lean Manufacturing.

2.1.2 Lean Manufacturing

Lean manufacturing originated around 1980. The traditional (or mass production system) had by then been transformed into a more efficient, responsive system, which became known as "lean production" (Womack et al., 1990; Gann, 1996)

After describing the successful example of the Toyota Production System, we will attempt to describe the broader implementation of lean thinking in the manufacturing field. The main goal of this chapter is to inform the reader about differences that exist between traditional practices and lean approaches. We consider this comparison very important in order to understand what exactly lean thinking tried to eliminate or alter in the traditional manufacturing procedure. A more detailed comparison will follow in chapter 2.1.3.

A list of five bullet points was developed to summarize those differences:

1. Manufacturing process as a whole
2. Inventories
3. Definition of efficiency
4. "Push" versus "Pull" Marketing Strategies

5. Relations with Customers and Suppliers

Manufacturing process as a whole

The lean approach tends to optimize the manufacturing process as a whole. It does not focus only on optimizing specific components of the process but the overall performance instead. Actually, it moves one step further and is not even restrained within the plant itself. The goal is to optimize everything starting before the actual manufacturing begins, working with material suppliers and all other kinds of companies cooperating with the plant. (Womack et al, 1996)

The key word that best describes this approach is “Transparency”. Lean thinking always aims at developing transparent relationships between all project stakeholders: Suppliers, employees and customers where everyone is aware of the process. (Koskela, 1992)

In contrast, traditional production methods view the process as individual components and believe that optimizing each one of those components separately will eventually lead to optimization of the whole process. (Koskela, 1992)

Definition of Efficiency

There are many kinds of “Efficiencies”. What we focus on this thesis is the “Economical Efficiency”. Economical efficiency refers to the use of resources so as to maximize the production of goods and services. (Sullivan and Sheffrin, 2003)

In other words, efficiency is a measure that shows of what share of a fee paid actually produces value-adding activities. For example, if a specific worker has an efficiency of 70%, this means that the salary paid to this worker contributes in 70% value-adding activities. If he/she is paid $100/hour, only $70 actually generates value. The remaining $30 is “waste”.

After defining what we consider efficiency for the purpose of this thesis, we can focus on how lean and traditional techniques differ based on their interpretations. Goldratt et al in their book “The goal: a process of ongoing improvement” present where misleading measurements exist within a traditionally managed manufacturing plant. (Goldratt et al, 1992) They present the case of a factory that fails to generate profits but the managing directors are unable to spot where the problems are located since their measures don’t show any.

More specifically, the indicators showed that employees and machinery are "efficient" because they were being kept busy all day. Lean thinking however, considers only value-adding activities in such indices and not the total amount of work. Interesting examples are mentioned which are summarized in the bullet points that follow in order to make clear to the reader the difference in overall philosophy:

1. The plant had large inventories. Either finished products or unfinished ones that were patiently waiting for either quality control or missing parts

2. The plant had purchased cutting-edge manufacturing machinery. In order to keep them "efficient" though, they were running all day producing in very fast rates, which led to the creation of large inventories as mentioned above.

3. The best way to demonstrate the difference in philosophy comes probably from page 42 where the manager of the plant notices 3 workers moving material from one side of the factory to the other and thinks: "I know it's probably something to keep them busy, but what the hell; at least those guys are working". The reader can probably see how the misunderstanding of efficiency is illustrated by the notion that "Busy people are value-adding people". On the other hand, according to lean thinking "a plant in which everyone is working all the time is inefficient".

4. The factory was facing late shipments. They were unable to ship their products on time for a number of reasons and were up to four months late in their deliveries.

It becomes apparent once again that in order to solve a problem, the first step is to accept that there is one. Measurements are a means to spot problems, based on a critical assumption: that the right indicators are measured. The second step is to define the critical issues correctly and apply appropriate solutions. The paragraphs above attempted to demonstrate to the reader the plausibility of a company failing to make profits and the measurements showing at the same time that everything works correctly.

Inventories

As described above, big inventories are considered a problem for lean manufacturing plants. They show lack of organization because products are finished earlier than they need to be. (Goldratt et al, 1992)

Reasons for which inventories are considered problematic are:

- Ergonomics. It is difficult to work in limited space if finished products occupy big areas within the plant.

- Rent costs. More space is needed in order to store products. The extra square foot requirements could be avoided by reducing inventories.

An effective solution to avoid large inventories is to supply materials just-in-time (JIT). The JIT system is flexible and delivers parts for the "next customer" neither early nor late but on time. (Koskela, 1992) As next customer, it is defined the next step in the manufacturing process till the end customer that is the person who actually buys the finished product. It is obvious though, that such a practice is not easy to develop and requires sophisticated analysis by the managing directors of the plant.

Another solution to the inventory problem -that if applied in tandem with JIT can lead to very successful production lines- is the "Pull Marketing Strategy". Lean manufacturing favors this marketing technique that is described thoroughly in the section to follow.

"Pull" and "Push" Marketing Strategies

As it has already been mentioned briefly, the Marketing Strategy selection is a major difference between traditional and lean systems. While traditional approaches have been using for years the "push" strategy in order to sell their products, Toyota and the subsequent lean manufacturing plants introduced an alternative way: the "Pull" system. (Womack et al 1990) But what is "push" and "pull"?

"Push Strategy": "A production and distribution strategy based upon forecasts rather than on specific demand." (Hinkelman and Putzi, 2005) Companies base their sales strategy on promotions and advertisements trying to persuade customers to buy their product. Push strategy may lead to creation of big inventories as production is based on forecasts that frequently turn out to be inaccurate.

"Pull Strategy": "A production and distribution strategy based on specific customer demand. In a pure pull strategy only goods and services actually ordered by customers are produced and shipped; there is no inventory of completed products." (Hinkelman and Putzi, 2005) In other words, companies let the customers pull the product rather than pushing it to them. Consequently, they do not need sales forecasts and they are able to respond to fluctuations in demand. Furthermore, producers do not need periodic discounts in order to get rid of inventory and products that no one wants as they simply produce what people really need. (Womack and Jones, 2003)

The figure that follows helps visualize the difference in these two techniques.

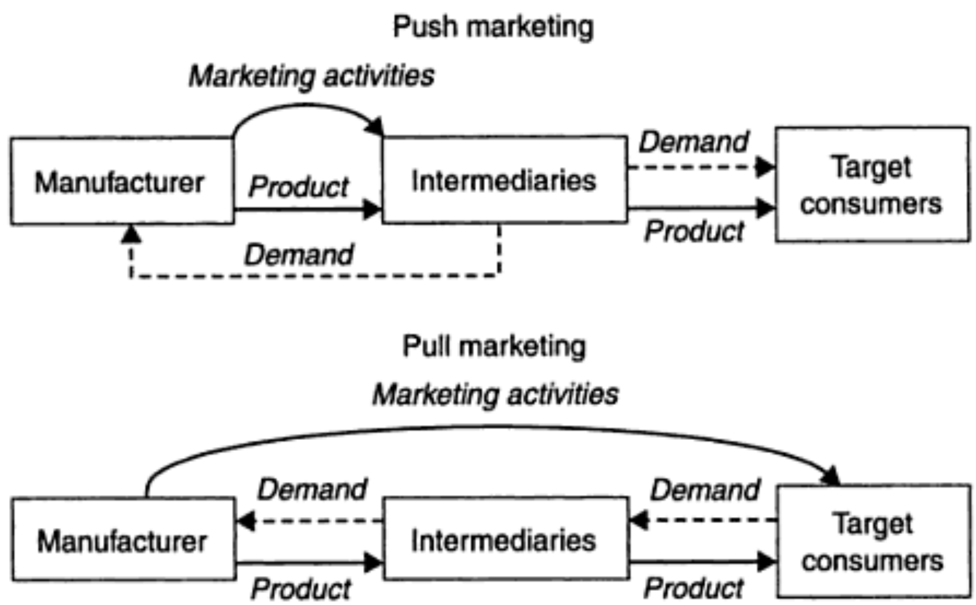


Figure 2.1-2: Pull versus Push Marketing Strategy (Dowling, 2004)

Relations with Employees, Customers and Suppliers

The relation between a company and its employees is a major factor for its success. What Toyota applied to their factories was an increased set of responsibilities assigned to each employee such that each one of them felt a real and important part of the company overall. Workers were allowed to stop the manufacturing line at any point and in addition to this they were given the opportunity to evaluate the performance of the factory overall. (Womack et al, 1990) They were able to make suggestions about potential improvements in the manufacturing process, a procedure that became known as "Quality Cycles". Furthermore, education, self-improvement of the employees and problem-solving became part of everyone's job. (Gann, 1996) Consequently, it's no surprise that the morale of employees was much better in Toyota factories compared to factories of the Western part of the world. (Womack et al, 1990)

Since lean philosophy is based upon the "pull" strategy, where consumers "pull" the products they want from the producers, the key objective of factories in Japan has been lifetime loyalty of customers. They aimed to build trust relationships with their customers so that they would be satisfied at all costs. In other words, companies aimed to maximize their profits in the long run. On the contrary, the "western system" was based on totally impersonal relationships and the traditional “push” strategy where producers “push” their products to customers by advertisements, discounts etc. (Womack et al, 1990)

Throughout the literature review the author discovered many interesting examples (coming again from Japan) that make clear how lean manufacturers approach customer relations. The salesperson of the company tries to build a strong bond with the clients and calls them to ask if everything is ok with the car they just bought, calls to ask when the family would need a new car, or even calls to say happy birthday. In addition, representatives of the firms visit houses to gather information and opinions about the needs of the customers in order to remain in direct contact with them. This strong bond leads customers to call their “trusted” salesman to order a new product when they desire so. (Womack et al, 1990)

The same philosophy is implemented in the relationship between factories and suppliers. A strong, lifelong relationship is the goal. Manufacturing plants work closely with their suppliers based on the principles of transparency. Business principals of the western world involve many areas that are considered “confidential” leading to companies not sharing information about their production process with their vendors and vice versa. Lean philosophy however, strongly believes that another type of relation must be created so that both of them can enjoy higher market share and profits.

A very interesting idea comes again from Japan where plants move to the opposite direction of financial principles expecting cost to fall over time rather than rise as it usually happens. A mutual agreement is made with the suppliers in order to achieve this goal and any cost savings beyond the agreed percentage goes to suppliers and not the assembler. In this way, vendors are given tremendous incentives to decrease their costs and cooperate with the manufacturer for a long time. In addition, a commitment to share bad moments is widespread. During recession periods, the assembler does not tend to draw all the activities within his plant, but does try to work with the supplier and expand to other business areas. (Womack et al, 1990)

2.1.3 Comparison between Lean and Traditional organization

All those concepts described above were part of the research of Womack, Jones, Ross and their big worldwide research presented in the book “The machine that changed the world”. (Womack et al, 1996) Students of Massachusetts Institute of Technology back in the day, they decided to go all around the world and conduct the biggest international survey ever undertaken at the automobile industry. Based on their work, we present differences between the two techniques in this section.

All the results their research presented were very useful to the manufacturing industry, but the author of this thesis considers most important the fact that they busted a well-established myth that claimed: "Speeding up requires more cost and effort". They demonstrated that good organization and lean thinking are the most powerful tools one has. Effort and cost rise only after one has reached the optimum level of this organization (if this can ever be achieved).

Their observations are summarized in the table that follows:

Table 2.1-1: Differences between lean and traditional organization (Womack et al, 1996)

Lean Organization	Traditional Organization
The aisles were empty	The aisles were full
There was a clear elimination of non-value adding activities	Many workers were non-value adding
No inventories	Big inventories
Any worker could stop the production line if needed. However, this was almost never needed because all the mistakes were already identified and solved.	Only senior managers could stop the production line. The production line needed to stop more frequently because problems were spotted in a much more frequent basis.
There was almost no rework area. Finished products were ready to be shipped	Finished products needed lots of rework before being ready for shipment
Minutes of inventory	Days of inventory (if not weeks)
High morale amongst the workers	Low morale amongst the workers
Lean is a "market price minus" system. The survey revealed that lean factories had around 300 suppliers (for example Nissan had only one supplier for passenger seats)	The traditional is a "supplier cost plus" system. The same survey revealed that traditional factories had 1000-2500 suppliers (for example GM had as many as 25 suppliers for passenger seats in some cases)

2.1.4 Lean Construction

Lean Construction is the application of lean thinking in the construction industry. It is an alternative way of project management that views the construction process as whole rather than as individual activities. It tends to involve all project stakeholders at an early stage in order for agreements about individual tasks to be reached in advance and in order for everyone to be fully informed about the process (transparency). The "Choosing by Advantages" methodology that is described in chapter 3 can be a useful tool to be used in this stage of lean planning.

Construction should be viewed as a series of flow processes, which are either conversion or waste. The goal, besides eliminating waste, is to make the conversion processes more efficient. The construction process is characterized by a big amount of non-value adding activities such as waiting, moving materials, demolition of existing structures, inspection, cleaning of waste, looking for equipment, storing inventory and so on. Those activities are not generally modeled in the traditional Critical Path Models because of three root causes (Koskela, 1992):

- Design. Non-value adding activities emerge when a task is divided in subtasks that need to be executed by different specialists. Waste and losses associated with design are sometimes more than the cost of the design phase itself.

- Ignorance. This is an administrative problem because the processes have not been designed appropriately. In addition, the share of non-value adding activities is not measured so there is no drive to eliminate them.

- Nature of production. Construction is viewed as a flow process and since work has to be moved from one conversion to the other defects might emerge or accidents might happen

Nevertheless, it is possible to drive improvements in the problematic areas of construction. Except for the major goal of reducing/eliminating non-value adding activities, there are principles which can lead to much improved results (Koskela, 1992):

1. Reduction of variability by standardization of activities. Variability is defined as any deviation from the original goals. It can be reduced by establishing a uniform approach throughout all projects; for instance in constructing concrete walls. In this way, it is more likely to achieve a consistent result across all projects.

2. Reduction of cycle time. Acceleration of the process that can be achieved through elimination of non-value adding activities. For example, the cycle time can be compressed by changing the plan layout in order to minimize moving distances for materials and people.

3. Increase of transparency. All workers of the project must be aware of the overall process. For example, it can be of major assistance to the project if the plumber is aware of the electrician's activities and tasks. They can more easily cooperate without creating problems to each other.

4. Simplification of the process by minimization of steps. Complexity increases cost. For instance, the more hand-offs bathroom construction requires the more coordination is needed. As coordination needs augment, more people are needed and it is only natural to notice increase in complexity and cost when more people are involved.

5. Focus on the complete process and not only on individual parts. By maximizing the value of individual components it does not mean that the overall value is maximized. The process must be viewed as a whole and components must be optimized having the overall improvement in mind. A good example follows in the next section describing how optimization of individual components does not necessarily lead to optimization of the overall result.

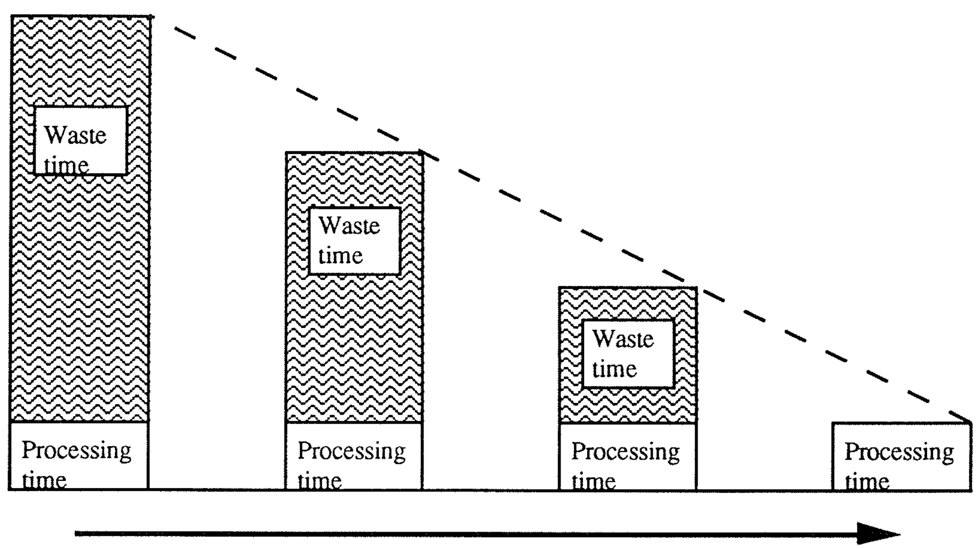


Figure 2.1-3: Eliminating waste overtime (Koskela, 1992)

Measurements

A key parameter in the correct application of Lean Construction is measuring some important values. Those measurements must be accurate, targeted appropriately and are needed mainly for two purposes: driving internal improvement in the company and comparing across projects and other companies. (Koskela, 1992)

There are four important factors that are important to measure during the construction process:

- Waste
- Value
- Cycle time
- Variability

Traditional measurements often fail to reveal problems because they are mainly focused on cost of productivity and do not attempt to understand the sources of indirect costs such as excessive focus on cost minimization during the procurement process. Such misjudgments may happen for instance during the procurement process, where the goal is usually to minimize cost of materials. As a result, cost is probably the only parameter considered when selecting a supplier. The problem can be described through the example that follows and is visually represented in figure 2.1.4.

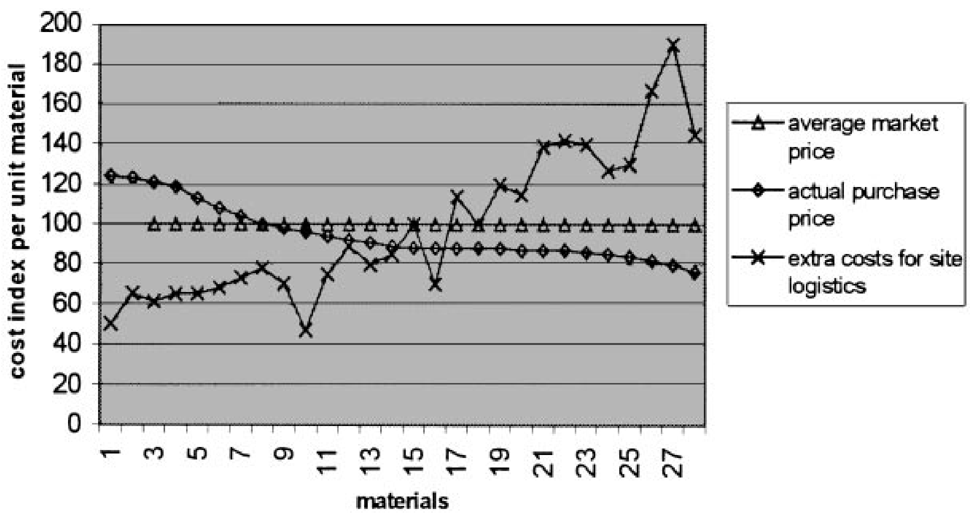


Figure 2.1-4: Example of increased costs for material 27 (Vrijhoef and Koskela, 2000)

Figure 2.1.4 shows that material 27 was ordered for a price 20% lower than the average market price, but the supplier delivered with no provision of the processes that would follow. We can see that the extra cost for site logistics was finally almost 140% more than the price paid for the material itself.

"The order for material 27 (sand-lime bricks) came on pallets that were far too large and heavy to get them with any ease all the way up using the elevator and through the building. In addition, the heavy weight of the pallets made it impossible to move the bricks around on the floors of the building. Therefore, one man had to spend approximately 50% of his time manually carrying the bricks across the floor to the location where the bricks had to be put in place." (Vrijhoef and Koskela, 2000)

We can see similar results for almost all materials that were ordered for a lower than the average market price. On the other hand, materials 1 to 7 that were ordered for a higher than the average market price required significantly smaller extra cost for site logistics. Consequently, it becomes apparent how important it is to consider the process as a whole and not only optimizing each component separately.

In addition, ordering for the lowest cost might show that the procurement personnel did their work correctly if the measurements used do not take into account the next step of the sequence. We can also see how "hidden costs" sometimes end up being bigger than the initial ones. (Hidden costs are presented in more depth in section 2.2.4)

Nevertheless, measurements in construction are not an easy task since it is difficult to collect data on site and construction is characterized by high level of uniqueness (no project is same as the previous one). Furthermore, since measurements are a non-value adding activity by themselves (following our definitions of value), they must be kept simple and transparent. A quick measurement that can provide a rough idea about a company's performance is benchmarking: Comparing one's performance against the best company in the particular area. (Koskela, 1992)

Lean thinking applied to construction

So far we have described the concepts of Lean Manufacturing and Lean Construction. However, the reader may imagine that manufacturing and construction are two fields that are not very closely related. So how can lean thinking be implemented in construction?

First of all, the overall philosophy remains the same. The goals are very similar in terms of organization and activities that must be eliminated. Both philosophies share same major goals like: elimination of waste by minimization of non-value adding activities, minimization of complexity, approach of the overall process as a whole, increase of transparency. In addition, nowadays both the manufacturing and the construction sector use advanced software to aid their process: Computer-integrated manufacturing techniques (CIM) and Building Information Modeling (BIM) respectively.

Nevertheless, there are certainly differences between the two sectors. For example construction is characterized by a high degree of uniqueness. It is not a repetitive product like in manufacturing plants. It is also not performed in the controlled environment of a manufacturing plant. In addition, construction is a more complex procedure with many different trades and higher number of people that need to be coordinated on a daily basis. Since lean thinking aims to eliminate complexity, construction seems to be a more difficult field overall.

