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Applying Manufacturing Engineering Principles to Modular Building Methods

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Construction Project Management:

Analysis of Modular Building Methods

A Major Qualifying Project

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Abstract

The goal of this project was to analyze a broad modular construction building process using the principles of manufacturing engineering. A construction project was hypothesized and the overall process was analyzed using Axiomatic Design in order to maximize the value added of modular construction to the project owner. After each step was analyzed, the process was reconstructed and compared to the original to determine value added. This paper will describe and explain the results of this analysis.

Acknowledgments

I would first like to extend my gratitude to the advisors of this project, Professor Walter T. Towner and Professor Helen Vassallo. I was fortunate enough to have significant discussions with both professors regarding the development and completion of this Major Qualifying Project as well as my personal goals and endeavors. Professor Towner shared with me his extensive knowledge of the principles of manufacturing engineering and the applications and uses for Axiomatic Design in fabrication and manufacturing processes. Also, at a time when I found myself struggling with my personal motivation, Professor Vassallo was able to remind me of all the opportunities I have been given by attending Worcester Polytechnic Institute and accepting a job offer with Kiewit Corporation. Through different approaches, both advisors were able to motivate and reinvigorate within me the spark that I needed to successfully complete my time as a student at WPI.

I would also like the thank Patrick Tompkins, Lyle Coghlin, and the CTA Construction Managers team for having given me the opportunity to gain valuable experience through their company and work. I was able to complete a Co-Op with CTA as an Assistant Project Manager throughout the summer of 2015 and become familiar with the processes and demands for construction project management. Mr. Tompkins also allowed me to interview him and agreed to share with me, not only his vast knowledge of construction project management, but also his experiences with projects using modular building methods.

Another crucial asset to the completion of this project was Research Librarian, Laura Hanlan at WPI's Gordon Library. Ms. Hanlan shared a multitude of available resources and scholarly articles with me via several search engines provided by the Gordon Library while also developing my skills for searching and evaluating different works that would become very important to the completion of this project.

I would like to thank María Gomez-Lara, a PhD candidate in Civil Engineering at WPI whom I was fortunate enough to meet with and discuss the application of Manufacturing Engineering principles and Axiomatic Design to construction processes and Civil and Environmental engineering. And finally, thank you to Professor Christopher Brown and his Design and Analysis of Manufacturing Processes class (ME543) for sharing their feedback and knowledge on the applications of Axiomatic Design and the development of my project.

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Introduction & Problem Statement

In an interview with Steve Kroft of CBS News, Ray LaHood, the secretary of transportation during the first Obama administration, explained that there are major issues with The United States' infrastructure that have not been addressed (Kroft, 2014). Infrastructure is the basic physical and organizational structures and facilities needed for the operation and functionality of a society or enterprise. Roads, bridges, railways, and buildings constantly undergo ambitious renovation projects that merely patch the problem for a short period of time but never address the crumbling foundation of these structures that play a key role in American day-to-day life. For public construction, these issues stem from a lack of funding and directive (Kroft, 2014) and for private projects, the cost of a brand new project is often too great and deters any potential investors who do not see the long-term value in reconstruction and rather focus on short-term returns. In reality, the long-term benefits of a new construction project can outweigh the short-term benefits of a renovation by allowing for the project to begin as a clean slate (Kreiss, 2013). This allows for the opportunity to redesign more efficiently to better accommodate the owner's needs and improve the functional requirements of the building as a whole (Tompkins, 2015). There are also ongoing studies and efforts being made to improve the quality and cost of construction with different methods being improved upon or redesigned.

One reason why a new project is usually unappealing is because traditional construction methods are infamous for being lengthy and unproductive (Exponent). This is due to a variety of reasons; the client's needs changing, mistakes that occur during construction, miscommunication of objectives, and even the weather can all factor into an increase in time and cost for the completion of a construction project (Lupberger, 2015).

As compared with traditional construction methods, modular construction is typically quicker and more efficient when erecting homes and smaller buildings (Lavinia, 2013). Many of the on-site activities can be completed off-site. Modular construction involves prefabricating modules (boxes) of the building at an off-site facility and then transporting the pieces for on-site assembly. This off-site manufacturing allows for fabrication and construction activities to be completed simultaneously. As modules begin to be produced, the site can be surveyed, prepared, and coordinated in order to allow for facilitated unloading and assembly processes.

Modular building methods are typically used to build or produce a large quantity of smaller, residential projects in a certain amount of time (Tomkins, 2015). This project will focus on breaking down the process of a construction project that is implementing modular building methods. Although modular construction has many advantages over conventional construction methods, it is still a lengthy process that involves many steps where non-value added time could be found. These process steps will be broken down, analyzed, and restructured in order to provide a more efficient building process.

The goal of this project is to analyze the modular construction building process using the principles of manufacturing engineering. This analysis will include financial, construction, and axiomatic design methods. Each step in the modular construction process will be evaluated and reformed in order to provide the project owner or client with the maximum value of their project.

Literature Review

Industry Analysis for Prefabricated Homes

Prefabricated home manufacturing is a $7.4 billion market that has seen an annual average growth of 4.9% since 2010. An overall increase in demand for residential housing has led this to be a lucrative industry with companies increasing the average production cost of a pre-manufactured home from $62,992 in 2010 to $64,543 in 2015 in order to increase revenue by taking advantage of growing demand. The market for prefabricated housing was also expected to increase by 4% in 2015 as compared to 3.9% in 2014, 8.5% in 2013, and 11.4% in 2012 (IBISWorld, 2015). Not only has there been increasing demand and growth within this market but there has also been an increase in research and development in attempts to improve the quality of projects that utilize modular and prefabrication construction methods. Several scholarly articles pertaining to the study of modular housing have been published in recent years. A search of modular housing and sustainability via Google Scholar and Summon results in a plethora of articles from a variety of sub disciplines. Below is a sample of articles found.

Example of Agricultural Application

Investigation of Heating and Cooling Potential of a Modular Housing System for Fattening Pigs with Integrated Geothermal Heat Exchanger (Krommweh, M., Rosmann, P., & Buscher, W. 2014). This article explored the need for innovations in energy use for livestock farming and conducted research on the feasibility of using recuperative air-to-air heat exchangers and geothermal heat exchangers in an attempt to reduce electricity and gas consumption.

Examples of Housing Applications

A Study on the Quality Improvement Strategies of Design through Analyzing the Domestic Modular Housing Cases (Jun, Y., Kim, K., & Lee, Y. 2015) where research was conducted on several existing housing projects that utilized different designs in an attempt to find an optimal design for reducing energy and maintenance costs.

