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By Chirag Garg

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Optimization of an HVAC Prefabricated Component in Modular Construction

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Bryan J Hubbard
Chair

Robert F Cox

Daphene C Koch

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OPTIMIZATION OF AN HVAC PREFABRICATED COMPONENT IN MODULAR CONSTRUCTION

A Thesis

Submitted to the Faculty

of

Purdue University

by

Chirag Garg

In Partial Fulfillment of the

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of

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This research work is dedicated to my parents. My father who always inspired me with his thought that "Education is best thing one can get in life" and motivated me to study and obtain higher education. My mother whose infinite love, support and dedication to my life have made me the person I am.

I would also dedicate this research to my family and friends for all the times they stood by me and corrected me for when I was wrong.

I would like to specially thank my younger brother who was has always been my best friend.

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ABSTRACT

Garg, Chirag. M.S., Purdue University, May 2013. Optimization of an HVAC Prefabricated Component in Modular Construction Major Professor: Bryan Hubbard.

Prefabrication and modularization has been used in the construction industry for decades. It has recently made a resurgence worldwide providing increased productivity, safety and quality. This research has focused on increasing productivity by optimizing the module size and on-site connection time utilizing a newly developed software routine. The research was applied to the prefabricated components for mechanical systems of a commercial building project.

Mechanical systems, consist of a variety of pipes, ducts, pumps, air handlers, and other mechanical equipment that serve the heating and cooling purposes of the building. These components are connected together using welding and bolting techniques that are typically assembled on-site. A prefabricated module consists of pipes and ducts connected together at the factory with a minimum number of open ends mounted on a steel frame for transportation. These prefabricated modules are assembled in place on–site per

the design. An ideal prefabricated mechanical module would have the majority of the connections done off site, thus minimizing on-site connection time.

Renovation of a large educational building owned by the University of Chicago (UoC) was used to develop and validate the research. The building was originally constructed between 1923 and 1927. The building will now be renovated to host the University's Department of Economics and will include classrooms, faculty offices, and research facilities. In addition to architectural changes, the facility's entire Heating, Ventilation and Air Cooling (HVAC) system was completely replaced in the existing structure creating unique constraints for the prefabricated module size of the HVAC components.

Modularization of the above HVAC system was done by breaking it into modules of optimum size. The module size was optimized using the physical parameters length, width, height, and weight. Equations for constraints and the objective were derived using these parameters for the primary objective to maximize volume and minimize connection time. Optimization was done using the Microsoft Excel optimization tool. The model was developed to solve multiple objective optimization problems utilizing the 'Pareto optimal' method with a Generalized Reduced Gradient (GRG) nonlinear technique. Various cases were taken and results for each were tabulated. As per the requirement for analysis, some of the results were graphed for clarity. The end result of this research was an optimized module for the relevant project as well as an optimization tool to assist contractors in sizing mechanical system modules in the future.

CHAPTER 1. INTRODUCTION

The industrial technique of breaking large units into smaller parts to increase productivity, facilitate control over the process and maintain the process has been used in a variety of industries for many decades. This concept was introduced for the first time in the construction industry towards the end of the 19th century. The process of constructing various smaller parts in a factory environment and then transferring them to the construction site for assembly to construct large parts was termed ‘prefabrication’ in the construction industry.

Another way to describe the process of prefabrication is to consider the simple analogy of ‘a child’s building blocks. These building blocks can be piled up together to form small rooms that can then be assembled to construct a model structure. Prefabrication has advanced over the years and is now a major part of the construction industry. This research will focus on the prefabrication of the mechanical system of an educational facility owned by the University of Chicago. Prefabrication technique will be employed to the mechanical room located in the basement of the building with constrained access. Basement of the building is not undergoing any architectural or structural change, thus prefabrication is employed for renovation of the space. Prefabrication concepts along with mathematical optimization techniques will be used to address constructability issues. Optimization will be used to deconstruct the mechanical system for ease of prefabrication. As a result of this research an optimization routine will be developed for future use.

1.1 Statement of the Problem

What is the optimum size of a Heating, Cooling, and Air Conditioning (HVAC) module for a commercial construction project?

1.2 Significance of the Problem

Prefabrication in construction is used to increase productivity. Optimization of prefabrication would lead to even higher productivity. The size of the element needs to be optimized so that off-site construction, transportation and on-site assembly are feasible. Also, the optimized size should be large enough that the benefits of modularization are not lost.

1.3 Scope of the Study

The research focuses of development of an optimization routine for prefabrication technique implementation on HVAC system of a commercial construction project. This routine could be further standardized as required for application on various projects.