However, construction industry has a way to combine both lean approaches by using prefabrication. Building projects that decide to use prefabrication allow for the components of the structure to be modularized. Those components can be constructed off-site using lean manufacturing principles while the on-site construction can proceed using lean construction principles. Building projects that serve as examples are presented in section 2.2.2.

Which technique is preferred

With so many advantages of lean thinking presented, why would people still use traditional techniques? Initially, lean thinking seemed counterintuitive. People were trained to manage either their manufacturing plant or their construction project in certain ways. Lean thinking introduced a new approach that was questioned for a long time. People in general, tend to have the need to see before they believe. Since results proved the effectiveness of the method, there was a shift in both industries (first in manufacturing and recently in construction).

Most manufacturing plants now operate implementing lean techniques. The construction sector was slower in implementing the respective methodology. Possible reasons for this could be the fact that it was developed more recently, or due to the complexities it carries.

However, in conversations with construction industry experts we learned that more and more projects demand the implementation of lean approaches, since owners saw the advantages lean can bring to their projects and demand it for their future ones.

Consequently, contractors educate their personnel in being able to deliver what the client requires.

2.1.5 Summary

In section 2.1, we described the history and philosophy of lean thinking. We presented in detail when and where it originated, how it was refined through the years, the important components it consists of and how it is applied for manufacturing and construction purposes. The goal of section 2.1 was to allow a smooth transition to the reader for the "Choosing by Advantages" technique that is based on lean principles and will be used in Chapter 3.

In addition, we attempted to investigate where costs that are difficult to identify ("hidden costs") might exist in building projects in order to present prefabrication principles in section 2.2 that follows. Advocates of prefabrication argue that it can significantly reduce the costs described. We attempt to investigate the validity of those arguments.

2.2 Prefabrication

Prefabrication has for a long time been viewed as one direction of progress. It is also referred as industrialization in a series of papers (Koskela, 1992). It is an appealing field for many companies, since it can potentially offer advantages like acceleration of the construction schedule, safer working environment, cost savings as presented in two example projects in section 2.2.2. This thesis attempts to quantify those potential advantages as well as gather thoughts and opinions from experts of the construction industry.

To begin with, there are countries that use prefabrication more than others based on availability of materials, design and structural considerations, demand from the buyers etc. Japan for example is a country where prefabrication of residential houses dominates. Even Toyota got involved in the housing industry trying to take advantage of the Toyota Production System (Gann, 1996) that we have already described in section 2.1.1. In addition, residential projects tend to use prefabricated parts on a more frequent basis. This thesis though, focuses on the commercial real estate market in the U.S. We try to evaluate the application of prefabrication in big commercial projects like hospitals, student dormitories, hotels, prisons etc.

What is most appealing about prefabrication however is that it combines both manufacturing and construction principles. According to the U.S. Economic Census (US

Census Bureau, 2004) activities performed on-site are considered “construction” while activities performed off-site are considered “manufacturing”. (Eastman and Sacks, 2008) As a result prefabrication can be connected with both components of lean thinking that were described in the previous chapter.

However, there are several differences between manufacturing in a typical plant and manufacturing components to be used in construction, mainly because:

1. Bigger parts are needed for construction (Gann, 1996)
2. Uniqueness/complexity/peculiarities in construction do not allow for a uniform approach to manufacturing
3. Construction needs more flexibility due to design preferences of the client, regulatory environments, local site conditions (Gann, 1996)
4. Construction needs more parts in assembly (200,000 versus 20,000) for a fully prefabricated house (Gann, 1996)
5. It is inevitable to have some works done on-site like foundations, steel erection, connections (Gann, 1996)

2.2.1 Potential areas and advantages of Prefabrication

In a commercial building project, not all activities can be moved off-site, but most components could potentially be prefabricated. Activities like foundation and basement construction, structural steel connections or composite slab construction are typical field works.

Components that are more frequently pre-constructed (if decided by the projects stakeholders) include:

- Curtain walls
- Structural Steel
- Concrete Walls
- MEP service racks
- Bathroom units

Curtain walls could probably be considered the component that contractors usually select to pre-construct. The author’s correspondence with major construction companies led to the conclusion that even companies which do not really attempt to push prefabrication for their projects, often select to pre-construct curtain walls in their big commercial building projects.

However, there are companies like SKANSKA, which try to push prefabrication to its currently assumed limits. A project that is presented in chapter 2.2.2 exemplifies the attempt of SKANSKA to modularize a whole 32-story building in downtown New York and is a very interesting application of the concept.

In general, prefabrication could lead to certain advantages. We summarize them in the following points. It must be noted though, that these represent only potential benefits and not advantages that one would notice universally throughout all projects.

- Off-site fabrication allows manufacturing technologies to be applied (Eastman and Sacks, 2008) and as a result, economies of scale are more likely to be developed. (Gann, 1996). Companies can enjoy the advantages of going through the learning curve, as the same activities need to be repeated many times. Workers can learn their specific tasks and become better and more efficient overtime.

- Waste reduction. On-site construction carries a certain amount of solid waste generation. It is widely accepted in the construction industry that prefabrication leads to significant reduction in solid waste. The factor is included in our case study with all construction industry experts accepting its validity.

- Time acceleration. Prefabrication can potentially lead to compressed construction schedule, which is a crucial advantage for any project. An example of accelerated project is the WT Barracks building, which is presented in section 2.2.2.

- Cost reduction. Prefabricated components can potentially lead to economical advantages if their cost is less than the cost of on-site construction.

- Quality enhancement. Quality is an important issue. Our correspondence with highly ranked professionals in the construction industry showed that it is widely accepted that prefabricated components offer enhanced quality. The overall quality though of the assembly needs further investigation. Quality is an important factor for our case study and is described in section 3.3.4.

- Safer work environment. Another advantage that most people of the construction industry agree on. Prefabrication is performed in controlled working conditions, which leads to less dangers for construction personnel.

- Easier to attract workers and decrease labor cost. Construction workers perform difficult tasks often in adverse conditions. Workers in prefabrication facilities on the other hand, enjoy better working conditions in the controlled environment we already mentioned. As a result, it is easier to find laborers willing to work in a construction factory.

- Better supervision. (Tam et al, 2006) The controlled activities performed in a prefabrication factory that usually approach a manufacturing plant offer easier supervision. Especially when lean techniques are used, the advantages are prominent, as it has already been described in section 2.1.

Among the potential disadvantages we could consider:

- Inflexible design. (Tam et al, 2006) The design needs to freeze early. Architects and owners cannot change their minds late in the process, which is considered an advantage for contractors though.

- Higher initial costs. (Tam et al, 2006) The whole project development phase is shifted towards the start of the project. Many people need to be involved at an early stage. For example, in the case that components are ordered from a third party, extra care must be taken to make sure that the supplier chosen is reliable and can meet schedule and quality requirements. Again, this might actually be considered an advantage for some people depending on how they want to manage their project.

- Aesthetically monotone. (Tam et al, 2006) Prefabrication factories might have a certain flexibility concerning components they can construct. On-site construction on the other hand, is clearly more flexible. Almost anything can be constructed on-site in contrast with a prefabrication plant, where the design is more restricted.

- Increased space requirements for lifting prefabricated components into place. Prefabricated components could potentially require more space for installation. Especially within big cities, this issue might be quite important.

2.2.2 Examples of Prefabrication Projects

This section presents two projects that have decided to use prefabrication for their construction alongside with lean approaches:

- The Atlantic Yards B2 in New York, a fully modularized building that will give the chance to the reader to see where the industry is going, since this project was started in December of 2012 and will be completed in the summer of 2014.

- The Warriors in Transition (WT) Barracks that presents how prefabrication in tandem with lean construction helped accelerate the project.

Atlantis Yard B2 (New York)

The Atlantic Yards B2 is an $117M building project located in downtown New York. It is developed by Forest City Ratner Companies (FCRC), designed by architects from SHoP and engineers from Arup and constructed by SKANSKA. It introduces a high degree of innovation in the building industry, as it will be the tallest modular building in New York City. Atlantic Yards B2 consists of 32 stories and an area of 348,000sf. The project is expected to achieve LEED® Silver certification. (SKANSKA, 2013)

Figure 2.2-1: The Atlantic Yards B2 (SHoP architects) (Skanska, 2013)

The building consists of 930 modular units. Union workers are trained to construct with lean manufacturing techniques so that they can work in the off-site warehouse that has been established for those units. The project introduces a great deal of advantages like: (SKANSKA, 2013)

- Significant reduction in truck traffic, noise and dust
- Generation of 70 to 90% less waste
- Safer working environment. The construction method reduces (or eliminates) working at heights
- Removes environmental factors. Construction can move unobstructed in the warehouse regardless of weather conditions

WT Barracks (Fort Carson, Colorado)

The second project is a building, which was developed to provide shelter for wounded warriors and help towards their rehabilitation. It was a Design-Build contract awarded to Mortenson Construction. It is a 4-story building with 96,400 square feet and 160 beds. Owner of this project is the US Army Corps of Engineers.

The project faced strict time constraints. It was necessary to be completed quickly due to a high number of waiting soldiers. The existing facilities could not meet the demand and as a result, warriors were staying in hotels, which was creating two major problems: increased costs for their stay and incorrect implementation of their transition program. Mortenson Construction decided to use Virtual Design and Construction (VDC) alongside with Building information Modeling (BIM) and prefabricated parts for: Load Bearing Precast Wall Panels, Roof Truss and Deck Sections and Pre-fabricated Modular Bathrooms. (Mortenson Construction, 2011)

Figure 2.2-2: Prefabricated roof truss installation (Mortenson Construction, 2011)

Figure 2.2-3: Precast load bearing wall panels (Mortenson Construction, 2011)

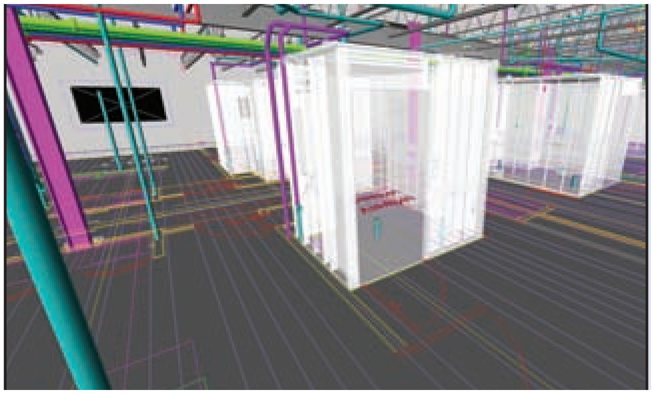


Figure 2.2-4 Building model with bathroom pods (Mortenson Construction, 2011)

Figure 2.2-5: Pod installation (Mortenson Construction, 2011)

Mortenson Construction reported a great deal of benefits they saw by using the approach described above: (Mortenson Construction, 2011)

- The design process was completed in 4 ½ months instead of 6-7 months that would be needed in a more standard design frame

- The building was fully enclosed with all the bathrooms installed 5 months after foundations were started. A typical project would require 7-8 months for the same activities
- The overall project (design and construction) was completed in 15 ½ months resulting in 2 ½ time savings (The RFP set 18 months as the upper limit in completion)
- General conditions' costs were saved by not having to enclose and heat for winter masonry work. This was achieved because the design phase was reduced and the project was able to start in August instead of October-November.
- Quality was enhanced. Mortenson reports enhanced quality both in bathrooms and precast masonry work that derives from the controlled working environment in the prefabrication plants. In addition, the amount of punch list items and the time needed to complete them was halved.
- Only one minor injury occurred during the project. The off-site activities increased overall safety.
- Waste was reduced significantly, which helped avoid non-value adding activities such as removing debris

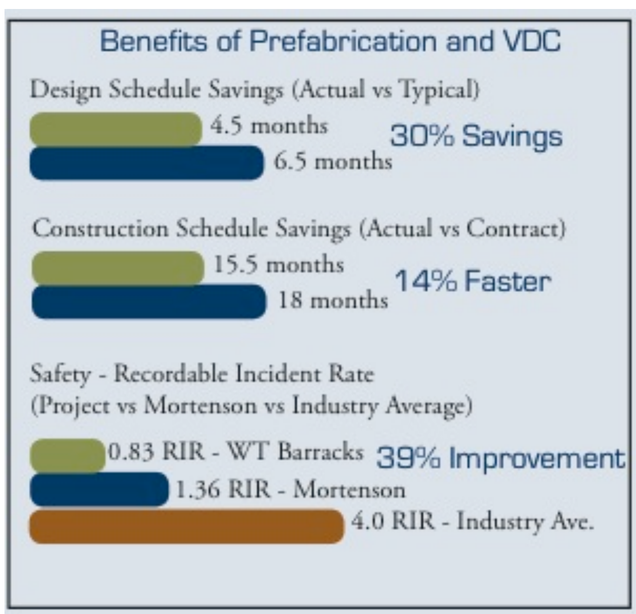


Figure 2.2-6: Summary of 3 important benefits (Mortenson Construction, 2011)

The Atlantic Yards B2 project was presented in order to give an idea to the reader about the latest attempts in the field. This fully modularized building tries to revolutionize the industry by breaking down the structure to a series of components that will be prefabricated off-site and assembled in the field. At the same time, it provides a great opportunity to connect all the concepts we have already talked about. Lean construction, lean manufacturing, prefabrication are all used in one project. The results will be shown in the summer of 2014.

The WT Barracks case offered a good example of a successful implementation of prefabrication in a project. The construction company (Mortenson Construction) aimed to accelerate the process and achieved it. They also reported significant benefits in several other areas, which demonstrates that the advantages we have already discussed are feasible. Since the information for both projects was taken by the companies' websites, we are not aware about any limitations and problems this solution resulted to. Usually such information is considered confidential, since people tend to speak openly about their successes but not their failures.

2.2.3 Why the hesitation towards Prefabrication

Professionals were similarly hesitant towards prefabrication as they were towards lean construction, but we now clearly see a big shift in the industry. Many big building projects require lean approaches in their development. The same path might be followed by prefabrication. Extensive research in the field can potentially lead to a better understanding of the components influencing decisions and reveal possible advantages. But why do people seem hesitant? The following bullet points summarize six major reasons:

- Components that can be prefabricated are usually not on the critical path
- Risk aversion
- Prefabrication is a process that can show results in the long term since companies need to go through the "learning curve"
- Strong unions opposition
- Cost
- Lack of experience and research in the area

During this research, the author had the chance to talk with many major construction companies of the United States and attempted to understand their approach to this matter. It became quite clear that no one seemed to be strongly opposed to prefabrication. They all agreed on some fundamental benefits of the solution. Factors like time, quality, efficiency and waste reduction seemed to be objectively enhanced by prefabrication.

To be more exact, all of them agreed that pre-constructing the parts by themselves is faster. They did not all agree that the overall construction time of the project could be decreased though.

The argument against prefabricating bathroom units for example was that since they may not be on the critical path, their acceleration may not help accelerate the project delivery overall. On some projects, the facilitation of access for the prefabricated units into the building can delay the construction of other elements (e.g. size of the prefab unit may cause wall leave outs or widened corridors in order to transport the units into their final location(s)). (Chase, 2013) Nevertheless, contractors who usually select to prefabricate such components believe that time savings happen because the rest of the structure is accelerated based on better organization.

In addition, while quality of individual components is increased, it is questionable whether overall quality is enhanced as well (Chase, 2013). For instance, bathroom units would definitely be better in terms of their finishes but the overall robustness of the assembly might be worse than constructing them traditionally. Contractors in favor of bathroom prefabrication on the other hand, appeared reassured that overall robustness is not affected.

Furthermore, one of the major concepts of economic theory is that “people are risk averse”. When a company has not attempted to prefabricate, it seems natural to be more conservative. “People need to see the results prefabrication can bring before believing in it”, as suggested by a construction industry professional we corresponded with for our analysis. Lack of research in the area only aggravates the issue.

Our research attempts to fill this gap. We aim to identify all value adding components that influence the decision-making process of prefabricating or not. In this way, broader problems could potentially be addressed using the same approach. Furthermore, it would be great if we could inspire more people to get involved in the area and help the construction industry understand in depth how to make as accurate decisions as possible.

The above arguments coupled with the “learning curve” that each company must go through in order to master new techniques provide good reasons for hesitating. Prefabrication is a process that is difficult to show results in the short term. Companies need to attempt and be patient. For instance, SKANSKA went down this path and gradually started to see benefits. From project to project they were getting better and kept pushing the limit even further as we have already presented with the Atlantic Yards B2 building.

Furthermore, political considerations are often an obstacle that proves very difficult to overcome. There are states in which Labor Unions are extremely powerful and play a major role in such decisions. If their benefits are harmed, the prefabrication option loses ground. Discussions with contractors revealed this issue, which can cause additional problems in the construction industry and adversely affect innovation in this sector. Many contractors mentioned schedule delays caused by such factors. For instance, a project built by a major construction company in the Boston area was delayed 2 years in order to negotiate all relevant issues with the Unions.

Lastly, cost is obviously a very significant factor to consider. The author's personal correspondence with construction industry executives, whose companies do not tend to pursue prefabrication, shows that they do not see benefits based on their cost analysis. The following section attempts to shed some light in the cost analysis area of construction companies and investigate whether all the important factors are taken into account.

2.2.4 "Hidden" Costs

As mentioned, cost analysis leads many construction companies to discard the prefabrication solution. However, contractors who are either pre-constructing themselves or ordering from a third party as well as companies, which construct prefabricated components seem to disagree. Their main argument is that those contractors fail to incorporate in their cost analysis factors of indirect costs for the on-site construction process.

This thesis attempts to investigate where these costs might be located. We name them "hidden costs" and we define them as "all kinds of costs that are hard to identify and quantify". There is no such thing as "hidden cost" though in its literal meaning, as there is similarly no "side effect". People tend to name their mistakes using words that can hide their inability to see problems in advance. Every action has consequences, either good or bad. "Side effects" are nothing more than negative consequences of an action intended to do good. In the same sense, "hidden costs" are unaccounted negative cash flows not because they are hidden, but because one fails to predict them. It is a problem frequently encountered in construction companies and we have established four broad areas that such costs might appear during the construction process:

- Coordination
- Safety
- Material Procurement

- Aging workforce

Cost associated with coordination

Cost estimation is a rather complicated practice in general. Most contractors try to have well educated people in such positions in order to perform those tasks. The simplest way to run a cost estimation is to calculate how much time a task requires, calculate the labor cost based on hourly salaries, find the quantities of materials and calculate their prices.

But what about time spent from all those different people in order to coordinate the process? There are people involved in ordering material, managing the project in general, supervising the construction process, measuring and so on. There are factors that are hard to quantify like:

- How many people are involved in coordinating
- How much time each one spends
- How much money does coordinating cost overall

Based on our interviews with several people within construction companies and our research about cost estimations for specific projects, we encountered significant discrepancies. More specifically, in a big building project where two major construction firms provided cost estimations we discovered that contractor A calculated the cost of one bathroom unit (constructed on-site) to be $12,000 while Contractor B calculated the cost of the same bathroom to be $9,000.

The purpose of this thesis is not to argue about which one was right, we simply try to point out factors that might lead to erroneous decisions. It is hard to imagine how such a big difference might have occurred. However, there are people with their opinion on the matter: "Contractor B has obviously failed to calculate coordination costs in addition with the decreased efficiency that on-site construction carries." (Seery, 2013)

We have already described what we define as efficiency in chapter 2.1.2. Economical efficiency refers to the use of resources so as to maximize the production of goods and services. (Sullivan and Sheffrin. 2003) Efficiency for on-site construction is estimated to be around 43%. Most people the author interacted with agreed with this number. Consequently, if one fails to incorporate this number in his/her analysis, erroneous results are likely to appear.

In conclusion, Contractor B was selected for the project and decided to construct the bathrooms on-site. Based on their estimation, ordering the bathrooms from a third party prefabricator was not beneficial since the offer was in the range of $12,000 per unit ($3,000 more than their cost estimation for constructing it on-site). However, since such data is considered confidential the author was unable to further investigate which contractor was right in their estimation.

In fact, we don't even know if contractor B ran a post analysis to determine if the initial estimation was right. "Professionals are not capturing their cost and schedule data which would allow them to make informed decisions in the future." (Olsen and Ralston, 2013) We can easily imagine that if such a measurement is absent, the problems (if any) associated with cost estimation are very hard to identify.

Cost associated with Safety considerations

The second identified component for hidden costs is associated with safety. Construction companies are required to insure their projects. The premiums paid to insurance companies are closely coupled with the performance of the company in terms of accident prevention. As a result, a company that demonstrates a low number of accidents is considered less risky and is charged a smaller fee than another company more prone to accidents during construction.

The way insurance companies measure this risk is mostly based on the Experienced Modified Rate (EMR) index. The lower the EMR of a company the lower the insurance premiums they pay. An EMR of 1.0 is considered the industry average. An EMR of more than 1.0 means that there has been a claim for compensating a worker due to an accident. An EMR of 1.10 for example means that this contractor needs to pay 10% more than the average company of the industry. The EMR index sticks with a company for 3 years and consequently, generates negative cash flows in case there have been accidents. (Safety Management Group, 2013)

How does it affect our analysis though? It is apparent that companies, which decide to construct on-site take on more risk than the ones deciding to assign the construction to a fabricator. Even if contractors are very confident about their safety measures, construction is a risky business, where unexpected accidents are always a possibility regardless of precautions. However, this reduced risk is hard -if not impossible- to quantify. It is very hard to conclude for example that by assigning bathrooms' construction to a third party, the company saves $100 per unit based on reduced risk associated with safety. Nevertheless, it is a factor that contractors could consider in their cost analysis.