A Comparative Analysis on the Life Cycle CO_2 Emission Between Modular Housing and R.C. Apartment Housing (Park, J., Kim, S., & Chae, C. 2014). Here, the life cycle carbon dioxide emissions for different modular housing and residential college apartment housing units were studied to determine which would be a more environmentally friendly option for future housing projects.

Solar-powered, Modular, Emergency/Disaster Response Housing (Brandhorst, H. W. & Rodiek, J. A. (2009) where the need to be able to provide disaster victims, such as those affected by hurricanes Katrina and Ivan, with temporary modular housing was discussed and specific requirements for design, appliances, and insulation were proposed.

The scholarly works mentioned above are just a small sample of the extensive work and research that has been done regarding the improvement and optimization of modular housing while also exploring different benefits that this type of construction fabrication can provide. These articles, along with many others, represent an existing demand for modular construction and the benefits it can provide.

Beneficiaries

This Major Qualifying Project's intention was to explore the process of modular building through the application of manufacturing engineering principles. The conclusions and results of this project may serve as a foundation for improvements to varying processes for a number of stakeholders in the construction industry:

1) Construction Project Owners

   Benefit: Project Owners will be able to make the most out of their investment and the services that the building or project is intended to provide.

2) Contractors

   Benefit: Contractors may use this methodology in order to provide competitive bids and quality projects in order to gain ground in to large and lucrative market.

3) Design Engineers

   Benefit: The demand for design engineers will increase among construction companies who wish to apply principles of manufacturing engineering, such as Axiomatic Design, to future projects.

4) U.S. Government

   Benefit: An opportunity to improve the country's infrastructure in innovative and cost-efficient ways.

Methods and Materials

This Major Qualifying Project for Worcester Polytechnic Institute was completed through the research of several subject matters, discussions, and interviews. These subjects include manufacturing engineering principles, construction project management, modular building methods, and the application of Axiomatic Design to the manufacturing of construction processes.

Research and discussions were conducted independently. The WPI Gordon Library's Research Librarian, Laura Hanlan, was able to provide a multitude of scholarly articles, resources, and information pertaining to the subjects mentioned through her research expertise and The Gordon Library's vast collection of information. Meetings were held periodically with Professor Towner and Professor Vassallo, the advisors of this MQP, to discuss the application and principles of Axiomatic Design, project goals, and completion requirements for this project. Two presentations were also held during professor Christopher Brown's graduate class at WPI, Design and Analysis of Manufacturing Processes (ME543), where feedback was provided by the graduate students in regards to the decomposition of the process of modular building.

Interviews were also held with María Gomez-Lara, a PhD candidate in Civil Engineering at WPI, and Patrick Tompkins, one of the founders and Principal of CTA Construction Managers in Waltham, MA. During these interviews, information was gathered pertaining to the broad application of Axiomatic Design to construction project management, advantages and disadvantages of modular construction, and the development of processes for reducing non-value added time at construction projects utilizing modular building methods. This information will be referenced more specifically later on.

Results

By applying the principles of manufacturing engineering to the modular construction process, it was found that the value added to the project was significantly increased for the project owner. A hypothetical construction project needed to be created in order to quantify the amount of value added to the project. The value of this project was defined by the amount of days that the project was completed ahead of schedule and by how much money the contractor was able to stay within the owner's budget. For a 50-unit housing project, expected to be completed within five years, with a budget of about $15 million, it was found that the project could be completed in as little as 3 ½ years and save the owner a total of $1.8-$2.0 million.

Process Basics

When breaking down and analyzing the process, non-value added time was reduced at most of the functional requirements. For example, non-value added time was reduced during the manufacturing of modules, procurement of materials, delivery of modules, and completion of trade-work. This is due to their respective design parameters and coordination for the completion of previous steps. This means that, for example, as the architectural drawings are being created, the construction site can be prepared and the modules can begin being fabricated, all at the same time. This is due to a good design for the systems used to complete these activities and the identification of overlapping steps in the construction process. When steps overlap, the contractor, superintendent and trade-workers can begin to work on certain activities without depending on the completion of previous steps or phases in the project. Contractors already take advantage of these overlapping steps in an attempt to save time and keep the project on schedule. But, on the other hand, there are specific requirements that only apply to modular building where there exist several inefficiencies. Both the general and specific steps for these processes will be discussed later on.

Application of the Axiomatic Design Method

It was also found that it could be challenging to develop Axiomatic Design (AD) for a construction project for several reasons. The first being that there are unknown variables that can come up during a project that were not taken into account during the decomposition phase of the design process. Any of these can have a significant impact on the cost and scheduling of a construction project. Each of these variables will be explained and discussed.

Another challenge that can arise when applying AD, to modular construction specifically, involves customization. Modular construction is typically used for large construction projects where large amounts of certain modules need to be produced. For a project involving a singular home or building, it may not be cost-effective to use modules because manufacturing and transportation costs need to be taken into account plus any final trade-work that would need to be completed (Tompkins, 2015). For a large housing project where many of the same requirements and fabrication processes for modules can be duplicated during the manufacturing process, research shows that it is favorable to the project owner and contractor to use modular building. These requirements vary between projects, owners, and contractors. Therefore, specific designs must be formed for specific projects and a new design must be developed independently of previous projects in order to properly account for varying aspects of the projects. These include manpower requirements, the need for different subcontractors, specifications for materials, and many others.

The design used for this Major Qualifying Project was intended to serve as a base for the emergence of "design research and education in civil and environmental engineering" (Thompson 2013) and has been applied to a broad, hypothetical process that intends to execute a construction project using modular building methods.

Career opportunities within the field of design engineering were also identified through the completion of this project. Contractors and project owners may hire design engineers to develop and optimize the overall construction processes.

Discussion

Introduction to Manufacturing Engineering Principles

What are Manufacturing Engineering Principles?

Manufacturing engineering, at its root, is a discipline of engineering that deals with manufacturing practices and includes the research, design, and development of systems, processes, machines, tools, and equipment. A manufacturing engineer's primary focus is to turn raw materials into a new or updated product in the most economic, efficient, and effective way possible (Matisoff 1997). Through design engineering, processes can be optimized for a variety of activities in order to achieve a certain goal or produce a product in the most efficient way possible. The ultimate goal in manufacturing engineering is to be able to produce physical artifacts designated by the customer's needs (Matisoff 1997). This can be achieved through the application of different methods and analysis techniques such as Lean and Agile manufacturing, cost-value analysis, time-value analysis, and Axiomatic Design. Using this methodology, the production process can be optimized thereby potentially lowering the cost of the production process.

What is Axiomatic Design?