1.4 Purpose of the Study

The purpose of the research is to develop a procedure to determine the optimum size of an HVAC module to be used in modular construction. The module size will be determined using an optimization model that focuses on improved construction productivity given the parameters of a project site. The primary benefit of the research will be to reduce the schedule of the construction project by reducing the on-site construction time of the mechanical system. It will also help to develop an optimization tool for future use.

1.5 Definitions

Modular Elements: Volumetric elements are manufactured, assembled, and finished off-site, and are ready to use on-site after installation. For example office blocks, motels etc. (Gibb, 2001).

Non-volumetric Assembly: Elements manufactured off-site and assembled on-site which do not enclose space/volume. For example, wall façade, beams etc. In this type of fabrication, finishing of elements and joints is usually done on site. (Gibb, 2001).

Optimization: The process of making the system as efficient as possible (Koskisto, & Ellingwood, 1997).

Productivity: “Ratio of output to all or some of the resources used to produce that output.” (Berstein, Gudgel & Laquaidara, 2011).

Schedule: “Time required for the events related to project planning and construction” (Berstein, Gudgel & Laquaidara, 2011).

Subassembly: Small components like doors and windows which are not considered for on-site construction. (Gibb, 2001).

Volumetric assembly: Elements manufactured and assembled off-site while finishing is done on-site which enclose some space/volume in them. For example modular elevator shaft, bathroom pod, etc. (Gibb, 2001)

1.6 Assumptions

The following assumptions are made in this research

- The optimized module is assumed to be cuboidal or cube in shape.
- Density of the mechanical system was assumed to be average of density of pipe and ductwork.
- The module being produced using a manufacturing facility will be of the same or better quality than a product constructed on-site.
- Transportation and assembly of the module will be feasible using a standard truck trailer system and a standard crane.
- The results obtained could be generalized for other similar construction projects.
- Only end to end connections are required in the mechanical system between adjacent modules.

Figure 1-1 shows the example of a typical end to end connection that is assumed to be valid as a basis of research. The connection exists only along the length of the module as exhibited in the figure. .

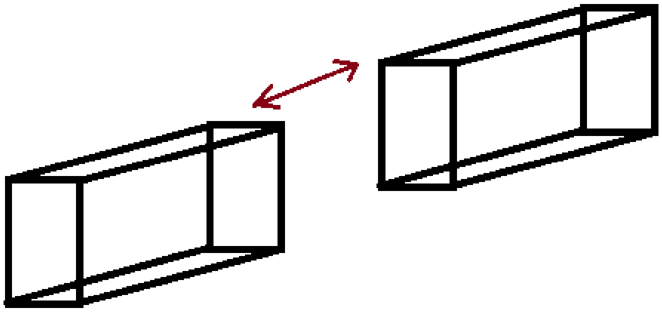


Figure 1-1 Figure showing a typical end to end connection for modules

1.7 Limitations

The following limitations are applied:

- The optimization parameters are limited to an optimization process for the commercial sector of the construction industry.
- Application of the research considers only HVAC components.
- Application of the developed module will be done on one project. Further work will be required to apply the module to various projects.

1.8 Delimitations

The following delimitations are applied:

- Heavy civil construction facilities are not in the scope of the research application.
- Fire protection systems which can be associated with HVAC systems are not in the scope of the research.

1.9 Chapter Summary

This chapter introduces the research that is to be done and the scope of the thesis work. Assumptions, significance, limitations and delimitations of the research are also listed. The chapter further highlights the important definitions which are required to be understood for in-depth comprehension of the research.

CHAPTER 2. LITERATURE REVIEW

The research presented in the thesis is unique in that very limited work has been done on the topic. This chapter includes a study of the literature that defines the basis of the research. The first few sections of the chapter rationalize why and when prefabrication is used in construction, its benefits, challenges and the cost associated. Later the chapter describes the application of prefabrication and optimization of prefabricated elements.

2.1 Productivity in Construction

Construction is a multi-stakeholder and multi-stage trade activity. Stakeholders in the construction industry include the clients, architects, contractors, subcontractors and suppliers. The stages of construction can be referred to as planning, design, actual construction, and commissioning. All of this forms a complex structure that depends on a number of variables that are derived from the stakeholder behavior and stage functions. These variables affect the productivity of construction activities.

Productivity is generally defined as input required per unit of output. It is difficult to measure productivity in construction because output is the entire project over months or years of effort with a variety of inputs and includes a large amount of material, labor, money, and time. Adrian (2004) reasons that the term productivity has different meaning for different people (p.3), nevertheless, it can be measured as average labor productivity or capital expenditure productivity (Adrian, 2004). However, Crawford and Vogl (2006) argue that, “Industry professionals have no consensus on which method is ideal, as both measures have advantages and disadvantages and are appropriate for different purposes” (p. 213).