Cost associated with aging workforce

Cost associated with aging workforce is a problem we discovered as were talking with people involved with prefabrication. While laborers get older and retire, younger generations show very limited interest in replacing them and work for the construction industry. As a result, locating workers willing to work on-site might become a challenge for construction companies in the years to come. It is easily understood, that adverse weather conditions and safety hazards are deterrent parameters.

Consequently, cost increases. Construction companies need to offer higher hourly salaries in order to attract people in the work. On the other hand, prefabrication factories or warehouses offer much better working conditions: Enclosed space that is not affected by weather conditions, controlled temperatures, very good lighting of the area, safer conditions and better ergonomics overall. As a result, locating workers for such activities is not as arduous and the salaries offered can be lower.

In conclusion, since this factor is more likely to affect the industry in the years to come, companies might enjoy benefits by shielding themselves against such issues. Even if their cost analysis shows that constructing on-site is more beneficial, they might need to consider that in the long term, training their staff in prefabrication and manufacturing principles might lead in cost savings overtime.

Cost associated with material procurement

As we have already mentioned, the most simplistic cost estimation concerning materials can be done by determining necessary quantities and calculating the minimum amount of money required to obtain them. When a comparison needs to be made between on-site construction versus prefabrication, factors like the ones described in section 2.1.4 can play a major role. The example used about materials ordered for a low price, which resulted in 140% increased cost due to lack of provisions is probably a very good way to describe the problem. The hidden cost in this case was the fact that the workers needed to transport these materials spending their hours on non-value adding activities.

In conclusion, the overall goal should be kept in mind with provisions about the next steps in the process. In order to compare two material offers for instance, it’s erroneous to blindly pick the lowest without investigating the issue in depth. Similarly, prefabricated components might appear more expensive in many cases, but estimators should make sure they have investigated all other factors that influence the cost of on-site construction.

Impact of our research on the area

In our research, as already mentioned, we attempt to identify all components that need to be accounted for a decision. By that, we include factors containing parts of the "hidden costs" described above. Of course, factors like the coordination cost are not accurately defined, since this would be a research field by itself. However, we include safety parameters in our case study for instance, by accounting the number of steps that include dangerous activities. In this way, companies could get a sense of the risk they undertake in each option. In any case though, the sections above attempted to summarize factors that might be "hidden" in a cost analysis. Accurate definition could be a tedious process and is not the goal of this thesis.

2.2.5 Summary

Section 2.2 attempted to present where the construction industry stands nowadays towards prefabrication. Potential advantages and disadvantages were presented as well as components of buildings that are most commonly selected to fabricate off-site. Two interesting projects were also described to offer the reader the opportunity to see practical implementations.

In our opinion, great interest is developed in the field and we are likely to see prefabrication boosting up in the years to come. Companies like SKANSKA have been pursuing this option for quite a long time and have started enjoying the benefits of their investment. Furthermore, even construction companies that have not attempted to walk down this path seem to acknowledge certain benefits of prefabricating certain components. Example reasons for which people are hesitant against prefabrication were presented in section 2.2.3 in an attempt to investigate the thought process of people involved in the industry.

Finally, factors that could affect cost estimation and result in incorrect comparisons between on-site construction versus prefabrication were examined in section 2.2.4 and will be examined further in the next chapter. The major goal of this thesis is to help people of the industry understand all value adding components and create a tool useful in the decision-making process.

We have established many attributes, advantages, disadvantages and limitations of prefabrication, however the big question remains: “How does one decide whether or not to use it in a project?” This is the question that the next chapters attempt to answer by using the decision-making tool we have already briefly mentioned, the “Choosing by Advantages” methodology.

3 The “Choosing by Advantages” method of decision-making

The Choosing by advantages (CBA) is a decision-making methodology created by Jim Suhr. It serves the purpose of helping people reach objective decisions when having to compare mutually exclusive solutions. It is considered an important tool because “people suffer the consequences of unsound decisions. They mask the causes by attributing them to human imperfection, natural probability or uncontrollable events.” (Koga, 2008) CBA introduces a new idea that can potentially lead (if used correctly and objectively) to better (if not optimal) decisions.

The broad question this thesis tries to answer is “How does one decide whether or not to use prefabrication in a project?” However, we focus on a smaller question for the purpose of this research which is “How does one decide whether to use prefabricated bathrooms in a project or not?” To tackle the problem, we have created a case study based on the “Choosing by Advantages” methodology considering three alternatives:

1. On-site construction
2. Prefabrication in a warehouse adjacent to the job site
3. Prefabrication in a factory.

The CBA tool has its own nomenclature, which is very important to be described to the reader so that he/she understands what those words mean in our analysis. The definitions of five important words follow:

“Alternative is a possible decision.” (Parish and Tommelein, 2009) The purpose of CBA is help in deciding between a certain amount of mutually exclusive choices. Those choices considered are the alternatives.

“Factor is a container for criteria, attributes, advantages, importance and other types of data” (Suhr, 1999). In every CBA analysis, it is important to carefully select and define all possible factors that play a role to the decision. Failure in doing so will result in a non-optimal decision.

“Criterion is a decision rule or guideline established by the decision-maker.” (Parish and Tommelein, 2009). In other words, each CBA analysis needs to set a goal for each factor. The person responsible for setting those goals (criteria) is the decision-maker.

“Attribute is a characteristic, quality or consequence of one alternative.” (Parish and Tommelein, 2009). Each factor has a characteristic for each alternative, which is called attribute.

“**Advantage** is a beneficial difference between two and only two attributes.” (Parish and Tommelein, 2009). It is very important to mention that: “Decisions must be based on the importance of advantages and not their quantity” (Koga, 2008)

It must be also noted that cost is not considered a criterion for the CBA method because it is treated separately. For example, there is no factor asking which alternative is cheaper. The goal is to identify the best alternative without considering initially their cost. The cost component could be addressed either before or after the CBA method. Two ways to deal with the problem are suggested by the author:

1. Address the cost of each alternative in advance. Alternatives that pass the defined cost limits are incorporated to the CBA for evaluation. In that case, the alternative with the biggest score is the one that should be selected since the cost factor was addressed in advance.

2. Run the CBA analysis with all possible alternatives. Scale the scores of all those alternatives and run a cost analysis. If the alternative with the biggest score passes the “cost control test”, it should be selected. If it does not, check the second best and so on until you find a solution that satisfies both CBA and cost criteria.

The Tabular Method of CBA (that is going to be used in this thesis) can be summarized in 5 steps:

1. Identification of factors. Careful consideration from the users of the method is needed in order to include in the analysis all factors affecting the process. This is the most crucial step by far.

2. Identification of criteria for each factor. The user must decide on the limits he/she would like to set for the factor’s characteristics.

3. Identification of the attributes of each alternative. A rather simple process, where the user would just need to figure out the characteristics of the alternatives for each factor.

4. Determination of the advantages of each alternative for each factor. The user should compare each alternative with the criteria set and always compare only two alternatives at a time. The “weakest” alternative must be identified (which

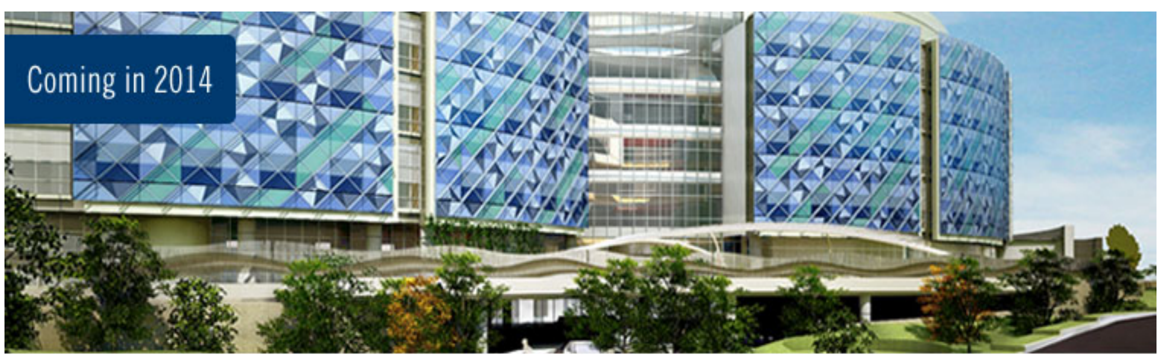
will have zero advantage apparently) and then the other alternatives must be compared with it in order to identify their advantages.

5. Assignment of degree of importance to each alternative. This step includes the opinion on the advantages. It is time for evaluation of those advantages in order to identify which ones are considered more important.

6. Selection of the alternative with the bigger score after summing up all degrees of importance for each alternative. The user should simply sum the grades and see which option is more beneficial to use.

For more information regarding the Choosing by advantages method, see the works of Jim Shur (1999), John Koga (2008), Parish and Tommelein (2007 and 2009) and Arroyo et al (2009).

3.1 Case Study: Expansion of Alfred I. duPont Hospital for Children (AIDHC)



General Project Information

- 192-bed expansion to the existing Alfred I. duPont Hospital for Children (AIDHC)
- Location: Wilmington, Delaware
- Owner: Nemours
- Estimated cost: $220M
- 425,000sf

(SKANSKA, 2013)

The expansion of Alfred I. DuPont hospital is a building project that is being constructed at the moment in Wilmington, Delaware. It is expected to be completed in the summer of 2014. “The first floor of the building will contain a new emergency department, atrium, and retail and dining facility. The second through fifth floors each contain two wings of 24 inpatient beds. The second floor contains 32 beds of critical care PICU beds and 16 beds of step-down and med-surg beds. The new building is connected to the existing facility with a three-story connecting link.” (SKANSKA, 2013)

It was considered suitable for our research because of the big number of bathroom facilities it contains. 144 new bathrooms will have to be constructed and the question we try to answer seems quite reasonable: “How does one decide whether or not to prefabricate those bathroom units?”

Figure 3.1-1: Expansion of Alfred I. duPont Hospital for Children

3.2 The "Choosing by Advantaged" for our case study.

The CBA we created for our case study is described in the figure that follows

		Alternative 1		Alternative 2		Alternative 3	
	Factors	On-site construction		Prefabrication adjacent to the worksite		Prefabrication in a factory. (Order from a 3rd party)	
1	Number of material suppliers						
Criteria	fewer is better						
Attribute		15		15		1	
Advantage		No advantage	0	No advantage	0	14 less	
2	Location of suppliers						
Criteria	closer is better						
Attribute		Within 100 miles		Within 100 miles		350 miles away	
Advantage		250 miles closer		250 miles closer		No advantage	0
3	Delivery time of raw materials						
Criteria	faster is better						
Attribute		20 days		20 days		1 day shipment	
Advantage		No advantage	0	No advantage	0	Not comparable	0
4	Reliability						
Criteria	Perfectly Reliable						
Attribute		YES		YES		YES	
Advantage		No advantage	0	No advantage	0	No advantage	0
5	Accessibility						
Criteria	Perfectly accessible						
Attribute		Perfectly accessible		Perfectly accessible		Perfectly accessible	
Advantage		No advantage	0	No advantage	0	No advantage	0
6	Local labor cost						
Criteria	Less is better						
Attribute		$65/hour		$65/hour		$35/hour	
Advantage		No advantage	0	No advantage	0	$30/hour less	
7	Factor: Time to install 4 bathroom units						
Criteria	Less days is better						
Attribute		33 days		28 days		20 days	
Advantage		No advantage	0	5 days less		13 days less	
8	Overall Quality: Robustness						
Criteria	Perfectly Robust						
Attribute		Perfectly Robust		Potentially a bit less robust		Potentially a bit less robust	
Advantage		Satisfies criteria		Potential disadvantage		Potential disadvantage	
9	Quality of floor Slopes to allow for proper draining						
Criteria	Perfect slopes according to designs						
Attribute		Subject to worksite uncertainty		Subject to worksite uncertainty		Perfectly constructed	
Advantage		Potential disadvantage		Potential disadvantage		Satisfies criteria	

10	Quality of Finishes						
Criteria	Perfect finishes						
Attribute		Less consistent		Consistent quality		Consistent quality	
Advantage		Potential disadvantage		Satisfies criteria		Satisfies criteria	
11	Number of layouts and units per layout						
Criteria	More identical units is better. More than 80 is required to consider prefabricating						
Attribute		Not comparable		144 units/102 in the same group and the rest divided in 8 more groups. **All will be prefabricated**		144 units/102 in the same group and the rest divided in 8 more groups. 102 will be prefabricated and **the rest will be stick built**	
Advantage		No advantage	0	22 identical units more than the minimum requirement of 80		22 identical units more than the minimum requirement of 80	
12	Safety considerations: Percentage of work steps done above-head or in dim lighting						
Criteria	Less than 15% of total activities						
Attribute		15%		0%		0%	
Advantage		0	0	15% less "risky" activities		15% less "risky" activities	
13	Coordination time						
Criteria	Less time is better						
Attribute		12 people on site, 8 in the office		12 people on site, 8 in the office		Unable to quantify	
Advantage		Not comparable	0	Not comparable	0	Not comparable	0
14	Overall construction time						
Criteria	faster is better						
Attribute		33		31		31	
Advantage		0		2		2	
15	Efficiency						
Criteria	Achieve efficiency of at least 43%						
Attribute		43%		65%		75%	
Advantage		No advantage	0	22% more efficient		32% more efficient	
16	Design Flexibility						
Criteria	Allow for changes at a later stage						
Attribute		The design can be modified even at a late stage but with schedule delays		No flexibility for late changes. The design needs to freeze early		No flexibility for late changes. The design needs to freeze early	
Advantage		Satisfies criteria		No advantage	0	No advantage	0
17	Environment impact: Solid waste generation						
Criteria	Less waste generation is better						
Attribute		Generates a certain amount of waste		Generates less waste		Generates less waste	
Advantage		No advantage	0	less waste		less waste	

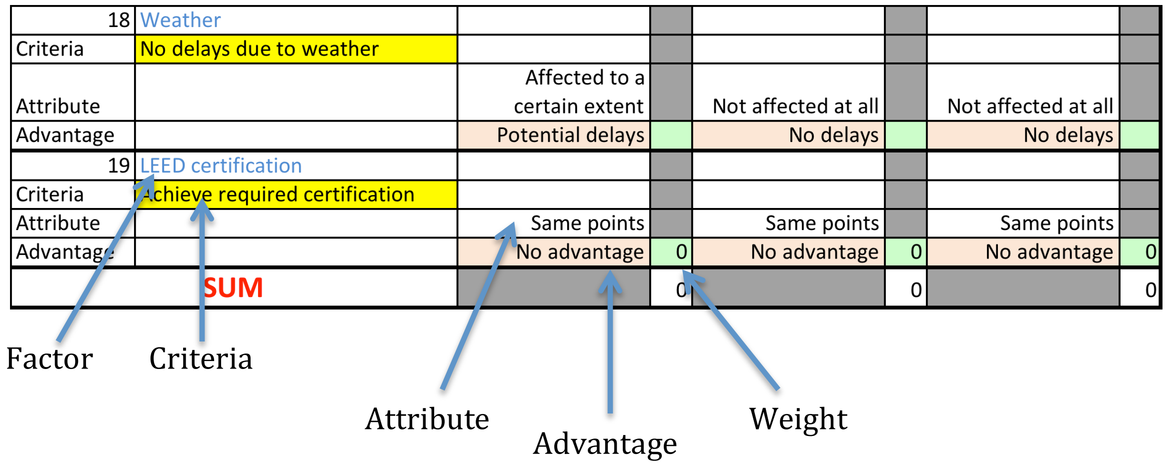


Figure 3.2-1: The "Choosing by Advantages" methodology for our case study

- 19 factors were established and are the ones with blue color.
- The cells filled with yellow contain the criteria set for each factor.
- The cells filled with light red contain the advantages of each factor. The attributes of each alternative are located right above them.
- The cells containing weight (with green color) are the ones experts from the construction industry were called to complete. Some boxes already have a zero (0) in them, since they have no advantage compared to the others. As we will see though, some experts disagreed with some qualitative advantages (concerning quality for example) and decided to modify them. They were given the freedom to modify anything they wanted in the case, because we wanted to see their opinions. They were also urged to leave comments on anything they considered necessary. We present their comments/observations in chapter 4.
- The instructions given to people filling the method were quite simple to follow. First, they should scan the case reading all advantages established to see if they agree with them. They could reverse advantages and make modifications if considered necessary. Then, they should locate the most crucial advantage of the whole case in their opinion and assign their biggest grade (we suggested to use 100, but some decided to assign less than 100). After that, they should scale their opinion on the other advantages proportionally. An important advantage would need a big grade, an unimportant a small grade and so on.
- Finally, the last line contains the sum, which is zero initially since no opinion is provided by us. The alternative with the biggest score represents the chosen one.
- Factors 3 (Delivery time of raw materials), 4 (Reliability), 5 (Accessibility), 13 (Coordination time) and 19 (LEED certification) are either not comparable or

identical. As a result, no alternative of those factors influences the decision-making process. Consequently, they will not be shown in our results, since they cannot change the final decision. However, they are included in the table because the can definitely play a role in other cases.

3.2.1 What we expect to see in the results

- The factors established and the characteristics of their alternatives point towards selecting one of the prefabrication options. Consequently, the first thing we expect is see people selecting one of them. It is important to repeat that those results apply only to this case and not universally to all building projects

- Secondly, we expect to see more people selecting prefabrication in factory because some of its advantages appear stronger compared to on-site prefabrication. The labor cost factor for example, or the installation time are expected to attract high rating.

- We are interested to see if people usually using on-site construction for their projects will find a way to support their opinion through this case. Since only factor 2 (Location of suppliers), 8 (Robustness) and 16 (Design flexibility) are “offering” advantages to on-site construction, it seems hard to scale the answers in favor of on-site construction. As we will see in chapter 4, no one finally selected it.

- The author expects to see factor 14 (overall construction time) receiving very high scores from all experts for reasons that will be explained in section 3.3.2. At least this is where he would give 100 if he completed the case study himself. As we will see though, many experts rated relatively low this factor.

- We expect architects and owners to rate very highly the design flexibility that on-site construction allows. However, it is not always the case, as we will see.

- We are very interested to see the evaluation of factors concerning quality (8,9,10). Since they are qualitative, people completing the case are free to modify the advantages and even reverse them if they disagree with our initial considerations (which happened for some of them indeed).

3.3 Factors

The problem this thesis tries to address is “how does one decide whether or not to use prefabricated bathrooms in a project”. To approach the problem with the CBA methodology a long and iterative process was conducted. 19 factors were established that contain almost all the important information needed in order to decide weather to select or not the prefabrication option. Experts decide how important those factors are considered for the final decision. For easier presentation to the reader, the factors are fitted in six categories that are described below in detail:

Categories of factors

1. Location/Transportation
2. Time considerations
3. Quality
4. Safety
5. Weather/Environment
6. Overall project characteristics

In the description that follows, we refer to:

- On-site Construction as "On-site"
- Prefabrication at the worksite as "Site prefab"
- Prefabrication at a factory as "Factory prefab"

3.3.1 Location/Transportation

Location and transportation factors play a critical role in the decision of using or not prefabricated parts. The factors that lie in this category are:

a. Number of material suppliers
b. Location of suppliers
c. Delivery time
d. Reliability of suppliers
e. Accessibility of the worksite
f. Local labor cost

A detailed description of each factor follows.

Number of material suppliers

The number of material suppliers is a factor related to the coordination of a project. A project's complexity is more likely to increase when more people are involved. A small number of vendors can provide easier procurement tasks for the contractor's personnel. A big number on the other hand, would increase those tasks and the coordination required in order to make sure that all materials arrive at the worksite on time. Certainly, reliability and distance are correlated in this problem as well. The number considered in this factor affects both “on-site” and “site prefab” in the same way.

On the other hand, ordering the bathroom units ready from a third party requires only one supplier: the factory that fabricates them. Consequently, coordination might not be as high as before. However, the project stakeholders must make sure in that case that the construction proceeds as planned, quality is acceptable, deliveries are made on time and so on. Coordination time is a factor that is generally difficult to quantify. It is potentially reduced since less people are involved but since the tasks of coordination alter, we cannot argue if they require less time or not.

In our case, “on-site” and “site prefab” would require 15 material suppliers instead of one for “factory prefab” as already mentioned.

Location of material suppliers

First of all, location of material suppliers is important for on-site construction in the sense that it is possible to avoid a great deal of problems if suppliers are located close to the worksite. The construction process is more likely to move smoothly since material orders are easier to process. Vendors are not required to travel long distances to deliver and the workflow is facilitated for everyone.

In contrast, if suppliers are far, procurement becomes an important issue for contractors. Accurate planning is necessary in order to avoid wasting time and money. Quantities must be measured very precisely since one extra delivery will take a long time and will cost money that could have been saved. We can assume that delivery time and cost increase with distance and that “on-site” and “site prefab” are affected to the same extent.

“Factory prefab” though, is less likely to be affected by distance. Of course freight cost increases with distance, but since one truck is needed to deliver one bathroom unit, the number of deliveries is certain and not subject to changes. Cost estimation has been done in advance and uncertainties have probably been eliminated. However, the problem is coupled with other factors and needs to be evaluated closely especially with the local labor cost. “California is a state where hourly salaries are so high, that Eggrock Modular Solutions could afford to send bathroom units all the way from the Boston factory and still be cost competitive” (Seery, 2013)

In our case, vendors for “on-site” and “site prefab” are located within 100 miles from the worksite, while the prefabrication factory is located 350 miles away.