Axiomatic design is a systems design methodology that uses matrices to analyze the transformation of customer needs and organizes them into domains, such as functional requirements (FRs), design parameters (DPs), and process variables (PVs). Essentially, the customer's needs are translated into the functional requirements, which defines what the design engineer wants to achieve. In order to satisfy the functional requirements, design parameters that fulfill the FR are selected. The DPs sustain how the design engineer plans to achieve the functional requirements. Then, the production variables become details used to fulfill the DPs and, subsequently, their respective FRs. (Suh 1990, Park 2007). Dr. Suh Nam Pyo of MIT's Department of Mechanical Engineering first proposed axiomatic design theory in the 1990s. This method for process analysis and optimization relies on two design principles, referred to as Axioms.

The first is the Independence Axiom, which is to maintain the independence of functional requirements. This means, that each functional element of an effective system should be able to operate separately from the other functional requirements and is analyzed individually without any interaction between one another (Suh 1990, Park 2007).

The second axiom is the Information Axiom. Here, the goal is to minimize the information content of the design using the least amount of steps to achieve the best design.

If both axioms are not satisfied, the functional requirements and their respective design parameters could couple, which may result in the failure of the total system (Suh 1990, Park 2007).

Applying Axiomatic Design to a Construction Project

In order to apply Axiomatic Design to a construction project, the project itself must first be treated as a manufacturing process where the ultimate goal is to produce a physical, final product. These final products, or artifacts, culminate to achieve one final system for satisfying the customer's needs. At each step in the construction process, the goal being achieved must be defined by a functional requirement. Systems must then be developed in order to define how these goals are to be achieved. For construction project management and design engineering, it is crucial that during the development of FRs, the design engineer takes into account any variables that may apply to the construction project at hand.

Without a specific project to develop a design for, quantifiable parameters cannot be established in their most basic form. Also, there is a multitude of different types of projects and variables that would require varying designs. For example, two housing projects for twenty homes being constructed within two years with budgets of $3 million each for the same client will be very different from each other if one is taking place in Texas while the other is based in Massachusetts. Therefore, the details of the system design for each project will be different in order to take into account certain variables such as weather, safety rules and regulations for each state, and even differences in construction materials and soil types.

Designs must be carefully adjusted and developed for each project or bid that takes into consideration many details such as project variables, external variables, and the client's specifications and requirements. It is not difficult to apply the principles of manufacturing engineering to a construction project, but for this Major Qualifying Project, a hypothetical, example construction project needed to be created to show how AD can be applied. This will serve as an example and foundation for the development of designs for future construction projects using modular building methods in hopes of providing the project owner with the most value to their investment.

Introduction to Modular Building

What is Modular Building?

A modular building is a type of structure that is composed of different sections or pieces. These pieces are called modules but are also referred to, in construction lingo, as "boxes" (Tompkins 2015). For a construction project that utilizes modular construction methods, there are several advantages and disadvantages that must be taken into consideration. These will be discussed in following sections. Ultimately, the boxes are designed and then fabricated at a factory off-site. The boxes must then be transported to the construction site for assembly.

This type of construction can be used for erecting most structures, whether they are bridges, railways, or buildings because it involves the off-site fabrication of the structure's pieces. As long as the final product can be broken down into different boxes, the construction project can implement modular building methods. But, the industry for modular building mostly consists of housing projects, where a certain amount of the same unit must be produced to obtain a final product. In this case, the final product could be a neighborhood or other residential area.

Defining the Project

This Major Qualifying Project needed to imagine a specific project to develop a design for a base case. A hypothetical project was developed in order to provide analysis for. Although it was previously mentioned that the cost of producing a prefabricated home was $62,992 and $64, 543 in 2010 and 2015, respectively, this price only takes into account the production of the modules for a much smaller home than what is being considered. For the production of a home using modular building methods, more accurate pricing needed to be established with certain costs being added to the price of production. This price is based on the average cost per square-foot of a home as of 2010. The average price of producing one square-foot was determined to be $65 (Lavinia 2013) and the average size of a home in the U.S. in 2013 was found to be 2,598 square-feet (Christie 2014). Therefore, for a project that intends to produce fifty units within five years, the total cost would be $8,443,500.

$65 per sq-ft x 2,598sq-ft = $168,870 cost of production per home

$168,870 per home x 50 units = $8,443,500 cost of producing fifty homes

That puts the cost of production of each home at about $168,870. Unfortunately, this value only takes into account the production of a prefabricated home without including the acquisition of construction permits, the development of architectural drawings and plans, site surveying and development, transportation costs, and trade-work. When all these factors are included, a final budget of $15 million was determined.

Inefficiencies in Construction

Background on Construction Processes and Steps

Every construction process begins with demand. It could be for a bridge over a river that will cut transportation time by an hour or a housing project that will provide homes for 100 families. It is up to the project owner to identify the demand and prepare the requirements for what the project hopes to achieve. After the project owner has established the specifications for the type of project, the architectural drawings will begin to be developed for the site, trade-work, and finishes. Later, a request to bid is sent out to different contractors. The bid and contractor's purpose is to take into account all the costs that will go into completing the project and proposing a cost-effective way to complete the project on time and within its budget.

Based on the bids submitted to the project owner, the owner chooses a contractor that best fits their requirements, pricing, and scheduling for the project. After a contractor has been chosen, building permits must begin to be acquired and a schematic design developed. While these steps are in the process of being completed, the contractor may also begin to survey the building site.

For modular construction, the modules can begin going into fabrication while the site is being developed and foundations are laid out. As mentioned before, one of the benefits of modular construction is that on-site activities can be completed while the boxes are being manufactured off-site. As modules begin to be completed, they can be transported to the construction site to begin assembly. Once assembly is complete, trade-work can begin for completing any finishes that the boxes may need. Here, is it crucial to successfully coordinate trade-work and communicate day-to-day objectives with the foreman for each trade.

Once trade-work is completed, the project manager will do a weekly walkthrough of the project and determine punch-list requirements. A punch-list is a way of mapping out and determining individual trade tasks. As the project manager walks through, each task is marked as complete or incomplete. When all the tasks on the punch-list have been completed, the project owner, project manager, and superintendent will do one final walkthrough of the entire project in order to determine if the final product meets the project owner's expectations.

Given that the project owner has approved the final product, the contractor will proceed with collecting the closeout documents from all the subcontractors. These consist of warranties for the work that was done any change order forms that were needed throughout the completion of the project. The closeout documents are needed for providing future maintenance to the completed project because they show which subcontractor needs to be notified about any of their work that may need to be checked up on and the change order forms represent any amendments that needed to be made to the original construction contract during the project (Glazov 2011). For example, if a change needed to be made to the plumbing system for ten units of a fifty-unit housing project, a change order form would be issued. The change order form will be needed later on for plumbing maintenance to show what changes were made and whether or not the layout for the plumbing was changed.