In spite of the inability to accurately quantify productivity, the construction industry has a reputation for lower productivities and efficiencies, as compared to other sectors like automotive and chemical manufacturing industries (Teicholz, 2001, Adrian, 2004). In these industries, the productivity has increased in the last few decades, unlike the construction industry where productivity has taken a downward trend (Teicholz, 2001). Prefabrication is considered a potential technique to increase productivity in construction. (National Research Council, 2009)

2.2 Prefabrication and Subcategories

Prefabrication and modularization are two terms differentiated on the basis of size of the module. For the purpose of this research, these terms will be used interchangeably. These terms refer to construction of building elements and components like beams, slabs, facades, etc. at a different location than where they will be finally installed. Gibb (2001) suggests off-site fabrication can be divided in four sub-categories:

1. Subassembly: Small components like doors and windows that are not considered for on-site construction.
2. Non-volumetric assembly: Elements manufactured off-site and assembled on-site that do not enclose space/volume. In this type of fabrication, finishing of elements and joints is usually done on site.
3. Volumetric assembly: Elements manufactured and assembled off-site, and finishing is done on-site. On-site assembly includes enclosing some space/volume in them. (e.g. modular lift shaft and toilet pods)
4. Modular elements: Volumetric elements that are manufactured, assembled, and finished off-site and are ready to use on-site after installation. (e.g., office blocks, motels etc.)

2.3 History of Prefabrication

Use of prefabrication in the construction industry gained momentum during and after World War II. The major driving factor was the requirement for a large amount of housing in a short period of time. Soon after that, use of modules became a common and everyday technique in the Danish residential market in the 1950’s (Bertelsen, 2005). Since then it has been commonly used in Eastern and Western Europe, as well as Asia, where China and Japan are using modular techniques in metropolitan areas.

In the United States, modularization has gained significant momentum in the residential sector for a few decades. This is commonly known as “house-in-a box” (Hass, O’Connor, Tucker, Eickmann, & Fagerlund, 2000). Prefabrication is also a common practice for construction of sheet metal ductwork applied by mechanical subcontractors (Tam, Tam, Zeng, & Ng, 2007). It has been well established that in order to use prefabrication in a construction project it should be introduced early in the planning stage (Blisman, Pasquire, & Gibb, 2007)

2.4 Benefits of Prefabrication

The benefits of prefabrication in the construction industry are seen in terms of schedule, quality, and safety. The major benefit of prefabrication is its impact on the project schedule. With the use of prefabrication, a number of activities can be performed simultaneously (Blisman, Pasquire, & Gibb, 2007). This significantly reduces the total time required. In a survey conducted by Berstein, Gudgel and Laquaidara (2011), almost 35% of the participants using prefabrication reported a decrease in the project schedule by four or more weeks. Similarly, in a survey done for Hong Kong high rise buildings, it was noticed that the construction cycle per floor was reduced by four to six days per floor using prefabrication (Jaillon & Poon, 2008). This could assist in avoiding liquidated damages and also dependency on fluctuation of material prices in the market (Gibb, & Isack, 2003).

Quality was determined to be the second most important driving factor for prefabrication. Prefabrication assists the delivery of better and more consistent quality components as elements are constructed in a factory setting under controlled environmental conditions with minimal rework on site (Gibb & Isack, 2003). Prefabricated elements also provide better finish, higher durability and reduce water leakage (Jaillon, & Poon, 2008). This was confirmed by survey results indicating that 50 percent of respondents observed a medium to very high positive impact on quality (Berstein, Gudgel & Laquaidara, 2011).

It is a well-established fact that safety is increased by using prefabrication. It has also been observed that prefabrication reduces the number of on-site personnel, ultimately increasing safety on the jobsite (Deemar, 1996, Gibb, 2001). Prefabrication also decreases the amount of scaffolding required, congestion on the jobsite, and health hazards because the environment of the prefabrication facility is much more controlled (Deemar, 1996). Berstein, Gudgel and Laquaidara (2011) conducted a survey which reported, “Over one third of the survey respondents (34%) who are currently using prefabrication/modularization find that they have seen site safety improve as a result” (p. 34).

Prefabrication also supports sustainable construction in lean building techniques. Waste produced could be reduced by a minimum of 70% using prefabrication as compared to use of traditional construction methods. Concrete, reinforcement and plastering waste could be reduced by more than 90% (Tam, Tam, Zeng, & Ng, 2007). The Modular Building Institute (2010) reported “Modular construction methods and material allow a building to be more readily ‘deconstructed’ and moved to another location should the need arise, so complete building reuse or recycling is an integral part of the design technology” (p. 13). Prefabrication also results in a reduction in inflow variation, a stabilization of work flow and an improvement in downstream performance; all of these lead to a higher standard of lean practice. (Ballard, & Howell, 1994).