Delivery time

Delivery time is a factor that affects “on-site” and “site prefab” alternatives. It is an important issue that concerns the construction schedule and its accurate application. Delivery time is defined the time needed from the supplier to deliver the material from the moment the order was made. An average of four weeks is the value for our case study. The factor is correlated with location and reliability of the vendor.

“Factory prefab” is not directly comparable though. The factory prefabricator has been notified well in advance, has started manufacturing units and all he needs is ship them. Shipping time for our case is about one day. The truck would leave the factory well in advance in order to reach the worksite first thing in the morning. The factory considered is 350 miles away from the project. Nevertheless, the manufacturer needs to be absolutely reliable, since delays from its part would jeopardize the schedule.

Reliability of suppliers

Reliability is a major issue for all project stakeholders. The construction schedule is based on certain time considerations. If material suppliers fail to deliver the materials ordered on time, the whole procedure is slowed down with apparent problems for the contractor. Since “on-site” and “site prefab” options contain more suppliers than “factory prefab”, a tentative background research should be performed by the construction company in order to make sure that all participating parties are able to respect their duties.

The prefabricator’s reliability is crucial as well for the same reasons. The manufacturer needs to start constructing well in advance and make sure that prefabricated units arrive on time for installation. Scheduling and managing big projects cannot allow for unexpected delays since all relevant issues should have been solved in advance as the Lean philosophy demands.

For our case all options are considered to be reliable. Consequently, this particular factor does not affect the decision-making process. However, there might be projects where it plays a crucial role.

Accessibility of the worksite

Accessibility of the worksite is an important issue that needs to be considered in general but it affects more the prefabrication options. We can assume that materials can reach the worksite one way or another without encountering great problems.

On the other hand, when a prefabricated unit is transported to the worksite for installation, there are accessibility factors that need to be considered:

- Condition of roads. Prefabricated bathroom units are much more vulnerable than raw materials. As a result, a bumpy or a non-asphalt road might create problems destroying parts that have already been constructed.

- Available space for lifting into place. When projects are constructed within busy roads of large cities, it might be difficult for cranes to lift the units into place. Thorough studies must be performed before selecting the prefabrication option in those cases

- Maximum height. The maximum height a prefabricated unit can be lifted must be investigated.

- Available space for setting up a warehouse or a space to use for prefabricating on-site. This factor affects only “site prefab”. Using the same example as above, it is almost impossible to find a warehouse to use for prefabricating parts of a building in Manhattan.

All those factors are prerequisites for the prefabrication options. They are so important that they might dismiss prefabrication options immediately without considering any other factor. However, according to experts from the prefabrication industry, those issues have already been addressed. They are confident that accessibility issues can be overcome.

For the project studied in our case, accessibility conditions are perfect. As a result, the factor does not affect the decision.

Local labor cost

Local labor cost is one of the main drivers for cost analysis and evaluation of the three options. It affects “on-site” and “site prefab” the same way if local labor force is used, but it plays a major role for the competitiveness of “factory prefab”.

In case labor cost in the area is low, the solution of factory prefabrication loses ground and gets less competitive. Florida for instance, is a state where salaries are low and consequently, on-site construction appears to be more beneficial from a cost perspective. On the other hand, high labor salaries have the opposite effect. Expanding the example used before, in California state salaries are high allowing “factory prefab” to offer a very competitive solution.

However, it is often encountered to see political considerations affecting the decision. Strong unions are able to play a significant role in the decision-making process, affecting all project stakeholders. Financial evaluation is not the only criterion in such cases. Those issues are investigated further in section 2.2.3.

In our case study, the project is located in Wilmington, Delaware. The local labor cost is in the range of $65/hour. In contrast, the prefabrication factory considered pays an average of $35/hour.

3.3.2 Time considerations

Time is a significant factor for all projects. People are used to saying “time is money” and they are exactly right (at least for the construction industry). The aforementioned fact became quite apparent through the author’s correspondence with construction industry experts. The benefits a project enjoys from early completion are enormous. The sub-factors considered in this category are:

a. Time needed for constructing one component
b. Coordination time
c. Overall construction time

Time needed for constructing one bathroom unit

Duration of construction is an important issue that needs to be addressed in all decision-making analyses. Each alternative might provide a different value as it happens in our case. Figure 4.3.1 shows the construction schedule of a set of four bathroom units from a hospital project in Orlando. 33 days are required for constructing one set (Cook, 2013). The reason we use this project as a benchmark is that the same company is constructing the project we evaluate in our case. Both of them are hospitals and their bathroom units are very similar. Consequently, we can legitimately assume that similar construction schedule would have been implemented in the case we study as well, if on-site construction had been selected.

"Site prefab" (that was selected by the contractor) results in a construction time of seven days per unit, while "factory prefab" requires five days. In order to compare similar quantities, we consider in our case that "site prefab" requires 28 days for constructing a set of four units and "prefab factory" needs 20 days for the same set.

Stick-Built Bathroom Schedule: NCH (Source: David Letlow, Project Manager, Skanska USA)				
Activity	**Duration**	**Start**	**Finish**	**Resource**
Layout (Top Metal Track)	1	1/1	1/1	Framing/Drywall
Above Ceiling Mechanical	2	1/2	1/3	HVAC
Inspection	1	1/4	1/4	Gov't
Duct Insulation	1	1/4	1/4	HVAC
Metal Framing incl HMF and blocking	1	1/5	1/5	Framing/Drywall
In-Wall Plumbing Rough	1	1/8	1/8	Plumber
In-Wall Electric Rough	1	1/9	1/9	Electrician
QC inspection for in-wall	1	1/10	1/10	CM/GC
Inspection- Rough Plumb and Elec	1	1/11	1/11	Gov't
Insulate and Hang GWB	1	1/12	1/12	Framing/Drywall
Frame Ceiling	1	1/15	1/15	Framing/Drywall
Above Ceiling Electric	1	1/16	1/16	Electrician
Above Ceiling Plumbing	1	1/17	1/17	Plumber
Fire Protection	1	1/17	1/17	Sprinkler
Mechanical drop and insulation	1	1/18	1/18	HVAC
Above Ceiling Inspection	1	1/19	1/19	Gov't
Hang Ceiling GWB	1	1/22	1/22	Framing/Drywall
Finish ceiling	4	1/23	1/26	Framing/Drywall
Paint Ceilings (base coat plus 2 finish)	3	1/29	1/31	Painter
Tile	4	2/1	2/6	Tile Sub
Install Casework	1	2/7	2/7	Carpenter
Install electric trim	1	2/8	2/8	Electrician
Install plumbing fixtures	2	2/9	2/12	Plumber
Install Fire protection trim	1	2/12	2/12	Sprinkler
Install handrails and accessories	1	2/13	2/13	Carpenter
Install door and hardware	1	2/14	2/14	Carpenter
Total work days	**33**			

Figure 3.3-1: On-site construction schedule for a set of 4 bathroom units (Cook, 2013)

Coordination time

Coordination time is defined as the time spent by people in coordinating the construction process. In all projects there are people whose cost cannot be directly calculated as we have described in the “Hidden Cost” section 2.2.4. Project managers, procurement personnel, superintendents, project engineers spend a significant amount of time organizing the construction process.

The purpose of our research is to identify all components that influence the decision making process. Coordination is the most complex factor we attempt to approach and unfortunately, it is very hard to quantify. It is actually a potential field for a future analysis. The construction industry could be highly benefited by such a research.

Consequently, it is not included in our “Choosing by advantages” case study in order to avoid selecting inaccurate numbers that would result in erroneous results. However, construction companies should definitely take it into account.

Overall construction time

As described earlier, this is one of the most critical factors if not the most critical of all. Advocates of prefabrication argue that they can help projects be delivered faster than the on-site construction can. However, companies that do not select prefabrication methods argue that bathrooms are not usually on the critical path and as a result their prefabrication cannot help in saving time as discussed in section 2.2.3. The selection depends apparently on the project though.

But why would accelerating the project be so significant? The following bullet points attempt to highlight a number of reasons:

- Most projects need to borrow money (raise debt) in order to be constructed. Borrowed money requires interest to be paid each month. Being able to pay back faster than scheduled is a major advantage

- Time is money. For example, if a hotel is delivered three months earlier than scheduled, the benefits from renting rooms three months earlier are tremendous. The net present value of the project is significantly increased as well by saving money from interests and receiving positive cash flows faster. Consequently, the overall investment might become much more favorable.

- Contractors can move faster to the next project, save money they pay for insurance and interests in case they have outstanding loans too.

All people involved in a building project can benefit from time savings in construction. In our case, the goal set by the owner of the project (Nemours) is completion in 35 months. SKANSKA estimates they will deliver the building in 31 months having saved at least two months in contrast with stick built construction. It must be noted however; bathrooms were not the only component to prefabricate and those two months savings cannot be attributed to bathrooms exclusively.

3.3.3 Safety/Accident prevention

Safety and accident prevention are very important issues for all stakeholders in a project but most importantly for contractors. Contractors are the professionals primarily responsible for ensuring safe working conditions. Safety factors also belong to the category of "hidden costs" that have been presented in section 2.2.4, since their cost is not easy to quantify.

But what is defined as dangerous and accident prone in construction? We consider two conditions for our case:

- Works performed above the head of the workers
- Works performed in limited lighting

Such tasks are required on many occasions during on-site construction. We attempted to measure them and quantify the number of those steps. After interacting with experts from the construction industry, we concluded that a legitimate percentage of such activities on-site would be around 15%. In contrast, the corresponding number for "prefab site" and "prefab factory" is 0% since all the activities are performed in controlled environments that are able to eliminate unsafe conditions. Figures 3.3.2-3 exemplify the quality of working conditions within a prefabrication factory. (Photos courtesy of Eggrock Modular Solutions)

Finally, there are safety parameters that we do not take into account for the purposes of this research but the reader might find useful to be informed about. For instance, weather conditions affect a lot the overall health of construction workers. "Cold weather and wind may affect the musculoskeletal and respiratory systems. Bright sunlight does increase the hazard of skin diseases." (Konningsveld and Van Der Molen, 2010)

Figure 3.3-2: Workers perform tasks in a safer environment (Eggrock Modular Solutions, 2013)

Figure 3.3-3: Workers perform tasks in a perfectly lighted space (Eggrock Modular Solutions, 2013)

3.3.4 Quality

During this research, we have been informed about a series of advantages prefabrication offers. It was unanimously accepted that controlled working conditions of prefabrication plants could significantly increase quality of the product. Nevertheless, quality should be viewed as:

- Overall quality
- Quality of components

The quality of components is increased by prefabrication. During the construction phase, a certain number of mock-ups is manufactured so that architects and owners can approve the solutions proposed. Consequently, errors can be spotted and eliminated from the end product.

We consider two factors as quality of components for our analysis:

- Accurate slope construction for the floors
- Better finishes

On the other hand, the overall quality in terms of robustness needs further investigation. For example, when deciding about building an underground parking, one can again select between prefabricated concrete wall parts or cast in place concrete. While those prefabricated parts are exceptional in quality (better than the same pieces of cast in place concrete would be), the overall structure is much more robust by using cast in place concrete. In the same sense, on-site construction of bathrooms could potentially provide a more robust assembly overall. (Chase, 2013)

Another potential disadvantage could be the entrance of pre-constructed bathrooms. Since prefabricated bathroom units have their own floor that needs to be installed on the existing slab of the structure, a small rung is created. Special care must be taken in order to avoid this "step" creation especially for bathrooms that need to be accessible by wheelchairs. (Our research showed that such care is taken in order to avoid this problem though)

To sum up, it is hard to argue in favor of any of the solutions available in terms of quality. In this section we tried to present all possible quality considerations. Our case study includes three quality factors, which allow for a qualitative comparison based on the opinion of the professional that uses the method. We were very interested to see how opinions of construction industry experts would agree or not about them. We actually received some quite surprising results that are presented in chapter 4.

3.3.5 Weather/Environment

This category is split in three groups:

a) Weather conditions
b) Impact on the environment
c) LEED certification

Weather conditions

Projects can be affected by weather conditions depending on their location and the time of the year. During winter periods, temporary heating might ne necessary in cold areas like New England. Excessive heat on the other hand is even more difficult to deal with. During very hot days, certain construction activities might have to be postponed.

The two prefabrication options are not affected by weather conditions (assuming a closed roof warehouse for "site prefab"). The only critical point for the prefabricated solutions is the installation procedure. In case adverse weather conditions are present at the day of the installation, lifting the components into place might be impossible. Windy days are more likely to cause problems but even in that case, installation would be delayed for only one day in most places as our correspondence with construction industry experts revealed.

In our case, the project is located in Wilmington, Delaware, where winters are often strong. On-site construction could potentially be affected. The warehouse set on the other hand, is fully enclosed so delays due to weather have been eliminated for both prefabrication alternatives.

Impact on the environment and LEED certification

All Options use the same raw materials for construction. However, prefabrication, either on-site or in a factory, offers significant waste reduction. All contractors that the author contacted during this research, agreed on this significant reduction.

Trades	Average wastage level (in %)		Percentage of waste reduction $[C = (A - B)/A]$ (%)
	Conventional (A)	Prefabrication (B)	
Concreting	20	2	90
Rebar fixing	25	2	92
Bricklaying	15	–	–
Drywall	–	5	–
Plastering	23	0	100
Screeding	25	–	–
Tiling	27	7	74

Figure 3.3-4: Waste reduction per activity (Tam et al, 2006)

The controlled conditions of a warehouse or even better a factory allow for more precise cutting of materials and more accurate assembly. (Figures 3.3.5-6)

Figure 3.3-5: Waste reduction through accurate cutting of tiles (Eggrock Modular Solutions, 2013)

Figure 3.3-6: Waste reduction through accurate cutting of pipes (Eggrock Modular Solutions, 2013)

Nevertheless, since raw materials are the same, points gained in the LEED system will be the same for all options. The LEED system does not give points for a construction technique that allows waste reduction, which is not considered fair within people of the prefabrication industry.

3.3.6 Overall project characteristics

This category includes characteristics of the project that don't fit in any of the categories described above. They are:

a) Total number of bathroom units, number of identical units
b) Efficiency
c) Design Flexibility

Total Number of Bathrooms

The total number of bathrooms and the units per type factor pertains to the prerequisites in considering "site prefab" or "factory prefab". Prefabrication can offer the potential advantages described earlier when a significant amount of repetitive work is moved off-site. A big number of identical bathroom units is required in order for modularization to exist. The building considered in our case consists of 144 bathroom units, 102 of which are identical. The remaining 42 are divided in eight more groups. Our criterion for considering prefabrication is a minimum amount of 80 same units. This number was derived by our conversations with people from the industry.

The number of bathrooms does not affect on-site construction, since it would require the exact same steps to be followed regardless of this number. "Site prefab" would most likely lead to prefabrication of all 144 units in the warehouse established. "Factory prefab" would probably lead to ordering the 102 identical units (since the prefabricator needs a certain number of units in order for his offer to be competitive) and the rest 42 would be constructed traditionally, on-site.

Efficiency

The efficiency concept has been described in detail in section 2.1.2. Measuring or estimating the efficiency associated with on-site construction is an important, yet hard task. The limits a factory can reach in terms of overall efficiency can be established one way or another but that is not the case for construction with all its unique characteristics. For the purpose of our case study, efficiency of on site construction is selected to be 43% based on correspondence with construction industry experts.

The author's correspondence with construction industry experts also lead to a number of 65% for the "site prefab" efficiency and 75% for the "factory prefab". Prefabrication factories are considered to use lean manufacturing techniques that increase efficiency as described in section 2.1.3. "Site prefab" did not use lean techniques, which lead to a lower value.

Why would prefabrication alternatives offer more efficiency? We have already established that non-value adding activities decrease the efficiency index. Workers in "on-site" use a high share of their activities moving from one bathroom to the other, moving their tools, setting up their work every day, cooperating with other trades that might use the same space with them and so on. Options 2 and especially 3 -that uses lean manufacturing- in our case eliminate such activities. For instance, figure 3.3.7 shows how the equipment of workers is next to them. They do not need to move material or look for tools.

Figure 3.3-7: Increased efficiency by concentrated equipment around the workers (Eggrock Modular Solutions, 2013)

Design Flexibility

This factor addresses design issues and investigates the time frame each option allows. On-site construction allows design changes even at later stage of the process. Architects and owners are expected to prefer increased flexibility. In contrast, contractors are not expected to be fond of such changes because of the delays they cause in the project.

On the contrary, the design in both prefabrication options needs to freeze at an early stage. All relevant decisions must be made in advance and there is no flexibility afterwards. For the case of bathroom construction, the owner and the architect must decide on every single detail much earlier than they would have to if "on-site" were selected. For instance, the selection of tiles to be used must be made up to 14 months earlier in order for the production process to proceed.

4 Results

This section presents the results of our research. 13 people completed the CBA case we created. Some of them also provided comments that could make the method better or disagreements with certain factors. We are very happy to present those comments, since this was the exact goal of our analysis: collect opinions from experienced professionals on the problem we are trying to assess.

We present their final selection, their ratings for each factor, as well stacked bar charts showing the contribution of each factor to the rating of the alternatives. Comments are also presented if provided by the experts that evaluated the research. Finally, a comparison of their ratings is attempted across professionals of the same discipline and an interdisciplinary evaluation of their opinions as well.

4.1 Presentation of Construction Industry experts

A big number of invitations was sent to people involved in the construction industry asking for their opinion on our case study. 13 of them replied and we are very thankful for their help. They are briefly presented in the table to follow with alphabetic order:

Table 4.1-1: Table of Construction industry experts participating in the research

Name	Position/Company	"Role" in the case
Chase, Brian	Project Executive Turner Construction	Contractor
Lee, Douglas	Chief Estimator at Brasfield & Gorrie	Contractor
Menard, Scott	Vice President of preconstruction at Suffolk Construction	Contractor
Milbrand, John	Owners Representative	Owner
Muncy, Bernadette	Associate architect at TRO Jung|Brannen	Architect
Olsen, Darren	Assistant Professor, Auburn University	Academic
Ott, Timothy	Assistant Director Project Mgmt. UHS of Delaware, Inc.	Owner
Pikel, Christian	Regional Project Manager UHS of Delaware	Owner
Thomson, James	Senior Estimator at Commodore Builders	Contractor
Architect 1*	Architect/Project Manager	Architect
Contractor 1*	Senior Superintendent	Contractor
Contractor 2*	Field Engineer	Contractor
Contractor 3*	Field Superintendent	Contractor

* Architect 1 and Contractors 1,2 and 3 requested to remain anonymous

4.2 Architects

Architect 1. Architect/Project Manager within a major architecture firm in Boston

Architect 1 is an architect with a lot of experience in building design. He has been involved with a great deal of building projects throughout his career. The company he works for has designed many big-scale building projects like student dormitories for major universities in the New England area. His experience could only add value to our research.

He selected prefabrication in a factory. He considered very important factor 6 (local labor cost): "If it saves the project cost, then it definitely factors into Architects' decision analysis. Money can be used elsewhere". He also evaluated factor 8 (Overall quality robustness) highly reversing the default settings of our analysis: "Overall, I believe a prefabricated bathroom will provide the best robustness. I think your criteria should be 'Robust is better' rather than 'Perfectly robust". There is no such thing as 'perfectly' in construction". Factors 10 (quality of finishes) and 17 (Solid waste generation) also attracted a high grade as they play a crucial role in an architect's analysis.

We were surprised to see that he did not believe design flexibility to be a very important feature of on-site construction and he also disagreed with our initial evaluation of factor 9 (Quality of slopes to allow for proper draining): "Levelness and/or necessary slopes of factory-built units could also be problematic when trying to accommodate into the built condition."

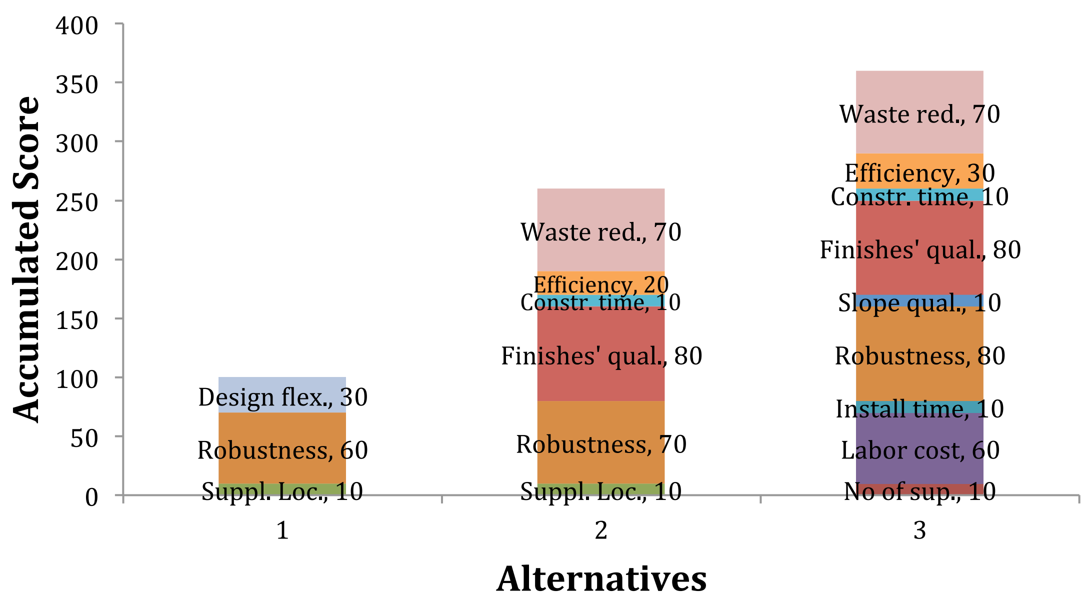


Figure 4.2-1: Visual representation of Architect 1 ratings.