Unexpected Variables

It has been observed that inefficiencies in construction come from unexpected variables that are not accounted for during the planning process. These observations were made throughout the course of a Co-Op that was completed with CTA Construction Managers as an Assistant Project Manager with the company. Most of these occur during construction and are impossible to consider before the project has begun. Certain changes always need to be made in order to account for a variety of situations arising. The most important part of any construction process is being able to recognize where these variables may turn up and understanding how to minimize them. For example, being able to account for weather, possible defects in modules, or undermanned trade-workers is a skill that all project managers and superintendents need to have. Some of these occurrences are likely to turn up during the functional requirements for this project and therefore, the design parameters have been established in a way so as to consider and minimize any discrepancies in the construction process.

Analysis of a Broad Modular Building Processes

Decomposition

In order to understand the objectives of the project, a decomposition of the processes needed to be made. Each step in completing this construction project was developed into a functional requirement. With FR0, the final product is defined with the following FRs being those that will need to be completed in order to achieve the final product. The goal of this project is defined by FR0 and has been decomposed below:

#	[FR] Functional Requirements	[DP] Design Parameters
0	Build modular buidings to satisfy the client's needs	System for Building modular buidings for thier owners
1	Maximize value added of modular contruction to the building owner	System for maximizing value added of modular contruction
1.1	Acquire construction documents	System to acquire the construction documents
1.1.1	Create architectural drawings	System to create architectural drawings
1.1.2	Create schematic design	System to create schematic desing
1.1.3	Coordinate the building design for trades	System to coordinate the building design for trades
1.1.4	Aquire the construction permits	System for aquiring the construction permits
1.2	Survey building site	Site survey
1.3	Finalize architectural drawings	Architectural drawings
1.4	Develop construction site	Site drawings
1.5	Manufacture modules just in time	Manufacturing system
1.6	Schedule modules at appropriate time	Scheduling system
1.7	Procure materials	Procurement system
1.7.1	Deliver modules at appropriate time	Delivery system
1.7.2	Minimize assembly errors	Quality assurance system - MFG
1.8	Coordinate trade-work	System to coordinate trade-work
1.8.1	Manage manpower requirements	Project Management System
1.8.2	Manage tools and equipment	Equipment management system
1.9	Complete trade-work in accordance with architectural drawings	Quality assurance system - Trades
1.10	Pass final walkthrough	System to coordinate walkthrough
1.11	Pass final building code inspection	Code Inpsection system
1.12	Provide maintnance for forty-year cycle	QA Maintince system

The image above shows the FRs and their subsections, also referred to as children, for the decomposition of this project with their respective DPs. This decomposition was achieved using the Acclaro software.

After the decomposition was completed, a matrix was created using the Acclaro software in order to identify which design parameters would impact several functional requirements. The DPs that directly impact FRs are marked below with a blue “x”.

	DP0: System for Building modular buidings for thier owners	DP1: System for maximizing value added of modular contruction	DP1.1: System to acquire the construction documents	DP1.2: Site survey	DP1.3: Architectural drawings	DP1.4: Site drawings	DP1.5: Manufacturing system	DP1.6: Scheduling system	DP1.7: Procurement system	DP1.8: System to coordinate trade-work	DP1.9: Quality assurance system - Trades	DP1.10: System to coordinate walkthrough	DP1.11: Code Inpsection system	DP1.12: QA Maintince system
FR0: Build modular buidings to satisfy the client's needs	X													
FR1: Maximize value added of modular contruction to the building owner		X												
FR1.1: Acquire construction documents			X											
FR1.2: Survey building site			O	X										
FR1.3: Finalize architectural drawings			X		X									
FR1.4: Develop construction site				X	X	X								
FR1.5: Manufacture modules just in time			X	O	O	O	X							
FR1.6: Schedule modules at appropriate time			X			O	X	X						
FR1.7: Procure materials						O	X	X	X					
FR1.8: Coordinate trade-work			X		X	X			X	X				
FR1.9: Complete trade-work in accordance with architectural drawings			X		X	O				X	X			
FR1.10: Pass final walkthrough					O	O			O	O	X	X		
FR1.11: Pass final building code inspection				X					O	X	X		X	
FR1.12: Provide maintnance for forty-year cycle					X	O					X			X

Birth of a Construction Project

Bidding process

As mentioned previously, a construction project cannot begin without the owner’s invitation to bid. During this phase, several contractors may receive an invitation to bid for the owner’s project. The contractor may choose to accept or deny the invitation to bid based their own desire to take on the project, their workload at the time or, how potentially lucrative they see the project being. If the contractor chooses to accept, they then need to compete against other contractors to provide the owner with the most beneficial bid without hurting their own opportunity to profit. The bid with the lowest cost of completion is not always chosen. A bid that seems to be too low will often raise concern for the project owner because it often shows that the contractor has not priced all of the work and materials correctly. (Tompkins 2015)

During this project, it was found that there is an opportunity to apply Axiomatic Design during the bidding process. If a general idea of the construction process is given, a design engineer may use AD to help make the bid more competitive. This would involve breaking down the process for which the owner's project intends to be completed in order to potentially make adjustments to pricing and timeframes.

Estimating

Acquiring accurate estimates is crucial to any bid and it is helpful to get pricing from different potential subcontractors. This ensures that a contractor will be able to get the lowest pricing for a certain job that needs to be done on the project. For example, a contractor has been chosen to build a new public school that requires a gymnasium with a hardwood basketball court, two baskets, and two bleachers that can fit 100 people each. During the estimating phase, the contractor may find several manufacturers of flooring, basketball hoops, and bleachers. Each manufacturer can give pricing on the three objects individually while another manufacturer of general athletic equipment may be able to provide the contractor with all three for a much lower price. This is how a contractor prepares a competitive bid. Contractors will often go to the same manufacturers that have performed quality work on past construction projects in order to get special deals on work that needs to be done.

For this project, assuming that the project owner has already chosen the contractor, the estimates that must be taken into account are as follows:

Cost Analysis		
Activity	**Cost**	**Reference**
Acquiring construction permits	$853 per permit x 50 units = **$42,650**	HomeAdvisor, 2016
Surveying	$477 per home x 50 units = **$23,850**	HomeAdvisor, 2015
Site Development	$79,937.50 avg x 50 units = **$3,996,875**	BuildingAdvisor, 2014
Manufacture, Transport, and Assemble Modules	$168,870 per home x 50 units = **$8,443,500**	Lavinia, 2013 Christie, 2014
Trade-work (finishes)	$17,000 per home x 50 units = **$850,000**	Elitzer, 2015
Miscellaneous and unforeseen expenses	**$1,000,000**	Tompkins, 2015
Initial Project Cost: $14,356,875 Budget: $15M		

Construction Documents

Acquisition

The documents needed for this modular construction project are the architectural drawings, which went into development before the project owner began the bidding process and the building permits. The architectural drawings are finished as the project owner finds an adequate contractor. That way, once the contractor is chosen, they are responsible for picking up the architectural drawings from either the project owner or the architect. The drawings contain information for site layout, fabrication of modules, assembly, and any finishes that would need to be made. The permits allow for the contractor to begin developing the site and signify that the state and federal government have acknowledged this project.