2.5 Challenges Encountered in Use of Prefabrication

Prefabrication techniques face a variety of challenges that include a lack of standardization, industry inexperience and time of design decision in the process of planning. Lennartsson, Bjornfot, and Stehn (2008) claimed that "Modularization requires standardization across the industry in order to improve production control" (p. 123). The general opinion in the industry is that prefabrication could be widely used in a market where all the joints of prefabricated systems are standard. This would provide architects and engineers a variety of options while using prefabricated systems in the design (Gibb, 2001). Lennartsson, Bjornfot, and Stehn (2008) claimed the, "Core of modularization is the division of complex product into functional parts that are easier to manage individually than in relation to the whole" (p. 124). One major challenge is determining the size of the module to be produced. Limited quantitative data is available on the sizing of modules. This issue has not been substantially addressed although qualitative answers are provided, such as: the size should be such that the number of units are not very large or small, should be easy to transport and the time to produce each should not be long (Lennartsson, Bjornfot, & Stehn, 2008).

Inexperience and reluctance to experiment has hindered the growth of prefabrication. "Reluctance among clients, architects and contractors to adopt off-site production is that they have difficulty in ascertaining the benefit that such approach would add to project", as quoted by Blisman, Pasquire and Gibb (2002, p. 126). Another challenge faced by prefabrication is that the design needs to be frozen at early stages with a high level of detail. Deemer (1996) said that, "More detailed project planning is necessary with modularization to ensure availability of design, components and material necessary to assemble modules" (p. 147). Further prefabrication reduces the flexibility in design and scope an owner has in the later stages of project cycle. (Construction Industry Institute (CII), 2002)

2.6 Cost of Prefabrication

One of the major driving factors for any technique in the construction industry is its impact on budget. If a technique or method is developed that would save the investor money, it is typically readily accepted. There is a common myth in the industry that prefabrication leads to an increase in budget as compared to traditional construction (Gibb, 2001).

Prefabrication has been shown to have a higher direct cost which includes the setup cost of the manufacturing plant, but its benefits can be recognized elsewhere (Gibb, 2001). "Cost saving using prefabrication is largely driven by field and shop labor rate differential and productivity differential" (CII, 2002). With the application of prefabrication, the indirect cost of construction is considerably reduced including material storage cost and supervision cost. (Gibb, 2001, & Isack, & Gibb, 2003). Prefabrication also reduces waste and reworks which result in significant savings. One of the main reasons for the misconception that prefabrication increases the budget is that the indirect benefits cannot be exclusively linked to prefabrication, and quantified.

2.7 Application of Prefabrication

In the past, prefabrication was proven to be very efficient in a variety of construction industry sectors including housing, hotels, dorms, hospitals and high rise buildings. In such projects, repetition of a particular type of element numerous times makes it feasible and economically viable to transfer it off-site (Gibb, 2001). It could also be concluded by economic theory that the unit cost of an item decreases as the number of units to be produced increases. A survey also conducted which ranked healthcare facilities, commercial warehouses, hotels and high rise buildings as the sectors with the most significant future opportunities for prefabrication (Berstein, Gudgel & Laquaidara, 2011).

In recent times, application of prefabrication was used extensively in the construction of a hospital facility in Dayton, Ohio. Prefabrication reduced the budget by 1% - 2% and resulted in a schedule savings of over 2 months (Post, 2010). The project has one of the highest levels of implementation of multi-trade prefabrication in the United States. The prefabrication of mechanical, electrical and plumbing trades was brought under a single umbrella for better synchronization. A very high degree of collaboration between the design team and subcontractors made the early design decisions easier. Potential constructability issues were also averted making the prefabrication a major success (Post, 2010).

Figure 2-1 Shows the pre-fabricated module under construction for the Miami Valley Hospital in Dayton, Ohio (Post, 2010)

2.8 Preliminary Industrial Survey

In order to determine the current application of prefabricated modules in the construction industry, meetings were held with industry professionals. The meetings focused on mechanical, electrical, and plumbing aspects of the construction trades. A meeting was held with a mechanical subcontractor, an electrical subcontractor and a general contractor. The industry professionals that were interviewed could be recognized as trend setters in the application of prefabrication technology.

The first meeting was held with a mechanical subcontractor that does a significant amount of HVAC work. The subcontractor owns a prefabrication workshop for the mechanical parts it uses in the variety of facilities they build. The meeting was held with the prefabrication facility manager of the company. The subcontractor realized direct economic benefits and experienced better quality, higher safety and a compressed schedule when implementing prefabrication. The subcontractor also employed ‘Building Information Modeling’ (BIM) with prefabrication to gain further insight into the connections required and potential system conflicts.