Bernadette Muncy. Associate architect at TRO Jung|Brannen

Ms. Muncy is an experienced architect working for TRO Jung|Brannen. The company she works for has a great deal of experience in hospital projects. Consequently, her opinion is very useful to our research.

She decided to select prefabrication in a factory but we must note that her choice would have been shifted to "site prefab" in case a factor concerning local labor selection had been used. She considers very important to use people from the local community for the construction process. Since "factory prefab" does not use local workers, she would have assigned 65 points to alternatives 1 and 2. Her final choice would have been prefabrication adjacent to the worksite in that case.

The most essential factor for her was the Quality of finishes, which is very important from an architect's standpoint. Construction time reduction (factor 14) and Robustness offered by "on-site" (factor 8) were significant as well, in contrast with Architect 1 who did not consider important construction time and disagreed that robustness is increased by stick-built construction. Ms. Muncy also evaluated highly factors concerning weather delays and installation time, while Architect 1 assigned very small or zero weight on them. She also assigned only 30 points to Design flexibility, which is again quite surprising for us. We expected architects to want flexibility in their designs.

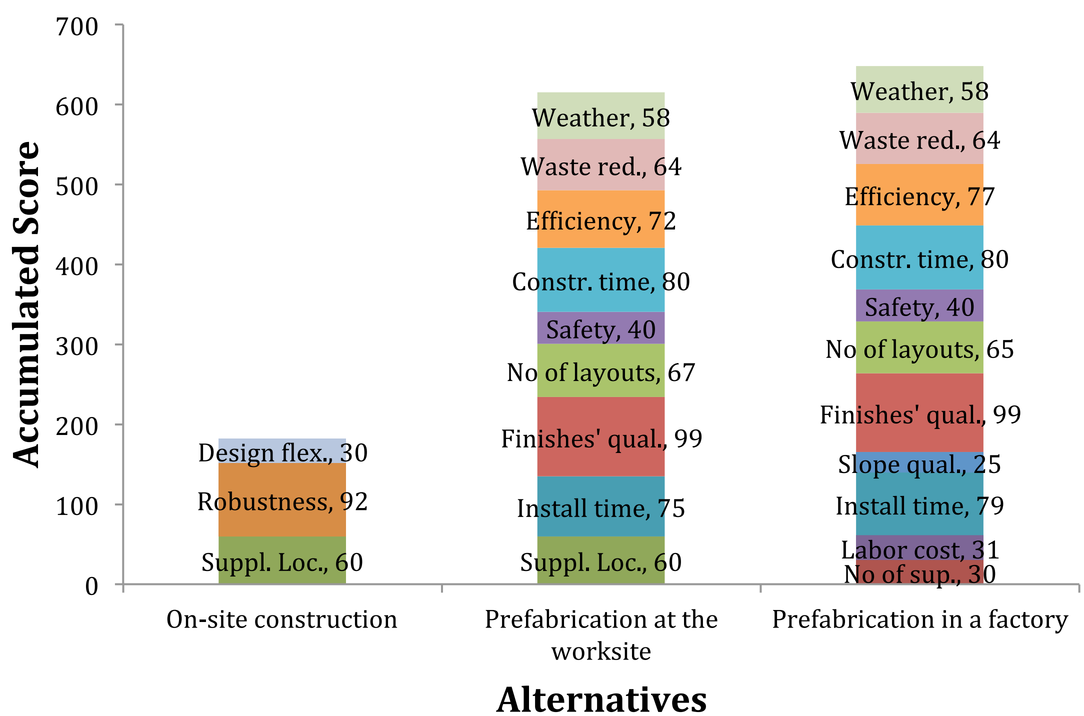


Figure 4.2-2: **Visual representation of Ms. Bernadette Muncy's ratings.**

4.3 Contractors

Brian Chase. Project Executive at Turner Construction

Mr. Chase is an experienced professional working for one of the biggest construction companies within the United States. He has been involved with many building projects throughout his career. It was an honor to have him involved in our research.

Mr. Chase would select factory prefabrication for this case. He considered very important factor 6 concerning local labor cost and as expected, factor 14 (overall construction time). His opinion over quality issues was that on-site construction offers a more robust end product indeed and prefabrication alternatives offer better finishes. He disagreed though, that prefabrication solutions could provide more accurate slopes and turned this advantage to stick-built construction.

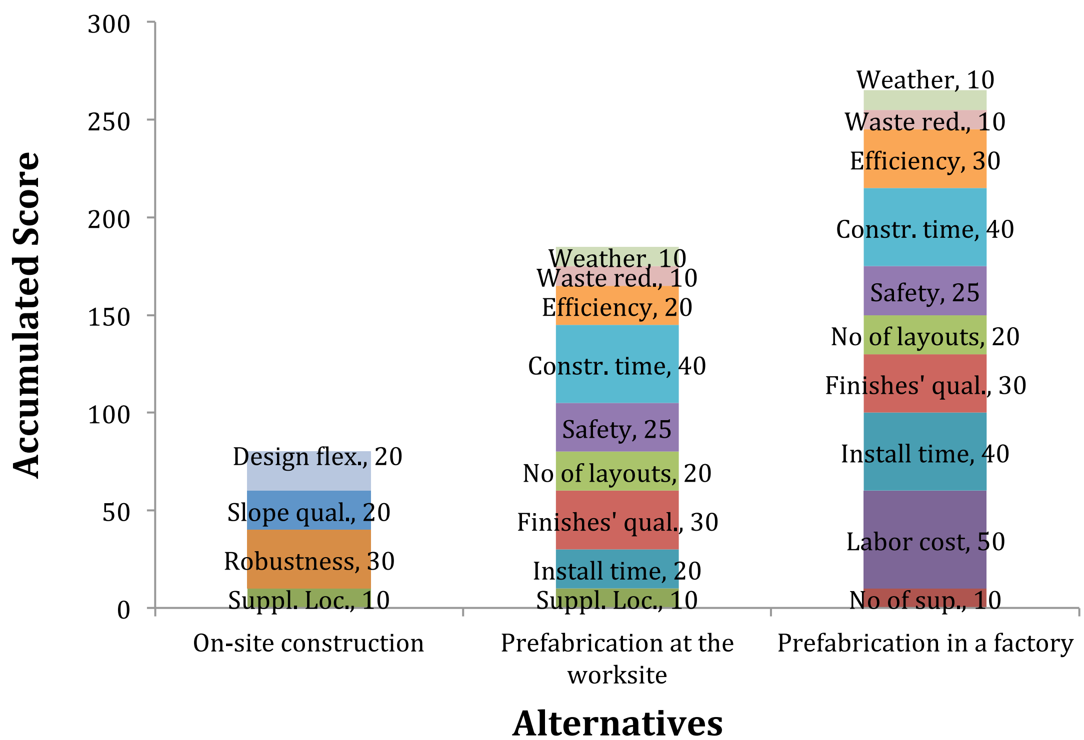


Figure 4.3-1: Visual representation of Brian Chase's ratings

Scott Menard. Vice President of preconstruction at Suffolk Construction

Mr. Menard offered significant help in our research. His role as Vice President of preconstruction within Suffolk Construction made him one of the most suitable persons we could reach out to. Suffolk Construction is a major construction company working particularly with building projects. We are very happy to present his opinion.

Mr. Menard would select prefabrication in a factory for this project and considered the quality of finishes it offers to be fundamental. It is interesting to see that he disagreed with our assumption that prefabrication adjacent to the worksite offers equal quality of finishes assigning 20 points versus 90 for factory prefabrication. In addition, he did not really consider more robust the result that on-site construction provides.

What we did not expect was his opinion on construction time. We clearly expected to see a number bigger than 30 assigned to the advantage of prefabrication. We also did not expect contractors to assign big weight on design flexibility but Mr. Menard gave 60 points to the advantage of "on-site". It is also interesting to notice that Mr. Menard does not consider prefabrication solutions to be safer than the worksite conditions.

Mr. Menard addressed the cost component of the method: "the nature of the questions without more concrete costing information (for instance the labor cost per hour and the increase in efficiency may lead one to believe the prefab solution is more cost effective without understanding the real differential) is kind of like "leading the witness"."

It is a very reasonable observation. Ways to address the cost component are suggested in section 6.1. Furthermore, the labor cost factor might need to be removed from future analyses if project stakeholders think so. We added it in our case in order to give a sense for the component. In the comments accompanying the case, it was noted that "Please note that in alternative 3, the labor cost is paid by a third party. Not by the contractor directly." We did not want to create the impression that option 3 is cheaper.

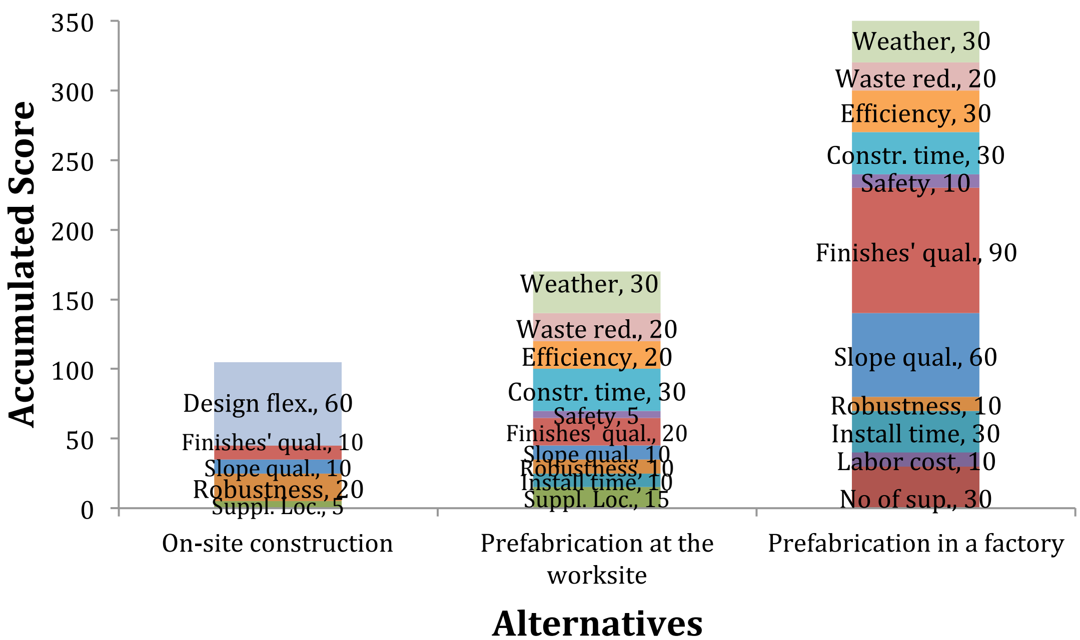


Figure 4.3-2: Visual representation of Mr. Scott Menard's ratings

Douglas Lee. Chief Estimator at Brasfield & Gorrie

Mr. Douglas Lee is another experienced professional that we are very happy to host in this thesis. Mr. Lee has profound knowledge of the CBA method we used and his comments might be of great interest for the reader and potential future researchers.

Mr. Lee selected factory prefabrication considering reduced construction time (factor 14) to be a major advantage of prefabrication. He also agreed that safety increases with prefabrication assigning 85 points on the relevant factor.

Mr. Lee suggested ways that could make comparisons more quantitative.

- Robustness (factor 8): “a quantity of punch list items post installation would be a more quantitative attribute”
- Quality of finishes (factor 10): “a quantity of quality control deficiencies would be beneficial here for each alternative”
- Safety (factor 12): “It would be great to see number of near misses / incidents / lost man-hours / etc, to give this a true metric and develop a more quantitative delta”
- Waste reduction (factor 17): A more quantitative approach could be achieved by calculating waste difference in cubic yards or tons
- Weather (factor 18): “If dealing in theory then these are just "potential" delays. I believe you should calculate average weather impact days, and list number of days in a calendar year that a project is exposed. This would be a more quantitative attribute and maybe spell a more defined advantage.”

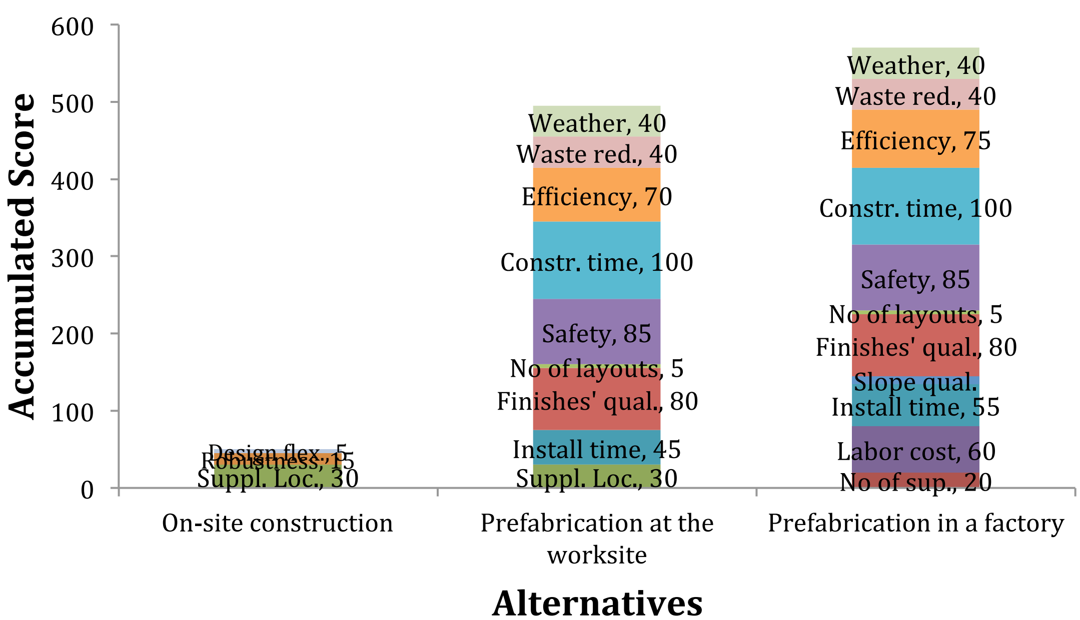


Figure 4.3-3: Visual representation of Mr. Douglas Lee’s ratings

Contractor 1. Senior Superintendent

Contractor 1 has a lot of experience in the building industry. He works for a company that is actively involved with healthcare projects and has worked with all three alternatives in his career.

Contractor 1 gave 100 points to local labor cost advantage of factory prefabrication and the overall quality offered by on-site construction. It is interesting to notice that he is the person who assigned the biggest grade on the overall quality. He apparently believes that on-site construction offers great benefits for this factor. Furthermore, he believes the accelerated installation time of "factory prefab" to be a great advantage.

On the other hand, it was quite unexpected to see that he did not consider advantageous the reduced construction time that prefabrication alternatives offer. He was actually the only person to give zero points to this advantage. In addition, most people gave higher ratings to factor 12 (safety) and factor 17 (waste reduction) than him.

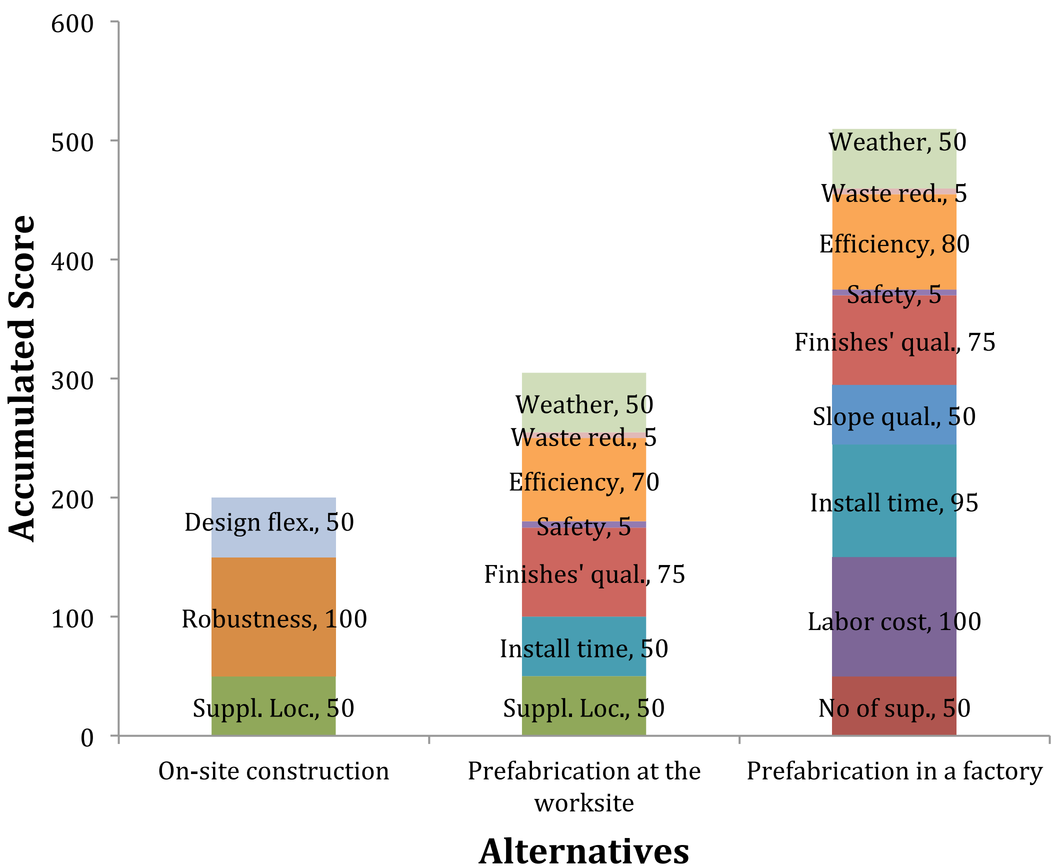


Figure 4.3-4: Visual representation of Contractor 1 ratings

Contractor 2. Field Engineer

Contractor 2 has been a great asset throughout our research. Her help has been invaluable in creating our case study and gathering important information. She also works for a company that is actively involved with healthcare projects.

She selected factory prefabrication assigning her biggest grade on the installation time it offers (100). She also considered the accelerated construction time to be fundamental along with the quality of finishes and the increased efficiency that prefabrication alternatives offer. All her highly rated selections were in the expected zone for professionals working for construction companies. It is interesting to notice that she rated very highly the number of suppliers factor, which not many experts considered influential.

Furthermore, she agreed that robustness is increased with on-site construction and that design flexibility is quite an important advantage.

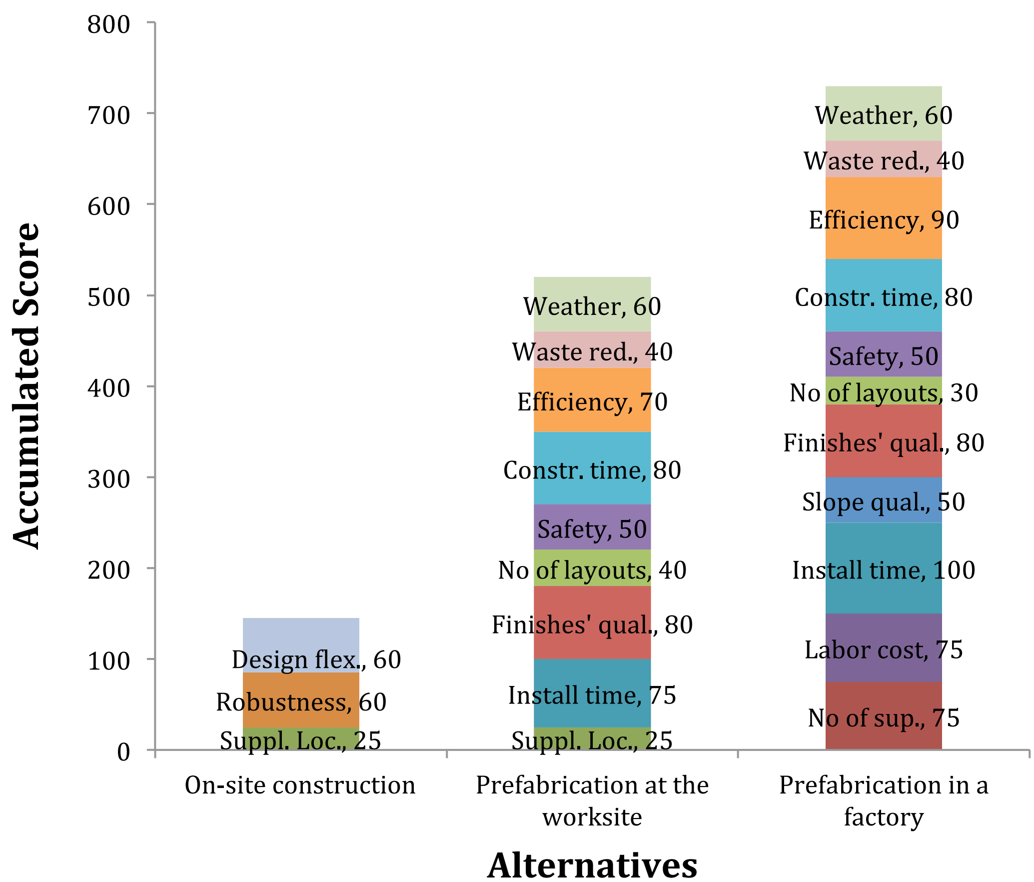


Figure 4.3-5: Visual representation of Contractor 2 ratings

Contractor 3. Field Superintendent

Contractor 3 works as a field superintendent for a company located in the New England area. He also has experience in both on-site construction and prefabrication.