Reducing Non-Value Added Time

Non-value added time is the amount of the production cycle time that does not directly produce goods or services (Manufacturing Improvement Specialists 2015). One of the main goals for the contractor, by applying the Axiomatic Design method to the manufacturing of residential homes, is to reduce non-value added time. Therefore, it is crucial for the contractor to analyze each step in the process. It is favorable to the owner, for this project; to begin the bidding process as the architectural drawings are being completed in order to reduce non-value added time. It is also crucial that the contractor be capable of recognizing the opportunity to begin processes as others are being completed.

Opportunity for Simultaneous Development

The opportunity for simultaneous development, at this step, is for the contractor to use the architectural drawings to begin site planning and develop a layout that will facilitate the unloading and assembly of modules once the site has been surveyed. During this time, the contractor is going to want the manufacturer to begin fabricating the modules for the homes. Typically, it takes less than two weeks to complete the modules for a home (Champion Home Builders, Inc). If production for ten homes begins at the same time surveying does, the contractor will have about five months to finish surveying and site development.

Determining the quantity of the first "batch" of homes being fabricated is extremely important since scheduling for transportation and on-site assembly must not couple with surveying and site development (Tompkins 2015). Systems for these will be discussed in later sections but for now, it can be assumed that ten homes will be manufactured and delivered for assembly within five months and will take another ten months to assemble ten homes. This puts the process for completing ten homes at fifteen months which, repeated five times to satisfy the demand for fifty homes, at a total of seventy-five months. This roughly equals six years and three months, which currently puts the project finishing a year and three months past the project owner's deadline.

Pre-Construction Requirements

Surveying the Site

The primary purpose of surveying the construction site is to define the physical boundaries of a property. Although the boundaries are described in the legal documents that were acquired by the project owner and contractor, it is the job of the surveyor to find these boundaries on the property and mark them. This allows for the contractor and sub contractors to know what land is being worked on and prevent them from encroaching on other people's property (HomeAdvisor 2015). For this project, surveying the area where fifty, 2,598 square-foot homes are to be built, will take about a week. It will take the surveyor two to three days to research and acquire any legal documentation pertaining to the land and surrounding area and another day or two to physically survey the land.

System for Surveying

Surveying the land is a straightforward process that does not take too much planning on the contractor's part. Most of the work is carried out and completed by the surveyor. Also, in this case, the modules must go into fabrication at the earliest possible time in order to reduce non-value added time on the site. It will take about five months before the modules for the first ten homes arrive on site. This means that, even if surveying runs late and is completed within two weeks, the contractor will still have about four and a half months to develop the site and its layout. This is more than enough time to complete those activities. Luckily for this project, the design parameters for FRs 1.5, Manufacture modules just in time and 1.6, Schedule modules at appropriate time, allows for the manufacturing time of the modules to be decreased from five months. This process will be explained in later sections.

Creating Architectural Drawings

As mentioned before, the architectural drawings went into production before the project owner began the bidding process. This allowed for the drawings to be made available to the contractor with the winning bid as soon as their bid was chosen. The contractor must then acquire the drawings.

For this process, the architectural drawings needed are minimal. The drawings needed are for the module design, home design and assembly, the layout for the homes within the neighborhood, and basic trade-work and finishes. Since all the homes will be the same, the manufacturer will only need one set of drawings for producing the modules and only one set of drawings needs to be created for the design and assembly of each home. This greatly reduces the amount of time that it takes to produces these drawings since, for bigger projects, creating the architectural drawings can be tedious. This is one of several advantages the modular construction process holds over traditional construction. For a traditional construction process, the architect must develop drawings for the building and each its rooms. Then, because all the trade-work is conducted on-site, drawings must be made for the carpentry, plumbing, electrical, heating, ventilation, and cooling systems (Tompkins 2015).

The manufacturer takes care of all of these during the fabrication process, which reduces the amount of drawings needed, thereby reducing the amount of time it will take to produce the final drawings for the project owner.

Planning Site Layout and Development

The manufacturer and contractor have received their respective sets of architectural drawings and two weeks into the project, the site has been surveyed. Now, the contractor can begin developing the site, establishing foundations for each home, and planning the site layout to facilitate the delivery, unloading, and assembly of the modules once they have been produced and delivered. The development of the site includes any demolition of existing structures, clearing and grading the land, installing utilities, and constructing improvements such as roads and foundations (Grella 2009). The manpower requirement will be about fifteen workers in total. There will be four workers for demolition, three for electrical wiring, four for plumbing and sewage, and four for general labor, which includes preparing roads and pavement and pouring cement.

There are two approaches to his process. The contractor may choose to develop the entire site and have all the foundations ready for when the modules begin to arrive, or only develop the area and pour the foundations for the first batch of homes being produced. Choosing between these two options relies entirely on the amount of time it takes to produce the modules. If the contractor is aware that the modules can be produced and transported quickly enough, they may choose to only pour foundations for those first few homes. If manufacturing the homes is taking longer, then the contractor will want to take advantage of this extra time to finish developing the site.

One of the advantages to developing the site and pouring the foundations for only the first group of homes is that as these homes are arriving, being assembled and finishes are completed, the development needed for the next group of homes can be completed. A disadvantage to this is that the requirements for manpower will almost double as teams will be needed to complete assembly, finishes, site development, and foundations simultaneously.

On the other hand, if the site can be fully developed with all the foundations completed, manpower can be focused entirely on assembly and finishes. Although this decreases the requirements for manpower, it puts the project at risk of experiencing situations where non-value added time would be found. For example, if it takes five months to fabricate ten homes and deliver them to the site, but it only takes three months to assemble them and complete the final finishes, there will be two months of non-value added time where trade-workers will not have work to do on site. The contractor then runs the risk of losing workers to other projects, thereby affecting the amount of total work and the time it takes to complete that work when the next group of homes has been manufactured and is ready for assembly.