The second meeting was held with a general contractor that holds the contract for the construction of the project being used for this research. The meeting was held with the project manager associated with the project. Recognizing the constructability issue with the mechanical room, the project manager was very receptive to the idea of prefabrication and supports the research endeavors. The project manager has had exposure to prefabrication concepts on other projects that have been completed by the construction company.

The third meeting was held with the shop manager of a large electrical subcontractor. Their firm has taken the lead in cutting edge technology of prefabrication in the electrical construction trade. This subcontractor also owns a prefabrication facility dedicated to their projects. When working in remote areas away from the prefabrication facility, they develop a temporary prefabrication plant. The subcontractor has a significant parts inventory for basic modules that could easily be applied in a range of projects even with different designs.

Furthermore, they have developed a catalog of products with detailed specifications to support the electrical system design.

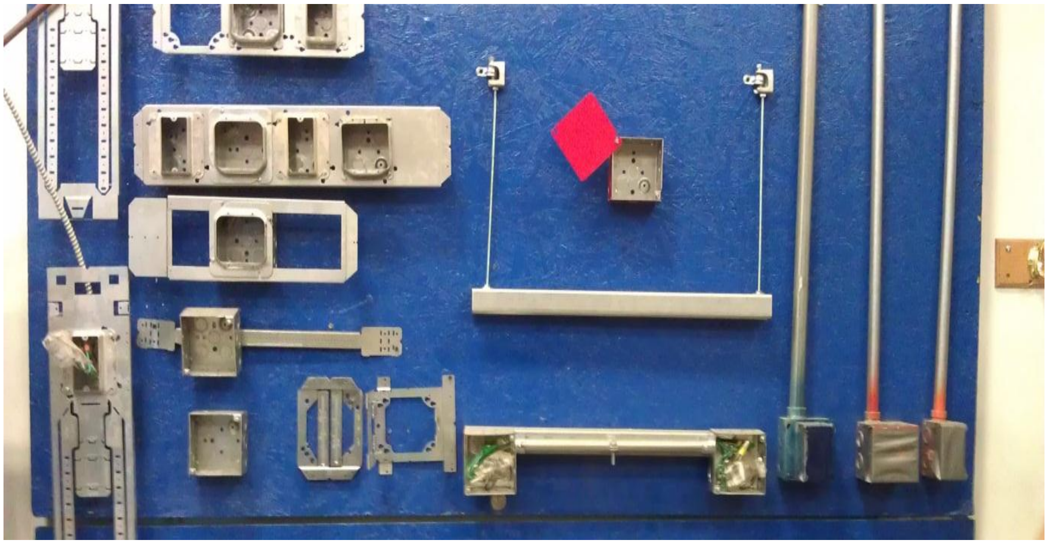


Figure 2-2 Shows a few prefabricated modules developed by the electrical subcontractor

2.9 Optimization

Optimization is defined as “the process of making the system as effective as possible” (Koskisto, & Ellingwood, 1997). Thus optimization and productivity are two different terms that go hand in hand with each other. Productivity is maximized when a process is optimized at all stages.

Properties of optimization problems and solutions are defined by the variables that constitute the component. Depending on the parameters and result desired, optimization can be divided into maximization and minimization of variables. Both maximization and minimization optimization are complimentary to each other. In most processes usually one or more parameters are minimized to maximize the result or vice-versa.

Optimization in prefabrication can be applied for a specific project as the material used and the supplier location relative to the project is being held constant Chen, Liu, Lin, & Xu (2008). Thus the only thing that could be varied is the physical size of the module.

2.10 Chapter Summary

This chapter provides the review of the research work done on relevant topics in the past. It describes the history of prefabrication, advantages, disadvantages, and its effect on budget of the project. The chapter also analyzes how off-site fabrication is subcategorized and its future potential applications. The chapter covers a brief description of the meetings held to determine present scope of prefabrication applications.

CHAPTER 3. MEHTODOLOGY

This chapter will cover the, sample set, population and success measures of the thesis. The chapter describes the project used to develop the parameters of research and the parameters that are used.

3.1 Project Description

. The project used to develop the parameters in this research is an educational building owned by the University of Chicago (UoC). The building was originally constructed between the years 1923 to 1927. The building will now be renovated to host the university's Department of Economics and will include classrooms, faculty offices, and research facilities. In addition to architectural changes, the umbrella of renovation also includes complete makeover of the mechanical and electrical systems.

Figure 3-1 shows the location of the mechanical room on the basement floor plan. Figure 3-2 shows the plan of all the equipment's associated with the mechanical room. Figure 3-3 shows a three dimensional view of the mechanical room equipment after assembly.