He selected factory prefabrication but we must note that the final score of his rating for "site prefab" would have been equal to "factory prefab" in case a factor concerning local labor selection had been used. He considers crucial that the alternative chosen employs people from the local community for the construction process. Since "factory prefab" does not use local workers, he would have assigned 75 points to "on-site" and "site prefab".

Contractor 3 was the person whose opinion was not close to the average results. He assigned 100 points to the efficiency of factory prefabrication and also considered decisive factor 18 concerning delays due to weather. It is interesting to notice that he is the person who assigned the biggest weight on factor 2 (Location of suppliers). The most surprising part of his analysis however was probably his evaluation of construction time reduction offered by prefabrication. He did not believe construction time acceleration is important and assigned only 10 points on it.

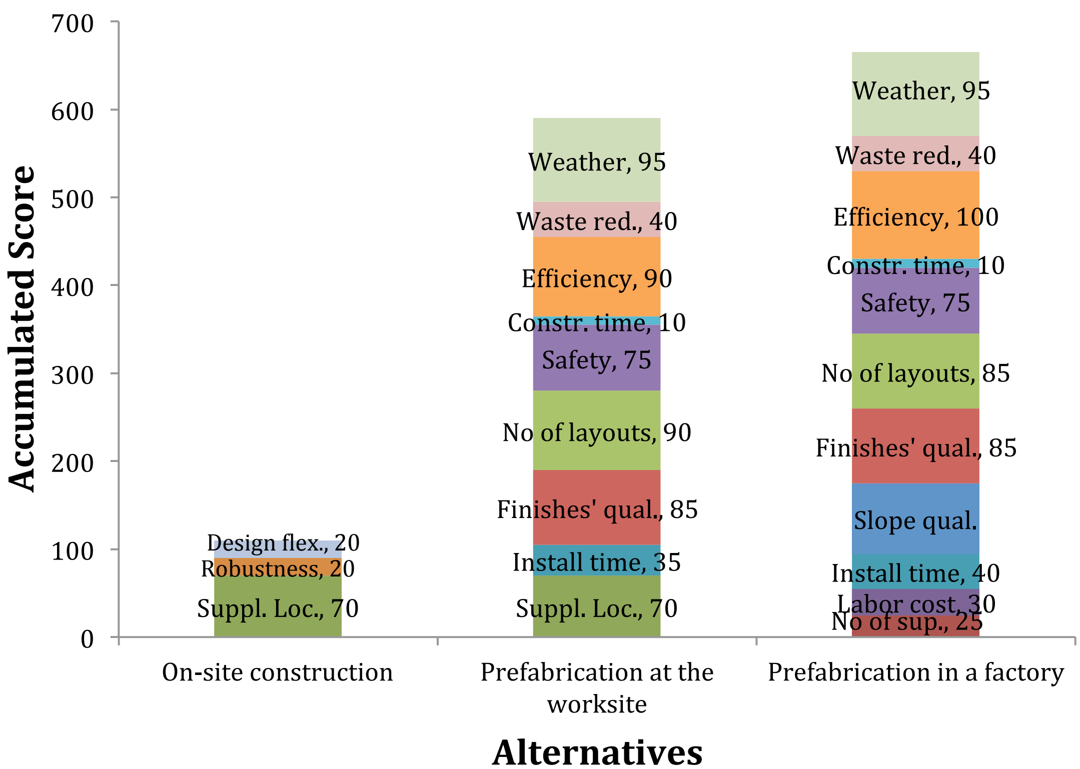


Figure 4.3-6: Visual representation of Contractor 3 ratings

James Thomson. Senior Estimator at Commodore Builders

Mr. Thomson is an experienced professional in the field of cost estimation. He has been involved in a series of building projects. His help in understanding components that influence the decision of bathroom construction was very important. Commodore Builders is a company very active in the commercial building industry, which usually selects on-site construction for its projects.

Mr. Thomson selected factory prefabrication and considered the accelerated construction time to be its major advantage. We definitely expected contractors to evaluate highly this particular advantage. He also assigned a high grade (95) to the decreased labor cost "factory prefab." allows, to quality of finishes (95) and to increased safety (80) of prefabrication options.

Mr. Thomson did not consider robustness of the assembly to increase with on-site construction and assigned only 15 points to this factor. He also gave only 5 points to design flexibility, a factor that we did not expect to attract interest from contractors.

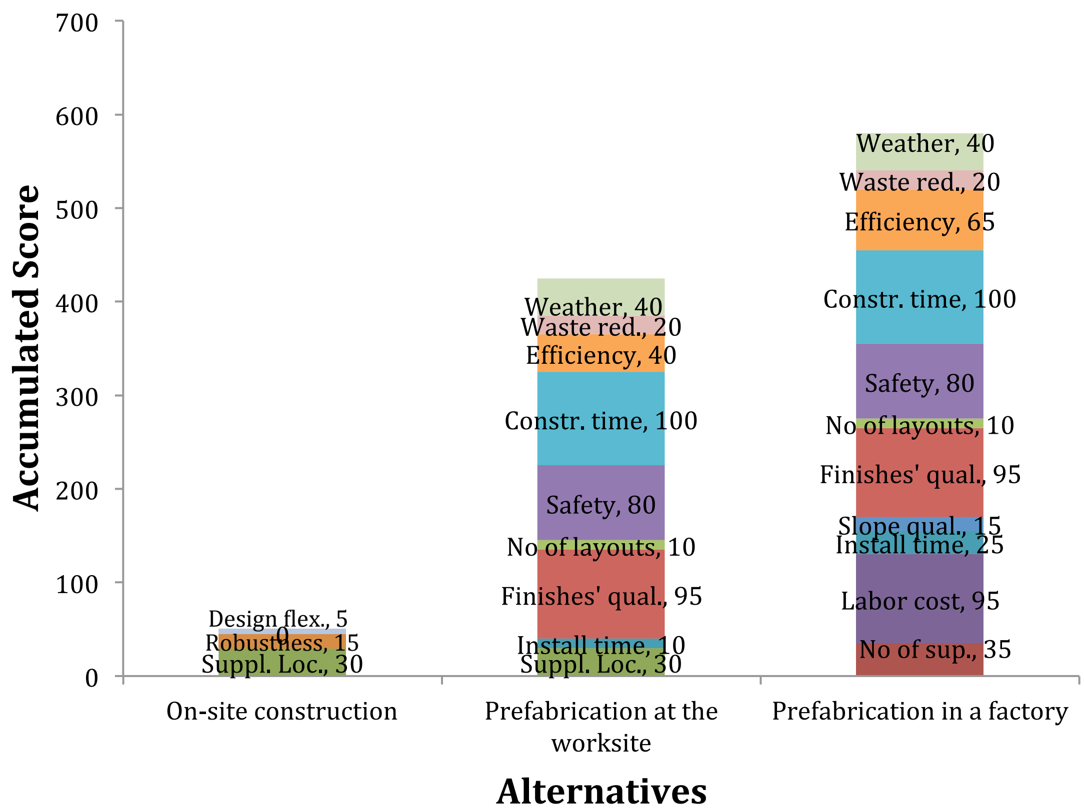


Figure 4.3-7: Visual representation of Mr. James Thomson's ratings

4.4 Owners

Timothy Ott. Assistant director of project management at UHS of Delaware, Inc.

Mr. Ott is another distinguished professional that we are very happy to include in our research. His prior experience with CBA makes his comments very valuable as well. Universal Health Services (UHS) is a company involved in the healthcare industry. Mr. Ott processes a highly ranked position within the firm.

He selected factory prefabrication for this particular project and considered crucial:

- The local labor cost advantage of factory prefabrication ("a nearly 50% reduction in labor cost is significant")
- The installation time of factory prefabrication ("time is extremely important so a nearly 50% reduction scores fairly high")
- The quality of finishes ("production line approach to bathroom construction provides a consistent high quality product"). It is interesting to notice that he considers quality offered by "site prefab." inferior to "factory prefab".
- The efficiency of factory prefabrication ("efficiency is very important")

Furthermore, in his opinion the biggest advantage for on-site construction is design flexibility: "unfortunately, change is part of the project even though we try hard to minimize it". He did not consider overall time savings to be quite feasible: "From my experience, we have struggled to realize overall schedule savings due to the bathrooms not being on the critical path", an argument that we heard from other experts as well. Finally, his opinion on safety issue is interesting as well: "Safety is important but there will still be work above head to connect prefabricated units".

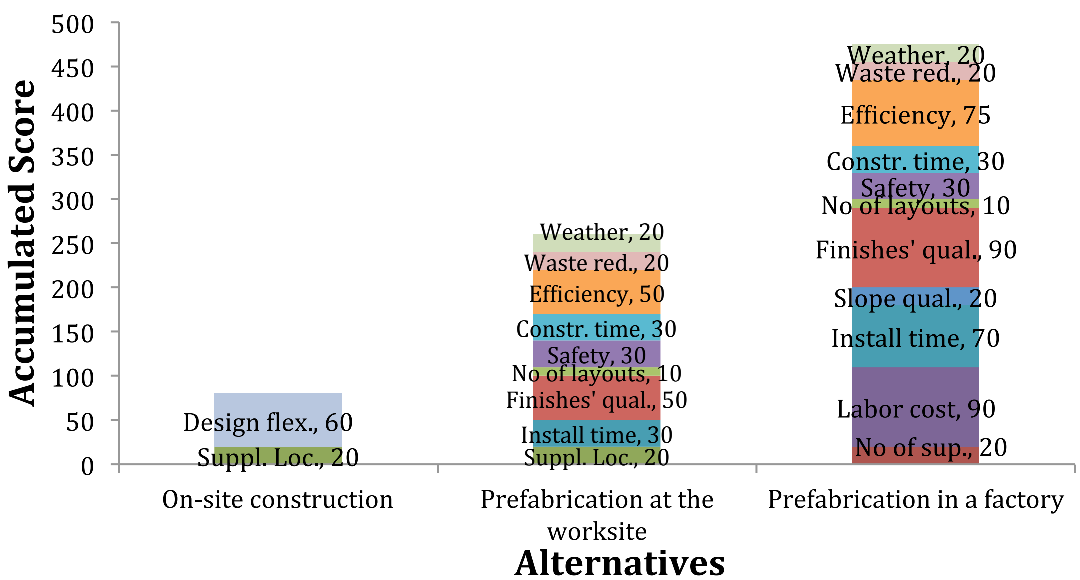


Figure 4.4-1: Visual representation of Mr. Timothy Ott's ratings

Christian Pikel. Regional Project Manager at UHS of Delaware

Mr. Christian Pikel is another highly ranked professional within UHS that we are happy to host in this thesis. He also has experience with the CBA method, so his opinion is very relevant to our research.

Mr. Pikel selected factory prefabrication with a small difference from prefabrication adjacent to the worksite. He rated highly factor 10 (Quality of finishes) and 14 (construction time). Both of them are factors we expected owners to evaluate highly in their analyses.

On the other hand, he did not consider design flexibility important at all which was not quite what we expected. In addition, he disagreed with the default quality attributes we established for factor 8 (robustness): "I disagree with the advantage. I would expect similar level of final product quality regardless of build method." and factor 9 (quality of slopes): " I would expect proper drainage in any of the 3 scenarios unless quality control is an issue in the field. In that case, I think the advantage is captured in factor 10 (quality of finishes)".

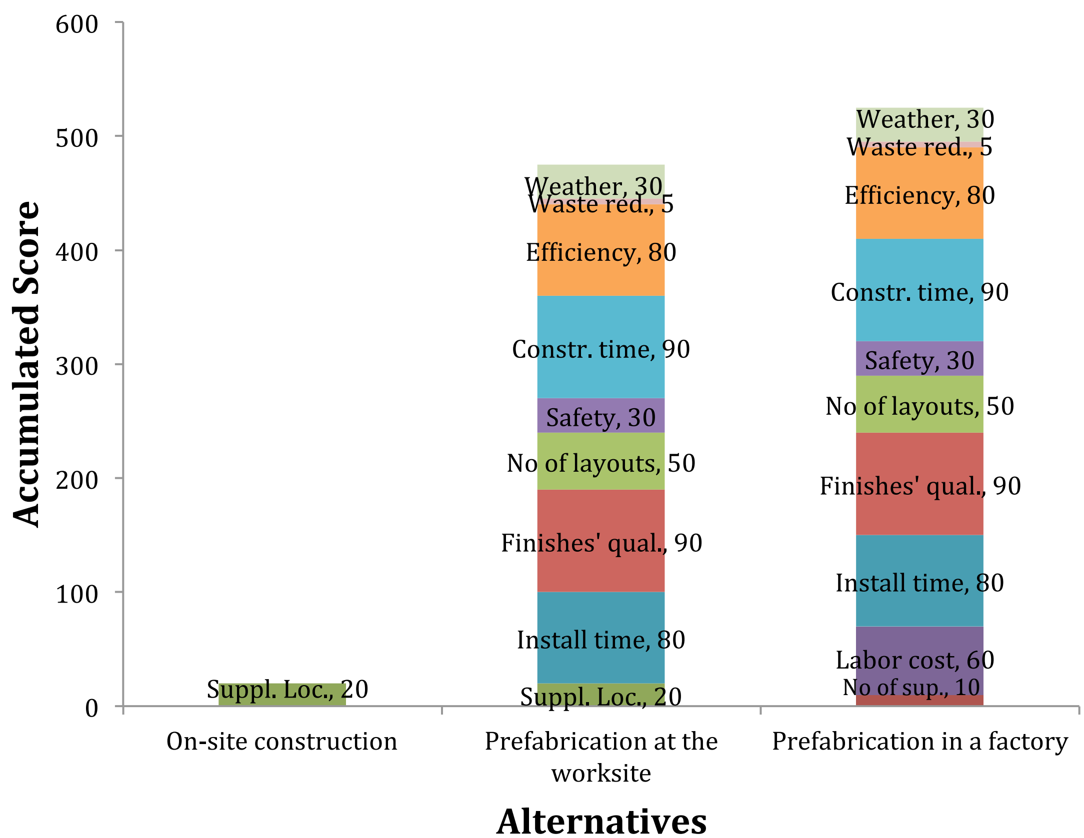


Figure 4.4-2: Visual representation of Mr. Christian Pikel's ratings

John Milbrand. Owners Representative

Mr. Milbrand is another experienced professional that participated in our case evaluation and selected the factory prefabrication alternative. It is interesting to notice that Mr. Milbrand is the only person considering the number of layouts (factor 11) of "site prefab" to be the most important advantage. He assigned 100 points on this factor.

In addition, he believes (as we expected) that the accelerated construction time prefabrication provides is crucial. 95 points were assigned in this characteristic. Mr. Milbrand was one of the persons who assigned very high grade on the weather parameters, giving 75 points to the advantage of prefabrication not being affected by weather conditions.

On the other hand, he did not give many points to quality parameters. Most experts assigned high rating to at least one of the three components we included in our research. In addition, he disagreed with our analysis concerning efficiency. He considered "site prefab" to be more efficient than 'factory prefab" which was clearly reflected to his ratings. He also gave a relatively low grade to design flexibility, a factor that we expected to score higher for an owner.

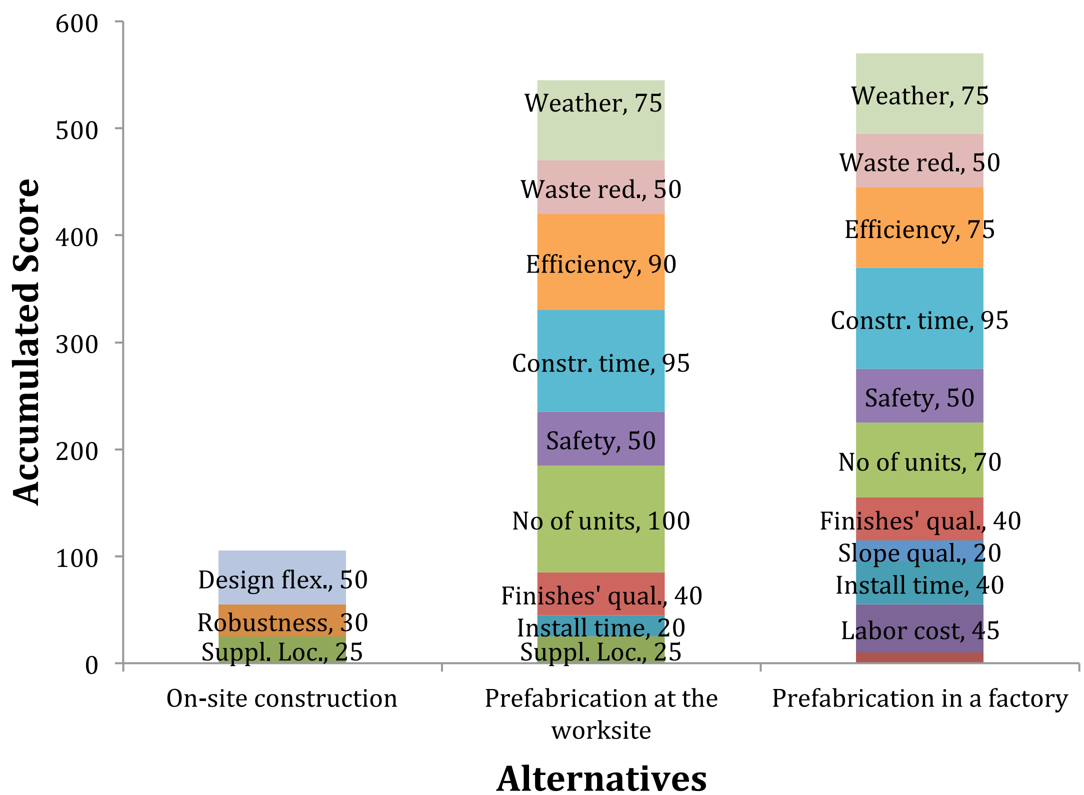


Figure 4.4-3: Visual representation of Mr. John Milbrand's ratings

4.5 Academics

Darren Olsen. Assistant Professor at Auburn University.

Professor Olsen's work has already been cited in this thesis. He has tried to investigate the field himself seeking answers to the exact same questions as us. Consequently, his opinion is very welcome in our research.

Mr. Olsen selected to prefabricate the bathrooms in a factory for our case. He considered the overall construction time reduction that prefabrication allows to be the most influential factor. Time was obviously very important for Mr. Olsen and as a result the second most influential factor was the one concerning installation time of bathrooms. On the other hand, it is interesting to see that robustness is considered equal for all options.

Furthermore, Mr. Olsen addressed the cost component which is absent from the CBA method: "One advantage that would have changed my weighting of the entire scale would be overall cost of the site-built bathrooms vs. prefabricated bathrooms. You included labor cost in the list which turned out as an advantage for prefabrication, but the overall cost for prefabrication vs. site-built can include additional engineering, supervision, coordination, design and delivery for prefabricated modules. My brief exposure to prefabricated bathrooms seems to suggest that their overall cost exceeds the site-built alternatives. I think the reduction in labor cost is an advantage but that advantage might be offset by other costs that are unique to prefabrication and do not apply to site-construction." The CBA methodology though, does not take cost into account but evaluates it separately. In section 6.1 two ways of dealing with cost are suggested by the author.