Reducing Non-Value Added Time During Pre-Construction Phase

In order to maximize the amount of work that can be completed while reducing non-value added time, a grid system was developed to complete site development and provide a layout that is easy to navigate. Each section of the grid represents the area that a house will occupy. Similar to a neighborhood containing identical "blocks", this system was applied for surveying, layout, and site development in order to keep activities organized and to facilitate navigation of the site for trade-workers and for the delivery of modules later on. The site was organized into three rows, two rows containing twenty houses each and the third containing the remaining ten. For the two rows containing twenty houses, the houses face away from each other so that each house is separated by their respective backyards and fencing on the sides. This system reduces non-value added time by minimizing the amount of time that trade-workers spend trekking the site, organizing the site in an easy-to-understand grid, and allowing for the unloading of modules at the doorstep of each home, which ultimately facilitates assembly of the modules. This system also helps the contractor determine what work has been completed. By organizing the houses into rows, two rows are worked on at all times. As one row of ten houses undergoes assembly and finishes, the next row's land and foundations undergoes development.

Manufacturing Modules

Advantages and Disadvantages

Modular construction offers the ability to construct portions of the work for a project in a factory. This provides the contractor and project owner with a lower cost of production and a controlled environment, which ultimately leads to a higher quality of material. Another advantage is the lead-time that the off-site activities can provide. This lead-time, where value-added work is being completed off-site, allows for on-site development to occur without the interruption of building assembly. However, there is only so much on-site work that can be done. If the fabrication of the modules is not scheduled and coordinated correctly, it could result in a disadvantage. If site work is completed before the boxes have been prepared for transportation, this will result in non-value added time where the crew that is on-site does not have work to do that leads to the completion of the final product. Also, if there is not enough work that can be completed off-site, then the on-site erection and cost of shipping can outweigh the savings (Tompkins 2015). Another disadvantage is that, in some occasions, finishes cannot be completed 100% in the factory. This leads to an inefficiency where 80-90% of the work is completed in the factory and then the remaining 10-20% needs to be completed on-site (Tompkins 2015). For the current project of 50 units being produced within five years, this inefficiency has already been accounted for in the budget because during the planning process, it was assumed that final finishes would need to be made on site for each unit produced.

System for Manufacturing Just In Time

The manufacturing of the modules is the most important phase of this project. Due to the lead-time of fabricating the modules for ten homes, which would currently take about five months, a system for dual production needed to be explored. Instead of producing the modules for ten homes on one production line, the contractor would need to produce five homes via the same manufacturer and two production lines or through two different manufacturers. Having different manufacturers would present the contractor with several risks. The first, being that the conditions in which the modules are produced may differ greatly and the quality of the materials could vary. Another risk would involve differences in scheduling for the production of the modules. It is highly likely that, with two manufacturers, the fabrication times for the modules will differ and assembly would then be impacted by transportation times.

For this project, it is assumed that the manufacturer is capable of satisfying the demand from multiple contractors for different projects. Therefore, they are able to carry out simultaneous production of the modules for this project. With five homes being produced at the same time on separate production lines within the same manufacturer, this would cut the original lead-time of five months to just two and a half months. With ten homes being produced within two and a half months, fifty homes would be manufactured in just over a year. Allowing for the contractor to have just under four years to complete any assembly, finishes, and inspections, and remain within the project owner's original timeline.

Scheduling for Manufacturing

Scheduling the fabrication of the modules will be tricky. The manufacturer must begin fabrication as soon as their set of architectural drawings and specifications for the modules are received. Since the fabrication and transportation for the first ten homes will take about two and a half months, the contractor will have more than enough time to develop the land and foundations for the first row of ten homes. Assuming that surveying the entire area will take about two weeks, this leaves the contractor with two months of lead-time for development. The contractor must schedule for the fabrication of the modules to be completed two to three days before the land has been developed to allow for transportation. It is crucial that the manufacturer finish fabrication within the two and a half-month period to avoid non-value added time being added onto the on-site activities. The primary goal of the manufacturer and contractor is to be able to repeat the processes for fabrication and site development five times, simultaneously, over the course of twelve and a half months.

Transportation System

The grid layout that was developed for this project facilitates the transportation and unloading of the modules upon arrival. The roads and driveways that were constructed during the development phase give the trucks, crane, and crew easy access to the areas where the homes are to be assembled. During this phase, most of the communication occurs between the manufacturer and the transportation service in order to allow the contractor to focus on preparations on-site. The manufacturer must be able to provide the contractor and transportation service a specific day for which the modules will be ready for pick up. That way, the transportation service can make itself available for picking up the modules for the first ten homes on the day they are completed. The manufacturer must also provide the transportation service with the approximate amount of modules being transported in order to accommodate this quantity with the necessary amount of trucks.

One major factor that plays into the transition between manufacturing plant and transportation is how the modules are stacked and oriented on the trucks. For example, the contractor would not want the module for the roof of the home stacked on top of the other boxes because that would mean that the crane would need to unload the roofing module, set it aside, assemble the remaining boxes, and later return to the roof for assembly. The manufacturer must be sure to load the modules on the trucks in the order that they will be assembled from top to bottom and orient them to facilitate attaching them to the crane for unloading and assembly.

As soon as the modules for the first ten homes have left the manufacturer, they must begin production for the next ten homes in order remain on schedule.

Off-Site Risks

There are some off-site risks that may affect the scheduling and completion of this project. First, if the manufacturer cannot construct enough of the building, then the added costs of shipping, on-site completion, and erection could outweigh the savings. Another off-site risk to the project is the long lead-time that goes into fabricating and shipping the boxes

(Tompkins 2015). It is up to the contractor and manufacturer to efficiently coordinate the processes taking place and manage the lead-time advantageously. This can be done through using simple methods such as maintaining day-to-day communications between the contractor and manufacturer and using daily and weekly reports to keep each other up to date on the progress of the fabrication and site developments.

On-Site Assembly

Procurement of Materials

For this project to run smoothly there are several materials that must be obtained. First, the modules must be delivered to the site at the appropriate time. As mentioned before, not only is the delivery time of the modules important, but the manufacturer must also orient and stack the modules on the truck in such a way so as to facilitate unloading and assembly. Also, since the scheduling for the fabrication and delivery of the modules has already been completed, the contractor must acquire five cranes for the time at which the modules will be delivered. It is crucial to call a crane service two to three weeks ahead of time, especially when the demand for five cranes is quite high (Tompkins 2015). But, because these are homes that need assembling and not three-four story buildings, smaller mobile cranes can be used.

Also, for trade-workers, the foremen are typically in charge of ordering and acquiring the materials they will need for the project as specified by the project owner and the architectural drawing for the assembly of the home. The contractor's project manager must look over the materials that each trade will need in order to approve the order.