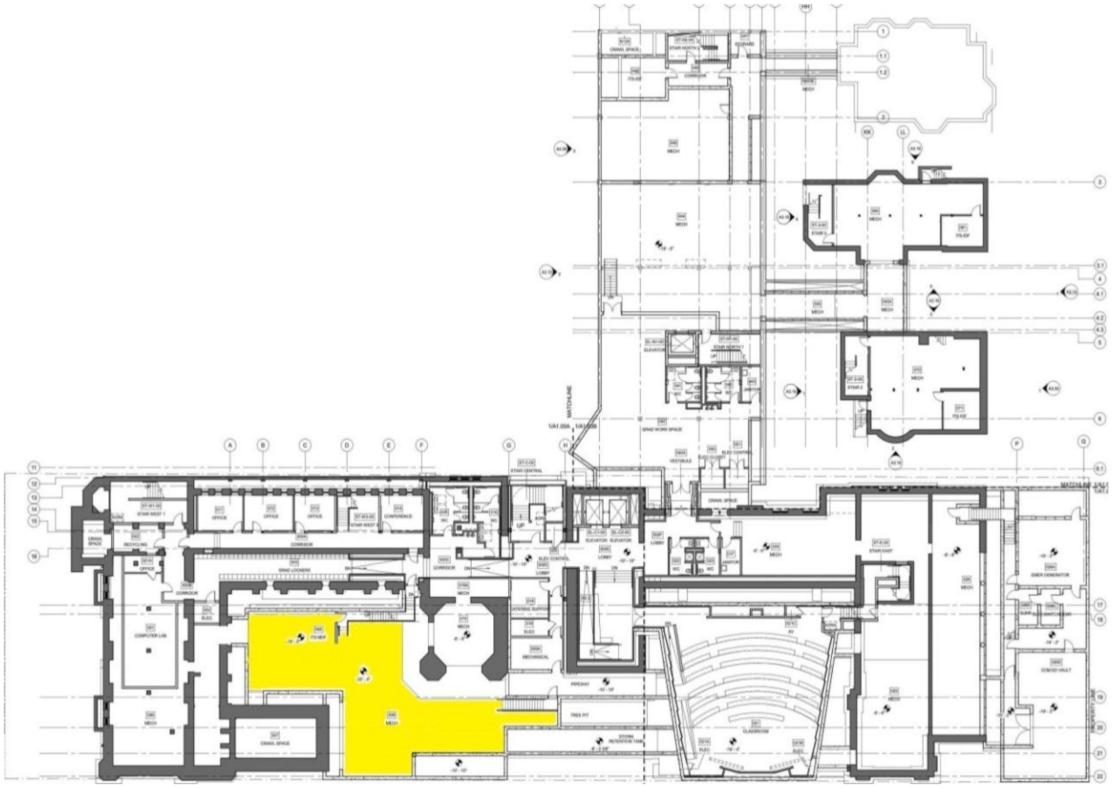


Figure 3-1 Basement Floor Plan (Plan-Issued for Construction, 2012)