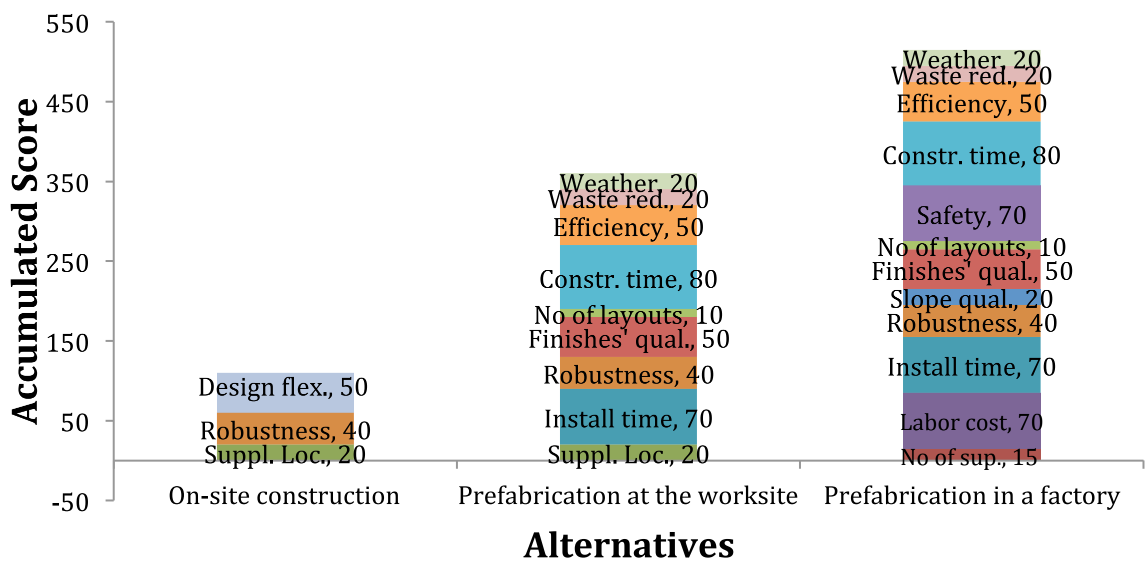


Figure 4.5-1: Visual representation of Mr. Darren Olsen's ratings

4.6 Combined results

In this section we present the combined results of the experts that evaluated the case. Figure 4.6.1 shows the combined results for all the experts, figure 4.6.2 presents the architects, 4.6.3 the contractors and 4.6.4 the owners. The average points for each alternative has been calculated for all the above cases

Table 4.6-1: Average ratings given to each alternative by all experts

All experts			
	On-site construction	Prefabrication at the worksite	Prefabrication in a factory
Mean points	109.0	414.6	540.6

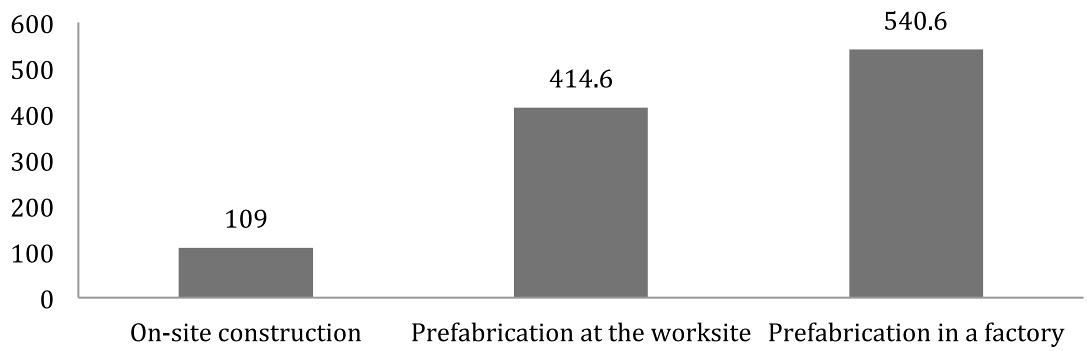


Figure 4.6-1: Bar chart of average ratings given to each alternative by all experts

Table 4.6-2: Average ratings given to each alternative by architects

Architects			
	On-site construction	Prefabrication at the worksite	Prefabrication in a factory
Mean points	141	437.5	504

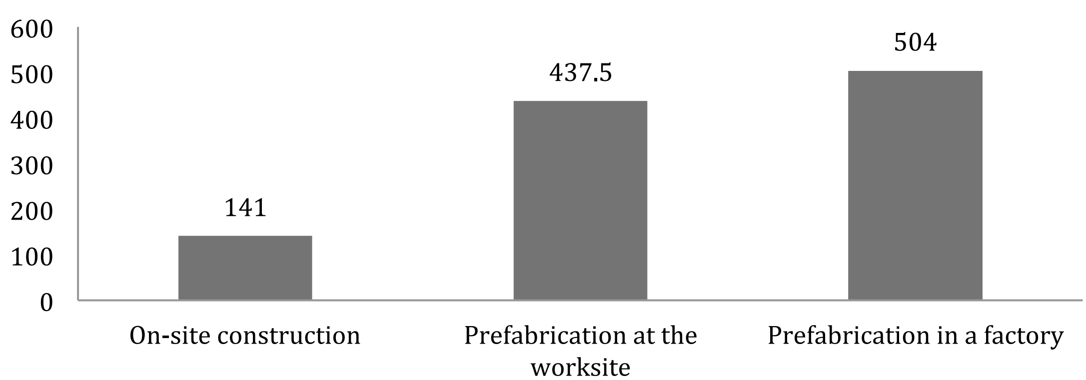


Figure 4.6-2: Bar chart of average ratings given to each alternative by architects

Table 4.6-3: Average ratings given to each alternative by contractors

Contractors			
	On-site construction	Prefabrication at the worksite	Prefabrication in a factory
Mean points	117.1	410.7	562.1

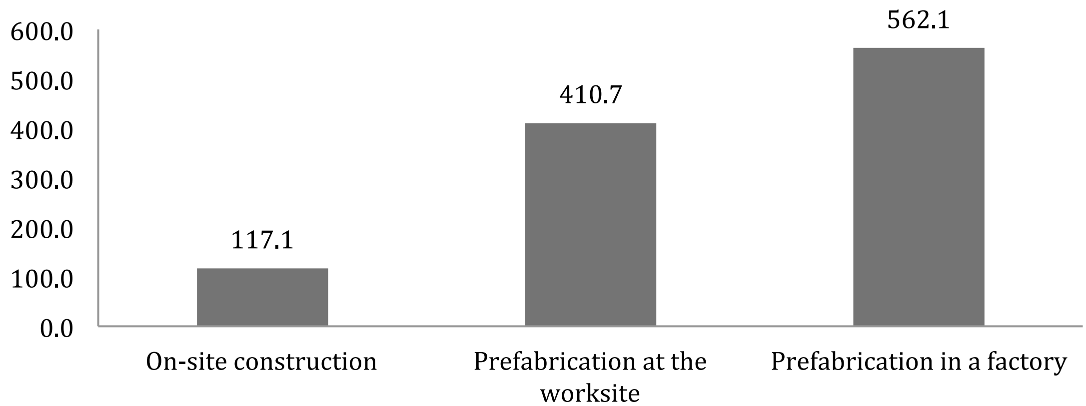


Figure 4.6-3: Bar chart of average ratings given to each alternative by contractors

Table 4.6-4: Average ratings given to each alternative by owners

Owners			
	On-site construction	Prefabrication at the worksite	Prefabrication in a factory
Mean points	68.3	426.7	523.3

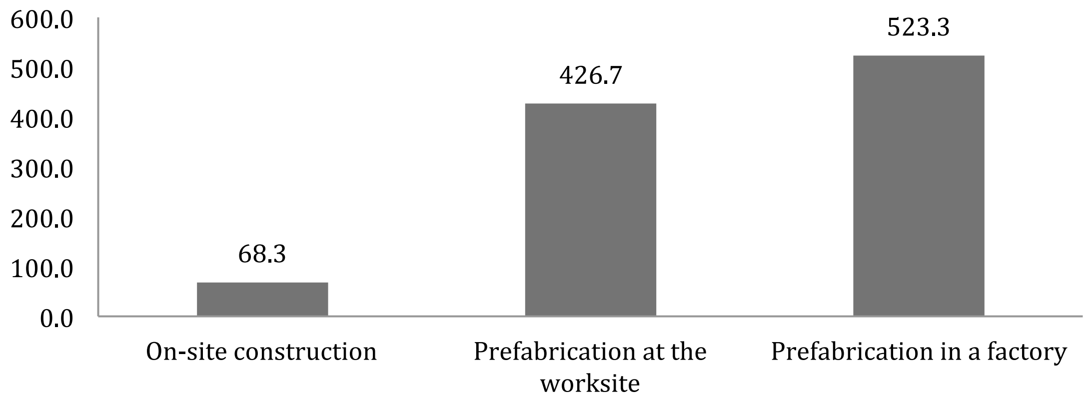


Figure 4.6-4: Bar chart of average ratings given to each alternative by owners

We see a clear pattern in all results. All people would select prefabrication in a factory. Architects are the professionals who assigned the biggest overall grade to on-site construction followed by contractors but the number is far from “factory prefab”.

Contractors clearly selected factory prefabrication with quite big difference from prefabrication adjacent to the worksite. Architects on the other hand and owners rated “site prefab.” very close to “factory prefab.” In another project, they could very easily shift their choice if parameters were different.

Summary/Comments on architects

The two responses to our case seem to be quite far from each other. We summarize their agreements and disagreements in the following bullet points:

They both agreed on:

- Design flexibility. Both assigned a small grade on the flexibility factor, which was quite surprising. We definitely expected architects to rate it more highly.
- Quality of finishes. Both clearly believe that this is a crucial factor. We expected to see such answers
- Waste reduction. High rating was assigned to the environmental factor
- Overall evaluation. The final rating that both gave to on-site construction was 28% of the final rating assigned to factory prefabrication.

They disagreed on:

- Robustness. Architect 1 did not consider robustness to increase with on-site construction. He assigned similar grades to all three options. Ms. Muncy on the other hand agreed that robustness increases with on-site construction and rated the advantage very highly.
- Installation time, Location of material suppliers. Architect 1 assigned very low ratings compared to Ms. Muncy.
- Number of layouts, safety considerations, weather delays, construction time. Architect 1 did not consider those factors interesting from an architect’s standpoint, while Ms. Muncy did. She considered construction time very important, something that we expected to see from all experts.
- Efficiency. Architect 1 again assigned low ratings to this particular factor in contrast with Ms. Muncy.

To sum up, we believe that those results yield some interesting observations. We aimed to spot those exact differences amongst people of the same discipline or between people in different fields. It is true that we expected a higher degree of agreement between architects but maybe Architect 1 evaluated the case having the architect's standpoint in mind, while Ms. Muncy did so having the overall process in mind.

Summary/Comments on contractors

Since seven people served as contactors in our case study, a table for each alternative is presented for their choices to allow for easier interpretation of the results.

Table 4.6-5: Ratings of contractors for the on-site construction alternative

On-site construction	Chase	Menard	Lee	Contractor 1	Contractor 2	Contractor 3	Thomson	Mean
1. Number of suppliers	0	0	0	0	0	0	0	0.0
2. Location of suppliers	20	5	30	50	25	70	30	32.9
6. Local labor cost	0	0	0	0	0	0	0	0.0
7. Installation time	0	0	0	0	0	0	0	0.0
8. Robustness	60	20	15	100	60	20	15	41.4
9. Quality of slopes	40	10	0	0	0	0	0	7.1
10. Quality of finishes	0	10	0	0	0	0	0	1.4
11. Number of layouts	0	0	0	0	0	0	0	0.0
12. Safety	0	0	0	0	0	0	0	0.0
14. Construction time	0	0	0	0	0	0	0	0.0
15. Efficiency	0	0	0	0	0	0	0	0.0
16. Design flexibility	40	60	5	50	60	20	5	34.3
17. Waste reduction	0	0	0	0	0	0	0	0.0
18. Weather	0	0	0	0	0	0	0	0.0
TOTAL	**160**	**105**	**50**	**200**	**145**	**110**	**50**	**117.1**

What we see in the table:

- Most contractors did not consider the advantage of location to be very important. Apparently, they do not believe that projects can benefit from having the suppliers within a small distance. Only Contractor 3 assigned a high grade.

- Most contractors did not really agree that robustness increases with on-site construction. Only Contractor 1 assigned a very high rating (100). Mr. Chase and Contractor 2 also assigned an above than the mean rating.
- Mr. Chase and Mr. Menard were the only professionals believing that quality of slopes increases with on-site construction. Mr. Chase in particular assigned a relatively high rating.
- The most surprising result was the high ratings assigned to flexibility by contractors. Contractors are not usually involved in the design phase and most importantly; changes at a later stage could harm their schedule. However, the mean of the factor was 34.3 with two professionals giving 60 points to this advantage.

Table 4.6-6: Ratings of contractors for the "site prefab" alternative

Prefabrication at the worksite	Chase	Menard	Lee	Contractor 1	Contractor 2	Contractor 3	Thomson	Mean
1. Number of suppliers	0	0	0	0	0	0	0	0.0
2. Location of suppliers	20	15	30	50	25	70	30	34.3
6. Local labor cost	0	0	0	0	0	0	0	0.0
7. Installation time	40	10	45	50	75	35	10	37.9
8. Robustness	0	10	0	0	0	0	0	1.4
9. Quality of slopes	0	10	0	0	0	0	0	1.4
10. Quality of finishes	60	20	80	75	80	85	95	70.7
11. Number of layouts	40	0	5	0	40	90	10	26.4
12. Safety	50	5	85	5	50	75	80	50.0
14. Construction time	80	30	100	0	80	10	100	57.1
15. Efficiency	40	20	70	70	70	90	40	57.1
16. Design flexibility	0	0	0	0	0	0	0	0.0
17. Waste reduction	20	20	40	5	40	40	20	26.4
18. Weather	20	30	40	50	60	95	40	47.9
TOTAL	**370**	**170**	**495**	**305**	**520**	**590**	**425**	**410.7**

Table 4.6-7: Ratings of contractors for the "factory prefab" alternative

Prefabrication in a factory	Chase	Menard	Lee	Contractor 1	Contractor 2	Contractor 3	Thomson	Mean
1. Number of suppliers	20	30	20	50	75	25	35	36.4
2. Location of suppliers	0	0	0	0	0	0	0	0.0
6. Local labor cost	100	10	60	100	75	30	95	67.1
7. Installation time	80	30	55	95	100	40	25	60.7
8. Robustness	0	10	0	0	0	0	0	1.4
9. Quality of slopes	0	60	10	50	50	80	15	37.9
10. Quality of finishes	60	90	80	75	80	85	95	80.7
11. Number of layouts	40	0	5	0	30	85	10	24.3
12. Safety	50	10	85	5	50	75	80	50.7
14. Construction time	80	30	100	0	80	10	100	57.1
15. Efficiency	60	30	75	80	90	100	65	71.4
16. Design flexibility	0	0	0	0	0	0	0	0.0
17. Waste reduction	20	20	40	5	40	40	20	26.4
18. Weather	20	30	40	50	60	95	40	47.9
TOTAL	**530**	**350**	**570**	**510**	**730**	**665**	**580**	**562.1**

Since both prefabrication options have similar advantages for most factors, we will comment simultaneously on both the above tables:

- What we expected to see was the factor concerning construction time to dominate the ratings of contractors. However, only four of them assigned high ratings. It was very surprising to see two professionals give 0 and 10 points.

- Safety considerations' factor was a surprising result for us as well. We expected contractors to rate more highly the advantages that prefabrication offers. The controlled factory or warehouse conditions minimize risks concerning accidents leading to potential financial savings as presented in sections 2.2.4 and 3.3.3.

- The waste reduction factor was definitely expected to score more than 26.4 points in average, based on our correspondence with construction industry experts and our literature review.

- The factor that gathered the highest mean rating on the other hand was the quality of finishes. All experts agreed that it is crucial for a project to enjoy high quality in this area. Architects and owners also agreed on the importance of the factor. It is interesting to see however, that some of them considered "factory prefab" to offer higher quality than "site prefab".

- Almost all professionals also agreed on the importance of efficiency, local labor cost and installation time. Local labor cost has an average of 67.1 and was either considered very important getting close to 100 points or not important at all getting close to 10. The advantage of installation time of "factory prefab" versus "site prefab" was calculated to a 23-point difference in average. In addition, the 10% difference in efficiency resulted in a 14-point difference in average.

- Quality of slopes, number of suppliers and number of layouts/units did not prove to be popular amongst contractors.

To sum up, we see contractors being more aligned than the architects presented before. Only Contractors 2 and 3 seem to have rated the advantages differently. Of course the number of architects was small and we cannot make broad conclusions from only two persons.

Summary/Comments on owners

Three owners evaluated the case study. We present our comments in two groups of bullet points. The first group presents the points of mutual agreement while the second includes the disagreements.

Factors of mutual agreement:

- Number and location of material suppliers were not of importance to any of them

- They all agreed that robustness is not improved with on-site construction, which is quite interesting.

- They also assigned very small or zero grades to quality of slopes that prefabrication offers

- Safety considerations. All gave few points. We expected safety considerations to be of major interest mainly to contractors.

- Efficiency. They all assigned high ratings. Mr. Pikel believes efficiency is equal for both prefabrication alternatives.

- Waste reduction was not really important to any of them. Only Mr. Milbrand assigned somewhat more weight on the factor (50 points).

Disagreements:

- The factor of local labor cost gathered 90-65 and 40 points respectively.

- Installation time also had some dissimilarities to its assessment.

- Quality of finishes is important only for Mr. Ott and Mr. Pikel. Mr. Milbrand gave low score to the factor (40).

- The number of units was considered crucial for Mr. Milbrand in contrast with the other two owners and especially Mr. Ott.

- Construction time was not uniformly evaluated. Mr. Ott assigned a low rating (30) compared to the others that thought it is a significant advantage of prefabrication.

- Design flexibility was somewhat important to Mr. Ott and Mr. Milbrand but totally irrelevant to Mr. Pikel in contrast to our expectations.

- Weather delays affected a lot only Mr. Milbrand's evaluation.

Overall comparisons across architects-contractors-owners

In this section we present visually the differences in ratings between architects, contractors and owners. Figures 4.6.5-7 show the difference in average ratings of each factor for the 3 alternatives.

In figure 4.6.5 we see that architects considered on-site construction to be very robust. We did not see many differences in the other factors. We expected to see architects evaluating design flexibility much higher than the other professionals though.

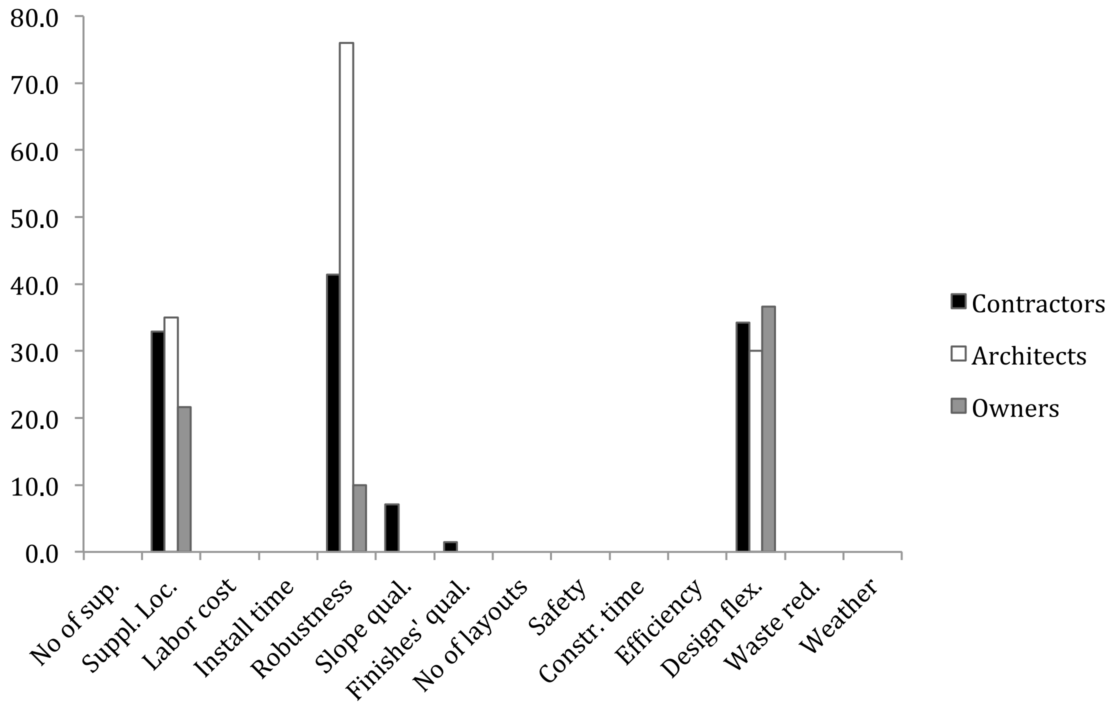


Figure 4.6-5: Comparison of average ratings for on-site construction factors

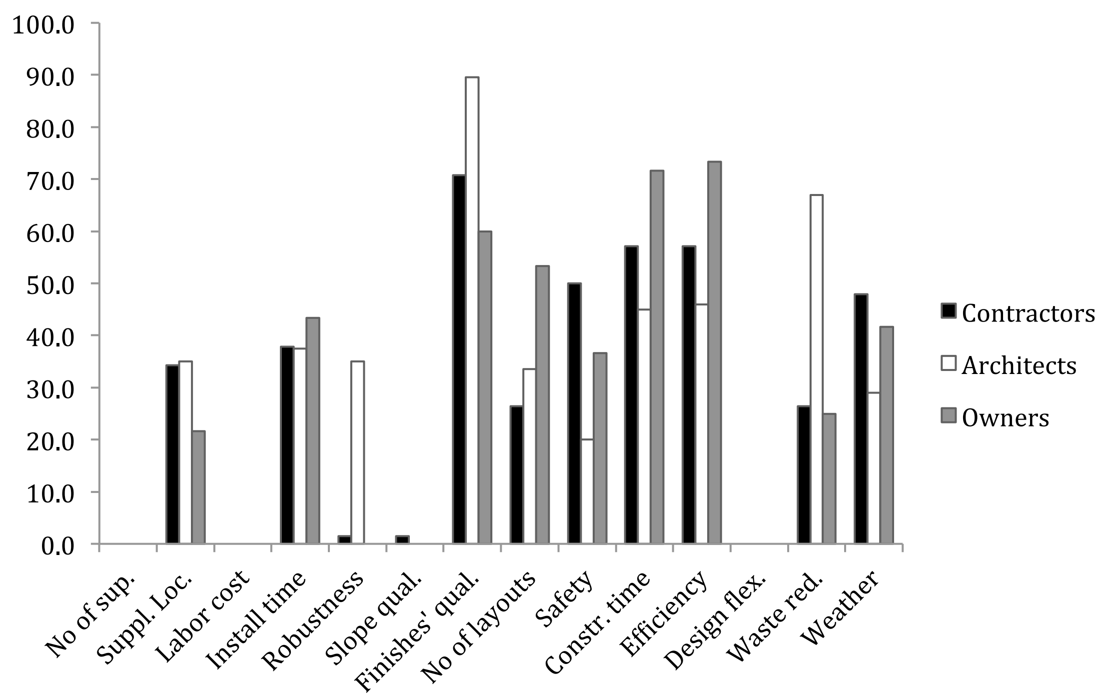


Figure 4.6-6: Comparison of average ratings for site prefabrication factors

Things we notice in this graph:

- Architects value quality of finishes higher than any other professional.
- Architects also rate very highly the environmental impact of the projects as we can see from the waste reduction factor.
- Owners value higher than anyone else the number of layouts/units the project has. The factor influences a lot their decision.
- Owners also evaluate higher than anyone else the construction time of the project and the efficiency of the workers. They are the ones paying, so it makes total sense.
- Contractors rate highly weather delays and safety considerations followed by owners, which was highly expected as well.
- Factors concerning suppliers and installation time were very balanced

Overall, the three areas do not seem to have huge discrepancies in their evaluations. Most factors were evaluated quite similarly.