System for Assembly of Modules

The two main factors that will facilitate and expedite the assembly process will be the orientation of the modules on the delivery truck and the grid system that was developed during the planning phase. During the assembly process, the main concern for the contractor will be to manage the manpower requirements for assembly and development. As the builders and laborers are assembling the first ten homes, the land for the next ten homes is also being developed and prepared. It takes about thirty days to assemble a home, which puts the assembly process for the first ten homes at being completed in ten months. This puts the project at a high risk of being delayed. In order to reduce this time, crews of five to six laborers will be needed for five homes. This puts the manpower requirement for assembly between twenty-five and thirty workers. Assuming that there are twenty-five workers for assembly, this puts the total manpower count at forty, which includes the fifteen needed for site preparations and development. The contractor will also need five cranes, one for two homes. Since the homes are in one row, each crane will be stationed between two homes. Meaning that, there will be a crane positioned between the first and second homes, another between the third and fourth, another between the fifth and sixth, and so on. This allows the contractor to have five homes being assembled at once, which cuts the assembly time in half. From ten months to five months. Unfortunately, this means that the next shipment of modules for the next ten homes will be on site for about two and a half months without anyone to be available to assemble them.

Scheduling for Assembly

As mentioned before, fabricating the first ten homes with only take about two and a half months because the manufacturer is using two production line to simultaneously produce five homes at about two weeks per home. Now, the contractor was able to shorten the assembly time for ten homes from ten months to five months by allocating workers and resources appropriately. This means that the modules for the second set of ten homes will be fabricated and delivered again, assuming that production runs smoothly, within two and a half months. This would mean that the modules would set on site for two and a half months while the five-month assembly of the first ten homes is being completed.

After the first ten homes have been fabricated and delivered, the restraining factor moving forward becomes the on-site assembly time. Therefore, for the next four sets of ten homes, the manufacturer will need to revert to using a single manufacturing line to produce the modules for one home every two weeks. This brings the fabrication and delivery time back to the original five months. With this in mind, the scheduling for fabrication and assembly is now as follows:

First ten homes: Fabricated in 2 ½ months, assembled in 5 months

Second-Fifth batch of ten homes: Fabricated in 5 months, assembled in 5 months

The total time between the beginning of fabrication and the final assembly for the last ten homes is 27 ½ months, which is equal to 2 years and 3 ½ months.

Reducing Non-Value Added Time

By having the manufacturer organize the modules on the trucks after fabrication per the contractor's instruction, the time and hassle of unloading the modules on site and having to sort through and organize them is avoided. For this project, the contractor's goal for assembly is to carry out this process as fluently as possible. This is achieved by having the trucks prepared to be loaded on the day the manufacturer is finished fabricating the modules for the first ten home. The modules are loaded directly onto the trucks without having to keep them at the manufacturer for any period of time. The trucks then go directly to the site where the contractor has already acquired the cranes for unloading and assembly. The manufacturer loaded the trucks to facilitate unloading. This means that the top module (that last one loaded) is the first one that is unloaded for direct assembly. The crane and crew then work their way through the modules to produce one home.

Accountability amongst the trade-workers also plays a major role in the assembly process. The goal being that each home is completed at the same time. If there are five crews working on the same home, using the same materials, putting in the same amount of labor hours, then theoretically, they should be able to finish within a day of each other at most. There is also minimal lead-time between finishing the assembly for the first ten homes and the arrival of the second shipment of modules.

The time for assembly is the limiting factor during this process because it takes five months to complete the assembly for the ten homes while it only takes two and a half months to complete fabrication. Increasing the requirements for cranes and manpower could have reduced the assembly time further but this would have resulted in a severely crowded construction zone that would have been at risk of exceeding the assembly, transportation, and trade-work budgets. The increase in workers, equipment, and activity would have also made for a very unsafe work environment where injuries could set back the project far more than the time being saved by applying the increase in manpower and equipment.

Tradework Coordination

Communicating Tradework Effectively

Although the foremen and trade-workers have access to their own architectural drawings for reference to the work that needs to be done within their trades, the goals for completing work must be communicated by the contractor. It is up to the contractor's project manager to ensure that work requirements are being met on a daily and weekly basis. A self-evaluation system was proposed, where trade-workers would be held fully accountable for the work they performed but this raised several concerns.

The first being that sometimes, trade-workers believe that it is in the project owner's best interest for them to complete an activity in a certain way that differs from how it is to be performed according to the drawings. It is crucial that the trade-workers follow the drawings to avoid running into problems later on in the project. For example, if the plumber has decided to install a drainage pipe that runs underneath the living room rather than underneath the garage to save a couple feet on pipes, the plumber runs the risk of his drainage pipe possibly interfering with the electricians wiring that has not been installed yet. The second reason is that, unfortunately, some workers may try to cut corners if their work is not being supervised (Tompkins 2015). This may happen on any job with any worker. Even the cement being poured for the roadways and sidewalks has to meet certain requirements for moisture, density, and load capacity. If the cement brought to the site does not meet these requirements, it is sent back and this goes for all work being done for this project. The final reason that trade-workers must be supervised is because contractors and project owners will usually require that the project manager and/or superintendent fill out daily reports. CTA Construction Managers, for example, requires that the superintendent fill out daily reports that record the weather, number of workers on site, and the type of work being done. CTA also has their project manager fill out a weekly report and punch list to record what work has been done throughout the week.

For this project, this type of system was applied. The superintendant oversees day-to-day activities on site and sees to these being completed per the construction contract and the project owner's specifications. The contractor's project manager also checks in one to two times a week in order to perform a walkthrough of the site and fill out a weekly report.

Although this means that there will be more people on site and may increase the amount of time the project takes to be completed, the benefits certainly outweigh the consequences. This walkthrough system minimizes on-site errors in order to provide quality work while also allowing for the project to run smoothly. If trade-workers are not supervised properly, the final product may be put at risk, which, went it comes to a person's home and safety, could result in costly legal consequences.

Planning Tradework

Trade-work for this project began during the site development phase. After surveying had been completed within the first two weeks of the project, trade-workers were needed to carry out certain activities such as demolition of existing structures, clearing and grading the land, installing utilities, and constructing improvements such as roads and foundations (Grella 2009). As discussed before, since it takes two and a half months to fabricate the modules for the first ten homes and it took about two weeks to survey the construction site. Trade-workers had about two months to prepare the site for the first ten homes. Over the course of these two months, the area for the first row of homes needed to be excavated in order to pour foundations and install utilities. The four demolition workers and four general laborers handled the clearing of the site, excavation, and pouring of the foundations. This work would take about twenty days to complete, assuming that the eight workers can clear the area for each home in one day and excavate and pour the foundations the next. While this is being done, the electrical wiring (three electricians) and plumbing and sewage systems (four plumber) can be installed simultaneously but will take longer than twenty days because of its complexity. The trade-work being executed before the modules arrive on site was scheduled to be completed within a month a half, allowing for two weeks of lead-time in case the foremen are undermanned on certain days or if the work takes longer than expected. The electrical, plumbing, and sewage systems do need to be finished above ground within the area where each home will be located. This way, once the modules arrive on-site, there would only need to be minor installation and piping to be done after the modules have been assembled.