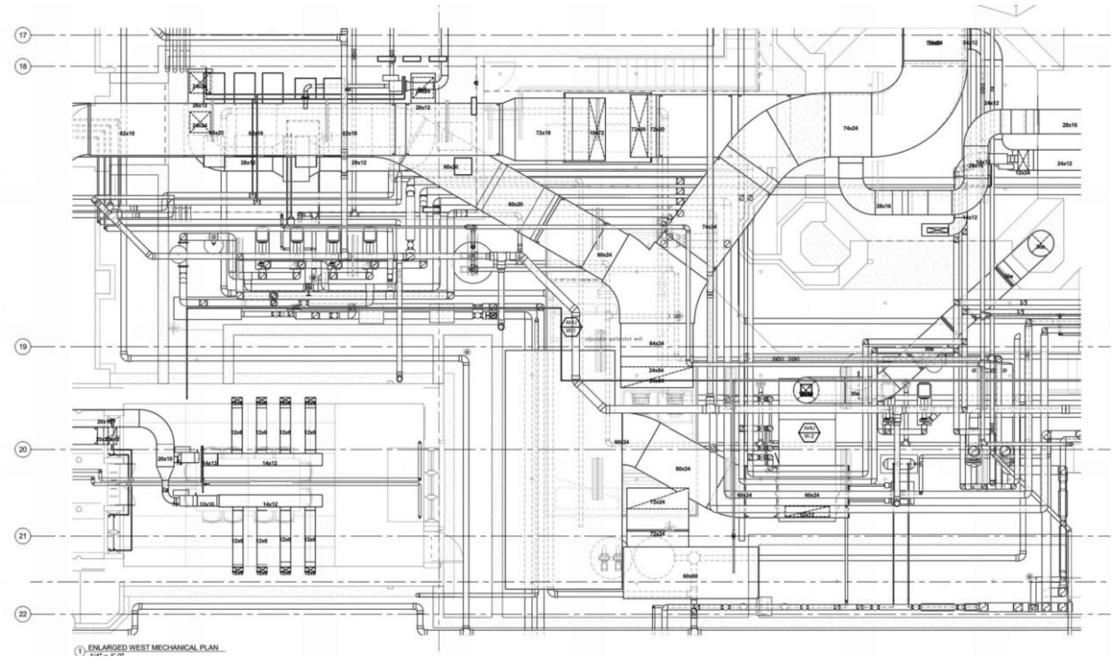


Figure 3-2 Plan of Mechanical Room (Plan-Issued for Construction, 2012)

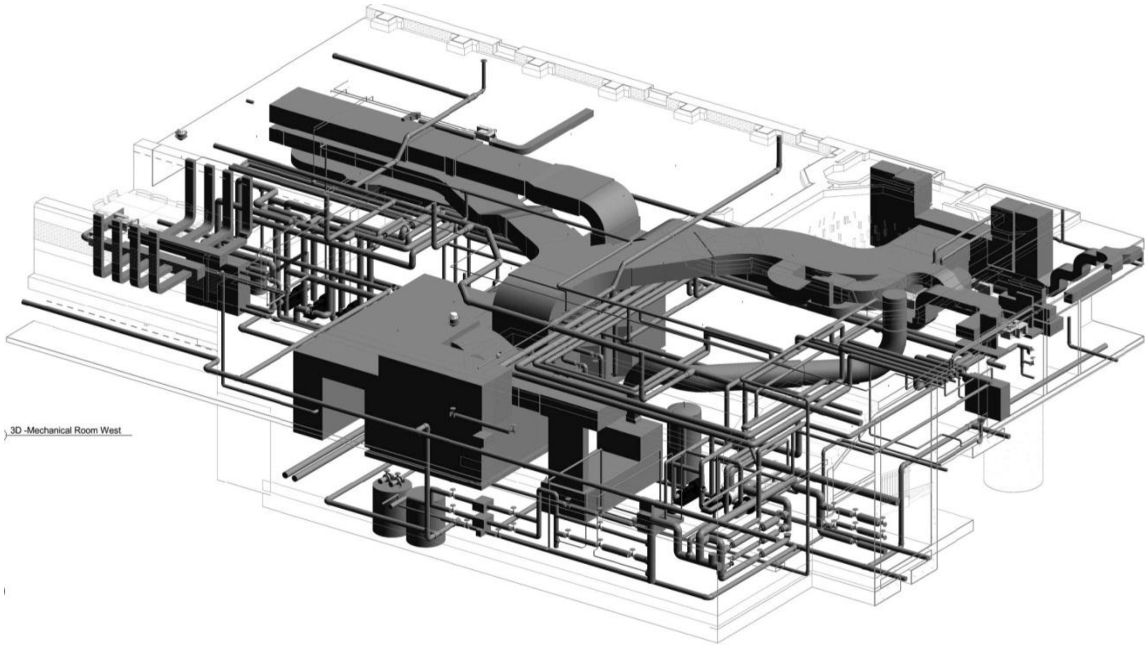


Figure 3-3 Three dimensional view of mechanical room (Plan-Issued for Construction, 2012)

Prefabrication is used to address the constructability issues pertaining to a mechanical room located in the basement of the building. The room under consideration is located on the southwest side of the building. The pre-existing basement, including the mechanical room, will not be undergoing any major structural change, thus the issue associated with the mechanical room is to transfer the components into the room and assemble them with minimum disruptions. To improve the construction process and reduce the budget of the project, the contractor is looking to prefabricate all the equipment piping and sheet metal work associated with the mechanical room. It is accessible by two elevators or two set of stair cases leading to the mechanical room via a corridor which would act as supply route for the material. The room is also located adjacent to a large classroom on the east side, a computer lab on the west side and a few graduate student offices across the corridor on the north side which could act as temporary storage facility.

The area of the room is approximately 2800 sq. feet and it will accommodate a range of boilers, heat pumps, glycol tank, an air handler, and an engine generator. It also has a variety of pipes and duct work serving the building that go in and out of the mechanical room.