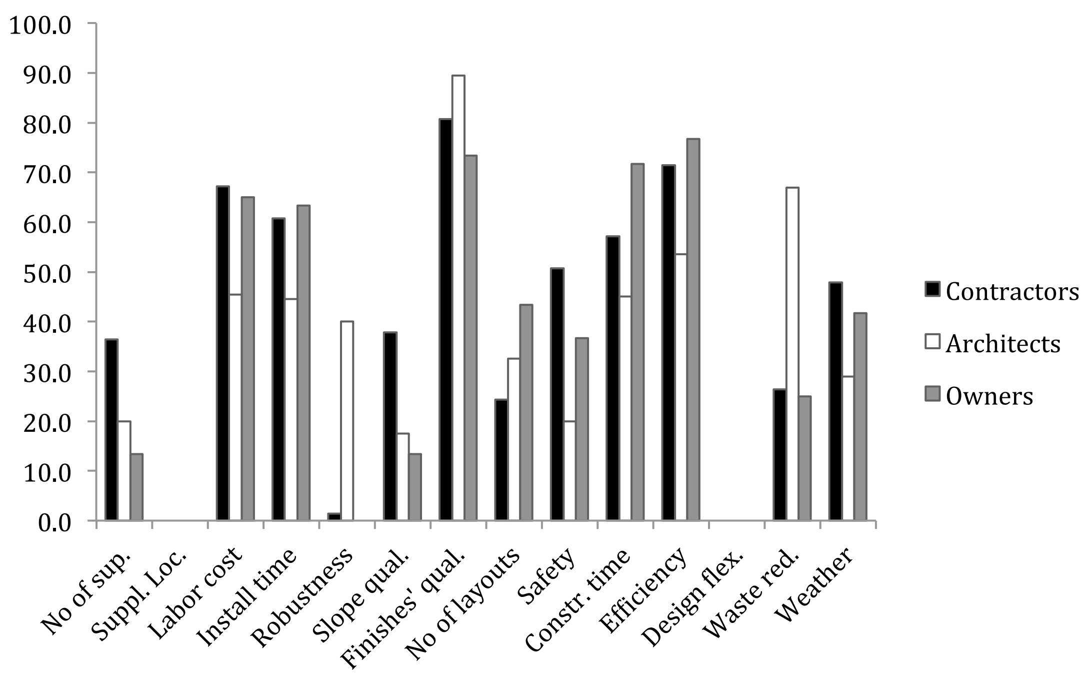


Figure 4.6-7: Comparison of average ratings for factory prefabrication factors

Things we notice in this graph:

- Contractors rate higher than the others the number of suppliers factor

- Labor cost and installation time is evaluated equally by contractors and owners but lower from architects
- Only architects seem to believe in the robustness of factory prefabrication
- Only contractors believe that quality of slopes can be increased with factory prefabrication
- All professionals rate very highly the quality of finishes with architects leading in ratings.
- Owners value higher than anyone else the number of layouts/units the project has.
- Owners also evaluate higher than anyone else the construction time of the project and the efficiency of the workers.
- Contractors rate highly weather delays and safety considerations followed by owners, which was highly expected as well.
- Architects rate very highly the environmental impact of the projects as we can see from the waste reduction factor.

Overall, we see again relatively small differences in the ratings of the three groups of professionals.

5 Conclusion

The author attempted to answer the question "how does one decide whether or not to use prefabrication in a project?" A case study was formed using the "Choosing by Advantages" decision-making methodology based on real project data. The project used for our case was the Expansion of Alfred I. DuPont Hospital for Children, which is being constructed in 2013 in Wilmington, Delaware. Three construction techniques were considered: on-site construction, prefabrication adjacent to the worksite and prefabrication in a factory.

The second chapter of the thesis presented the history of lean thinking and gave the chance to the reader to be informed about how people managed to improve overtime, acquiring better management skills and more profound knowledge both in the manufacturing and the construction industry. In our opinion, the next step is the development of an accurate decision-making tool that could help professionals make sound decisions. We attempted to evaluate the CBA methodology that is used like such a tool.

In the second chapter, we also presented the prefabrication sector with its attributes, its potential advantages and its limitations. Two successful implementations of prefabrication in tandem with lean approaches were also presented for the Atlantic Yards B2 modular building in New York and the Warriors in Transition Barracks in Fort Carson, Colorado.

After a long and iterative process and after corresponding with several people involved in the construction and prefabrication industries we identified 19 components that influence the decision-making process of bathrooms construction. Those components (called factors according to the CBA nomenclature we discussed in chapter 3) were incorporated to our case study. Advantages for each alternative were established based on the data we gathered from the project that served as our case study.

The next step was to reach out to construction industry experts and ask for their opinion on the advantages of each alternative. Those experts were categorized in four groups according to their discipline: architects, contractors, owners and academics. The goal was to investigate their differences in philosophy (if any) and to see if their selections would coincide.

The results showed a uniform preference towards prefabrication in a factory for this particular project. All professionals agreed on their selections having the prefabrication adjacent to the worksite as their second option. We did not witness vast differences among their opinions, but there were definitely discrepancies in their opinions concerning the weight of each advantage. The greatest difference in opinion was spotted between the two architects that evaluated the case. Owners and contractors were more aligned in their evaluations.

To sum up, the case study we developed demonstrated that the CBA methodology could be used at least as a preliminary analysis tool. It is quite useful to notice the discrepancies between project stakeholders when decisions need to be made. The most important step in using the method however, is the establishment of its factors. Inaccurate or biased selection of factors can easily shift the decision towards or against a certain alternative. Nevertheless, if all components affecting the decision process are included in the CBA analysis, their evaluation can show where the discrepancies in opinions exist as we did for our case study. In this way, the participating parties can focus on solving smaller and better-defined problems.

6 Discussion

The results in our case study revealed a clear domination of the prefabrication options and especially the factory prefabrication. It was exactly what we expected to see as described in section 3.2.1 because:

- The case was based on the data that had by default a clear inclination towards prefabrication options. Factors like reliability, accessibility and others that could potentially harm prefabrication were absent.

- We saw however that even professionals who usually select on-site construction or "site prefab" for their projects selected "factory prefab" in this case, which proves that this method is a possible tool for sound decisions. Even if we had created the case wrongly, we did not observe a bias in the results.

Nevertheless, should another case have been created, the results could have been reversed towards another alternative. The goal of our research was not to prove that prefabrication is a great option that can be selected across all projects. We wanted to create a case study in order to test the CBA method and investigate the differences in opinion between construction industry professionals.

The author attempted to create a second case study based on a hospital project that was built in the Boston area and constructed its bathrooms on-site, but failed to gather enough data. It would be very interesting to compare two projects -one that used and one that did not use prefabrication- and see if the CBA method would lead to the same decision taken by the general contractors in reality.

In addition, it would very nice if we could have a higher number of professionals providing input. We could present more accurate results and reach more valid conclusions. The time spent in establishing the case has been significant enough that it did not allow for more expert interviews. We reached out to about 25 professionals and received 13 answers. We would certainly like to have more input, but we believe we have set the foundation for further research in the area.

6.1 Critical Interpretation of CBA

The "Choosing by Advantages" decision-making methodology seems to offer a great deal of benefits to the user. The author's opinion for the method is overall positive. The problem addressed can be broken down in smaller pieces (factors) that can be tackled separately for each alternative allowing an easier approach. In addition, the experience gained by using the method, can benefit the decision-makers in general. Problem-solving ability is developed in a great extent as well as critical thinking.

Furthermore, the method offers the possibility for many people to cooperate in the decision-making process. The notion of disagreements between architects and engineers for example is widespread. As in all problems, the most important step towards solving them is to locate the source, the main reason behind them. The CBA tool can help in this direction. The components where discrepancies in opinion exist can be accurately identified and located. Consequently, the project stakeholders can focus on those particular factors rather than wasting time on trying to solve an ill-defined problem.

However, the author must note some potential disadvantages of the method, or rather of the way the method is applied by users. To begin with, locating all the factors influencing a problem is a major task for the users. It's a tedious process to establish and correctly include all factors affecting the decision-making process. Failing to include all of them in the CBA method could harm the end result and steer the decision in favor or against one alternative.

In our case for example, we attempted to identify the advantages for all three alternatives we wanted to evaluate. To achieve that, we contacted people within construction companies that select on-site construction, companies that prefabricate bathrooms adjacent to the worksite, companies that have purchased prefabricated bathroom facilities from a third party and manufacturing firms of prefabricated bathroom units. Afterwards, we attempted to include all the advantages we collected for each option in our case study. It is true that the case appeared to favor prefabrication options, but we could not locate more advantages for the on-site construction. The reader must also keep in mind that the cost component is not addressed by the CBA. Many people argued that the major advantage of on-site construction is cost. Of course, it is debatable if their analysis includes the "hidden costs" we presented in section 2.2.4.

On the other hand, if a similar analysis was attempted and the only source of information had been for example companies that select on-site construction, probably none of the advantages of prefabrication could have been captured. In that case, the CBA analysis would be unable to produce sound results.

In addition, decision-makers must be as objective as possible when using the method. In case they are strongly biased in favor or against an alternative, the numbers they assign as weights to the advantages will reflect this predisposition leading the result to be what they wanted in the first place. In that case, the method is clearly useless.

Furthermore, the cost component is not addressed with CBA. All other advantages are evaluated except for that because it is believed that cost could harm the objectiveness of the method, not allowing the users to investigate anything else beyond that. It is true however, that cost is a significant component to consider. The author suggests 2 approaches that can help engineer around the "problem":

1. Address the cost of each alternative in advance. Alternatives that pass the defined cost limits are incorporated to the CBA for evaluation. In that case, the alternative with the biggest score is the one that should be selected since the cost factor was addressed in advance.

2. Run the CBA analysis with all possible alternatives. Scale the scores of all those alternatives and run a cost analysis. If the alternative with the biggest score passes the "cost control test", it should be selected. If it does not, inspect the second best and so on until you find a solution that satisfies both CBA and cost criteria.

In conclusion, the CBA method offers significant advantages as long as the prerequisites mentioned are respected. As a result, the method itself is a useful tool but it relies exclusively on the abilities of its users. Applying it correctly can most likely lead to sound decisions. Applying it erroneously or incompletely could lead to wrong decisions.

6.2 Can this method be applied for broader decisions?

Our ultimate goal in this thesis was to establish a methodology that could tackle broader problems. The author did not create the CBA methodology, but the approach to the problem of prefabricated bathrooms with the establishment of all the relevant factors was part of our research. Prefabrication of bathrooms was only a small-scale problem that could be adequately addressed in the limited amount of time we had available. However, we have always been keeping an eye to the "bigger picture".

In our opinion, the CBA method is a valuable tool that, if used appropriately and objectively, can lead to useful conclusions. As has already been mentioned, all involved parties must know the procedure and report their opinion unbiased about the final solution. Lean thinking encourages all the relevant people of a project to get involved at an early stage, thoroughly analyze all issues and mutually agree on decisions. CBA is a tool that could be used during this process.

Consequently, we believe that the CBA method could very well be used in the decision-making process of any kind, at least for a preliminary analysis. Positive results can be derived from this process, since it could be used only as an advice benchmark tool if needed. Further research in the field could definitely provide useful insight. However, the author's correspondence with construction industry experts revealed that companies trained in lean thinking gradually start implementing this method for making decisions. We could certainly expect to hear more about it in the years to come.

6.3 Suggested Next Steps

A great deal of value is yet to be added in the field. Construction companies could highly benefit from expanding their understanding in certain areas. In our opinion, some steps that could contribute value to the industry are the following:

- Thorough investigation and identification of time and cost of coordination. A very hard cost to quantify for construction companies and a very important factor to consider in any CBA analysis. Unfortunately, our research was unable to yield tangible results in the area and the factor was not included in our CBA case to avoid using erroneous data. Research in the area could be very tedious, take a long time and require direct cooperation with construction companies.

- The same analysis could be repeated again for bathroom construction of other projects. Getting real data for a project is a time consuming process, as it requires collaboration with construction companies willing to share information. The author attempted to investigate a second hospital case study, but was unable to gather all required information from the general contractor of the project. As a result, the same analysis could potentially be repeated since many important factors have already been identified (of course the next researcher could add/drop factors based on his/her own judgment) in order to see if the results would be similar. The researcher could focus on establishing contacts with contractors and not spend the amounts of time we spent in this thesis for establishing the factors.

- A potential next attempt could include expanding the expert opinion pool. As already stated, the author of this thesis spent a significant amount of time establishing the factors necessary for the analysis. More time could be spent on locating experts of the construction industry willing to evaluate the case.

- The method could be used to evaluate a different case study except for bathroom prefabrication. It could be another prefabrication area (like investigate why curtain wall prefabrication appears to dominate or the MEP service racks case) or it could be a totally different evaluation. Many decisions need to be made during the project development phase and this method could be tested for many other decisions during that stage.

- Finally, an application of the method to broader decision-making could certainly be useful. A case where the CBA method attempts to evaluate the delivery method of a project (design-build, general contractor etc.) for example could be very interesting.

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A Appendix. Survey Data

Architects

Table A 1: Ratings from Architect 1

Architect 1	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	10
2. Location of suppliers	10	10	0
6. Local labor cost	0	0	60
7. Installation time	0	0	10
8. Robustness	60	70	80
9. Quality of slopes	0	0	10
10. Quality of finishes	0	80	80
11. Number of layouts	0	0	0
12. Safety	0	0	0
14. Construction time	0	10	10
15. Efficiency	0	20	30
16. Design flexibility	30	0	0
17. Waste reduction	0	70	70
18. Weather	0	0	0
SUM	**100**	**260**	**360**

Table A 2: Ratings from Ms. Bernadette Muncy

Bernadette Muncy	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	30
2. Location of suppliers	60	60	0
6. Local labor cost	0	0	31
7. Installation time	0	75	79
8. Robustness	92	0	0
9. Quality of slopes	0	0	25
10. Quality of finishes	0	99	99
11. Number of layouts	0	67	65
12. Safety	0	40	40
14. Construction time	0	80	80
15. Efficiency	0	72	77
16. Design flexibility	30	0	0
17. Waste reduction	0	64	64
18. Weather	0	58	58
SUM	**182**	**615**	**648**

Contractors

Table A 3: Ratings from Mr. Brian Chase*

Brian Chase	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	10
2. Location of suppliers	10	10	0
6. Local labor cost	0	0	50
7. Installation time	0	20	40
8. Robustness	30	0	0
9. Quality of slopes	20	0	0
10. Quality of finishes	0	30	30
11. Number of layouts	0	20	20
12. Safety	0	25	25
14. Construction time	0	40	40
15. Efficiency	0	20	30
16. Design flexibility	20	0	0
17. Waste reduction	0	10	10
18. Weather	0	10	10
SUM	**80**	**185**	**265**

Table A 4: Ratings from Mr. Scott Menard

Scott Menard	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	30
2. Location of suppliers	5	15	0
6. Local labor cost	0	0	10
7. Installation time	0	10	30
8. Robustness	20	10	10
9. Quality of slopes	10	10	60
10. Quality of finishes	10	20	90
11. Number of layouts	0	0	0
12. Safety	0	5	10
14. Construction time	0	30	30
15. Efficiency	0	20	30
16. Design flexibility	60	0	0
17. Waste reduction	0	20	20
18. Weather	0	30	30
SUM	**105**	**170**	**350**

* Mr. Chase assigned 50 as his biggest rating. For comparison purposes with the other professionals who assigned 100 as their biggest grade, his answers were multiplied by 2 in the main body of the thesis

Table A 5: Ratings from Mr. Douglas Lee

Douglas Lee	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	20
2. Location of suppliers	30	30	0
6. Local labor cost	0	0	60
7. Installation time	0	45	55
8. Robustness	15	0	0
9. Quality of slopes	0	0	10
10. Quality of finishes	0	80	80
11. Number of layouts	0	5	5
12. Safety	0	85	85
14. Construction time	0	100	100
15. Efficiency	0	70	75
16. Design flexibility	5	0	0
17. Waste reduction	0	40	40
18. Weather	0	40	40
SUM	**50**	**495**	**570**

Table A 6: Ratings from Contractor 1

Contractor 1	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	50
2. Location of suppliers	50	50	0
6. Local labor cost	0	0	100
7. Installation time	0	50	95
8. Robustness	100	0	0
9. Quality of slopes	0	0	50
10. Quality of finishes	0	75	75
11. Number of layouts	0	0	0
12. Safety	0	5	5
14. Construction time	0	0	0
15. Efficiency	0	70	80
16. Design flexibility	50	0	0
17. Waste reduction	0	5	5
18. Weather	0	50	50
SUM	**200**	**305**	**510**

Table A 7: Ratings from Contractor 2

Contractor 2	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	75
2. Location of suppliers	25	25	0
6. Local labor cost	0	0	75
7. Installation time	0	75	100
8. Robustness	60	0	0
9. Quality of slopes	0	0	50
10. Quality of finishes	0	80	80
11. Number of layouts	0	40	30
12. Safety	0	50	50
14. Construction time	0	80	80
15. Efficiency	0	70	90
16. Design flexibility	60	0	0
17. Waste reduction	0	40	40
18. Weather	0	60	60
SUM	**145**	**520**	**730**

Table A 8: Ratings from Contractor 3

Contractor 3	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	25
2. Location of suppliers	70	70	0
6. Local labor cost	0	0	30
7. Installation time	0	35	40
8. Robustness	20	0	0
9. Quality of slopes	0	0	80
10. Quality of finishes	0	85	85
11. Number of layouts	0	90	85
12. Safety	0	75	75
14. Construction time	0	10	10
15. Efficiency	0	90	100
16. Design flexibility	20	0	0
17. Waste reduction	0	40	40
18. Weather	0	95	95
SUM	**110**	**590**	**665**

Table A 9: Ratings from Mr. James Thomson

James Thomson	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	35
2. Location of suppliers	30	30	0
6. Local labor cost	0	0	95
7. Installation time	0	10	25
8. Robustness	15	0	0
9. Quality of slopes	0	0	15
10. Quality of finishes	0	95	95
11. Number of layouts	0	10	10
12. Safety	0	80	80
14. Construction time	0	100	100
15. Efficiency	0	40	65
16. Design flexibility	5	0	0
17. Waste reduction	0	20	20
18. Weather	0	40	40
SUM	**50**	**425**	**580**

Owners

Table A 10: Ratings from Mr. Timothy Ott

Timothy Ott	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	20
2. Location of suppliers	20	20	0
6. Local labor cost	0	0	90
7. Installation time	0	30	70
8. Robustness	0	0	0
9. Quality of slopes	0	0	20
10. Quality of finishes	0	50	90
11. Number of layouts	0	10	10
12. Safety	0	30	30
14. Construction time	0	30	30
15. Efficiency	0	50	75
16. Design flexibility	60	0	0
17. Waste reduction	0	20	20
18. Weather	0	20	20
SUM	**80**	**260**	**475**

Table A 11: Ratings from Mr. Christian Pikel

Christian Pikel	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	10
2. Location of suppliers	20	20	0
6. Local labor cost	0	0	60
7. Installation time	0	80	80
8. Robustness	0	0	0
9. Quality of slopes	0	0	0
10. Quality of finishes	0	90	90
11. Number of layouts	0	50	50
12. Safety	0	30	30
14. Construction time	0	90	90
15. Efficiency	0	80	80
16. Design flexibility	0	0	0
17. Waste reduction	0	5	5
18. Weather	0	30	30
SUM	**20**	**475**	**525**

Table A 12: Ratings from Mr. John Milbrand

John Milbrand	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	10
2. Location of suppliers	25	25	0
6. Local labor cost	0	0	45
7. Installation time	0	20	40
8. Robustness	30	0	0
9. Quality of slopes	0	0	20
10. Quality of finishes	0	40	40
11. Number of units	0	100	70
12. Safety	0	50	50
14. Construction time	0	95	95
15. Efficiency	0	90	75
16. Design flexibility	50	0	0
17. Waste reduction	0	50	50
18. Weather	0	75	75
SUM	**105**	**545**	**570**

Academics

Table A 13: Ratings from Mr. Darren Olsen

Darren Olsen	Alternatives		
Factors	On-site	Site prefab.	Factory Prefab.
1. Number of suppliers	0	0	15
2. Location of suppliers	20	20	0
6. Local labor cost	0	0	70
7. Installation time	0	70	70
8. Robustness	40	40	40
9. Quality of slopes	0	0	20
10. Quality of finishes	0	50	50
11. Number of layouts	0	10	10
12. Safety	0	0	70
14. Construction time	0	80	80
15. Efficiency	0	50	50
16. Design flexibility	50	0	0
17. Waste reduction	0	20	20
18. Weather	0	20	20
SUM	**110**	**360**	**515**