Once the modules arrive on-site and the foundation and development work has been completed, the land for the next row of ten homes begins development. Since assembling the homes will take five months and developing the land takes two and a half, the trade-workers will be able to develop the land and foundations for the next twenty homes while the assembly workers finish assembling the first ten homes. By the time the second set of ten homes has been assembled, the site development and foundations will have been completed for the entire site. This allows for the initial trade-workers to rotate back to the first set of assembled homes in order to conduct any final finishes. They would then follow the assembly workers through each row of homes that has been assembled and as assembly is completed, finishes can be started.

Self-Evaluation System

A self-evaluation system was considered at the beginning of this project. The system would eliminate the need for a superintendent to be on site everyday and for the project manager to have to visit the site on a weekly basis. The goal of the self-evaluation system would be to minimize lead-time cause by the activities carried out by the superintendent and project manager. This system would allow for the trade-workers to be held entirely accountable for any work that they produce. The system would work by having the contractor hold some type of leverage over the trade-workers or by utilizing a reward system where exceptional work is recognized.

It was later found that a self-evaluation system for trade-workers would not be in the best interest of the contractor or project manager because neither would be able to personally keep track of the work be performed. Also, the on-site superintendent/project manager system does not cause enough inconvenience or cost enough money to warrant consideration of its replacement.

Payment System

In order to ensure that quality work is being performed, it was decided that the companies providing the trade-work would not be paid until the project manager, contractor, and project owner conduct a final inspection. This does not signify that the trade-workers would go without pay until the end of the project. It is the responsibility of the companies providing trade-work to pay their respective employees for their work but the companies themselves, per contract, would not receive payment until the trade-work has been completed and approved. This payment system ensures that, not only are the project manager and superintendent making sure that the work is being done correctly, by also makes the companies providing the trade-work hold their employees accountable for their individual work. If the work done is not up to par, the company does not receive payment until said work has either been finished or adjusted per the specifications of the project owner and architectural drawings.

Concluding Tradework

Risk Analysis

Applying several systems to the project processes minimized the risk of defective or poor quality work thereby decreasing the potential for the project to exceed its budget or its time frame. With proper supervision, effective communication of goals, and the applied payment system that emphasizes accountability of the sub-contracted trades companies and their workers, the assembly and trade-work processes were executed with minimal flaws. Not only did these systems provide the project owner with quality work, but also ensured that the work was completed in accordance with the schedule. The schedule for trade-work and other project activities can be found in the Appendix.

Final Evaluation

Before payment is issued to the subcontracted companies for the completion of the trade-work, a final walkthrough must be completed in order to evaluate the quality of the work that was done and make sure that it is up to the standards of the project owner. In order to expedite this process, the owner, contractor, project manager, and superintendent met after the final finishes were completed for each of the ten homes. For example, after site development, the modules arrived for assembly and after assembly; the trade-workers came back from finishing land development to do final finishes on the assembled homes. As soon as finishes were completed, the final walkthrough was conducted and the homes were closed in order to avoid any potential damage and maintain cleanliness. Five total walkthroughs are conducted as finishes are completed. This is to avoid any unnecessary lead-time that could come from saving the final walkthrough for after all fifty homes have been finished.

Building Code Inspection System

Before potential residents can move in, each home also has to pass an inspection from a professional building inspector. Each state's building codes differ and the inspector's job is to make sure that each home meets the building code requirements for its location. During the inspection, building, plumbing, electrical, and mechanical systems are examined to make sure their operation and installment complies with the codes. Often during an inspection, workmanship is also examined to determine whether the home is structurally sound and safe for people to move and live in. A home inspection takes between two and three hours to complete (America's Home Inspection, LLC). Therefore, for fifty homes, considering that the inspector works and eight-hour workday, it may take up to two weeks to complete the inspection. This still puts the project well within its deadline.

Operations and Maintenance

System for a Forty-Year Cycle

Once the project has been completed, the contractor must put together two closeout binders. Theses binders hold all the warranties and information pertaining to the jobs that were done. The purpose of these binders is for the contractor and project owner to identify who to hold accountable in case something were to happen regarding the work that was done. For example, if General Electric were subcontracted to install appliances in each home, then GE would submit the warranties for that equipment as well as an operations manual or information booklet. These would then be organized into the closeout binders, typically by type of trade or work that was done. These warranties do not guarantee that the subcontractors will replace or fix any of their installations or equipment for forty years though. The purpose of the warranties is for the subcontractor to take responsibility for anything that may be faulty and the warranties usually last between five and ten years.

The operations and maintenance for a forty-year cycle also includes providing water and electricity to the homes. The average time that a building will operate before any major renovations must be made is forty years. Therefore, the project owner already knows that in about forty years, the housing project will most likely have to undergo extensive renovations to replace old piping and outdated electrical systems.

Conclusions & Recommendation

Applying manufacturing engineering principles to the construction process proved to be beneficial to the project owner and several other parties, as explained in the "Results" section. Approaching a construction project that is utilizing modular building methods as if it were a manufacturing line, allowed for the breakdown of the process into phases. This allowed the contractor analyze each step individually in order to reduce non-value added time and maximize the value added to the project.

There are many details that should be taken into consideration when analyzing a construction process, especially because no two construction projects are the same. Therefore, a broad modular building project was theorized in order to perform an analysis of each of its steps in order to provide the project owner with a project that would stay within budget and meet deadlines. After performing the analysis of each of the steps by applying the Axiomatic Design method, it was found that, not only would the project stay well within its budget, it would also be able to be completed within three years, rather than the original deadline of five years.

Fabricating and erecting modular homes is a challenging process to coordinate since there are certain variables that could affect scheduling. Ultimately, a project that required the production of fifty modular homes was executed in less than three years and within a budget of $15M. Decomposing the process into functional requirements that defined what each step was to achieve and developing design parameters for how each FR was to be satisfied allowed for the modular construction project to become successful.

For future groups that intend to pursue a project regarding the application of manufacturing engineering principles to construction processes, it is recommended to attempt and experiment with different types of projects. For example, would it be feasible to apply manufacturing engineering principles to the construction of a bridge? A railway? A multi-level office building? It would be interesting to test the extent to which the Axiomatic Design method can be applied to different projects while analyzing the benefits and drawbacks to production and lowering production costs.

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