Table 3-1 shows the various pipes used to serve the building from the mechanical room. The piping system in the room used for hot water heating has pipe sizes of 2 ½” and larger with an insulation cover 1 ½” thick on each. Chilled water and glycol cooling water piping systems have a 1 ¼” and larger diameter with an insulation cover of 1 ½”. Glycol cooling water pipes are typically 2 ½” and larger in diameter with 1 ½” of insulation cover. There are two sets of all the pipes, one set is used for heating/cooling the air and the other is used for heating/cooling the slab. All the pipes above ground are typically steel, while all the pipes in the slabs are copper or reinforced thermostat resin pipe (RTRP). The high pressure and medium pressure steam and condensate return pipes vary from 4” to 6” with insulation of 2 ½” to 3 ½” respectively. The rooms also contain condensate and blow down drain each having 2 ½” pipe assemblies with 1” of insulation. The standard insulation material used in the building is fiberglass. All the above pipes have standard safety and inlet-outlet valves. The ductwork used for supply and return of outdoor air is rectangular in shape with board insulation of 1 ½” thickness on all sides. The ductwork used for the generator and exhaust are round with fire wrap insulation 1 ½” thick.

Table 3-1
Pipe Material Schedule

S. No.	Service	Size	Insulation Thickness
1	Hot water heating	2 ½” and larger	1 ½”
2	Chilled Water	1 ¼” and larger	1 ½”
3	Glycol cooling water	2 ½” and larger	1 ½”
4	High and medium pressure steam	4” to 6”	2 ½” to 3 ½”

3.2 Research Framework

Research will be done using a technical quantitative approach in which a computerized optimization tool will be applied for producing results. Mutliple cases of optimization will be studied. Data for each will be tabulated and analyzed with help of graphs and figures to derive results

3.3 Optimization Parameters

In order to optimize the module size, optimization tools associated with a computer application will be utilized. Optimization of module size will aim to reduce the connections required on site while at the same time ensuring the transportation of the module is feasible.The size of the module will also be restricted in order to move it around in the basement for storage and later installation.

The parameters associated with the optimization problem is as follows:

- Length of the module
- Width of the module
- Height of the module
- Weight of the module
- Connection time required for each module
- Width of the corridor in the basement
- Door size of the hallway

3.4 Measures of Success

The success of the research will be measured by:

1) The completion of the module size optimization process.
2) The optimum size is considered to be a practical size for the given parameters by the contractors.
3) The contractors would consider utilizing the optimum size in this project.
4) The contractors would consider applying the research for future construction projects.

3.5 Chapter Summary

This chapter provided the project details and framework of the research. It also described the constraints of the optimization problem with the demonstration of the tool that would potentially be used to generate the solution

CHAPTER 4. OPTIMIZATION ROUTINE

. This chapter deals with the set of results for the optimization presented in previous chapters. Results are compiled for the four different cases discussed in Chapter 4. Results for each case are tabulated with respect to the description of the process described in Chapter 4. The chapter also includes a discussion of the results.

4.1 Excel Optimization Solver

After much trial and thought, with various optimization software's available commercially Excel was chosen to be appropriate for the purpose. Excel is an easy to use platform that is very flexible in nature. Excel is universally accepted and interface could be linked to various other software platforms, for example, BIM. The optimization solver in Excel is one of the most powerful and flexible tool for analysis. Optimization in Excel consist of two basic steps

1. Model development
2. Optimization of the model

4.1.1 Model Development

Model development in Excel consists of the following three basic steps:

- Definition of the variables
- Development of constraints and constraint equation
- Development of an objective function that is derived out of the variables

Variables are described as a set of symbols that can assume any set of values in optimization. There are two types of variable, the input variables and the decision variables. Input variables are the values determined by the user that are usually fixed for a particular model. Input variables in the relevant optimization are:

- Density of the module
- Total length, width and height of the complete mechanical system
- Time to connect 1’x1’ module

Table 4-1 shows all the input variables with respective symbols, values and units. Variable names, ‘Symbol’, were designated to all the input variables for the ease of representation in formulas and equations. All the values for the input variables were derived using the information provided by the contractor. This consisted of drawings and specifications for the project. Limited and mindful approximations of these values were done for the ease of calculations. All the values are represented in standard units used in the construction industry.

Table 4-1
Input variables, symbols, values and units of the variables

Input Variables	**Symbol**	**Value**	**Units**
Density	R	5	Lbs/ft^3
Total Length	TL	100	Feet
Total Width	TW	15	Feet
Total Height	TH	10	Feet

Decision variables are the variables subject to change with the progress of the optimization process. These are independent in nature and are of usually primary concern in terms of the result. Decision variables in the relevant optimization model are:

- Length of the module
- Width of the module
- Height of the module

Table 4-2 shows all the decision variables with the symbols used in the optimization model. Values of these variables would be determined by the model during the process of optimization.

Table 4-2
Decision variables, symbols, values and units of the variables

Decision Variables	***Symbol***	**Value**	**Units**
Length	*L*		Feet
Width	*W*		Feet
Height	*H*		Feet

Figure 4-1 represents a shape of a typical module with the decision variables. Units of these variables are kept relevant to standard industry units as well as similar to units of input variables.

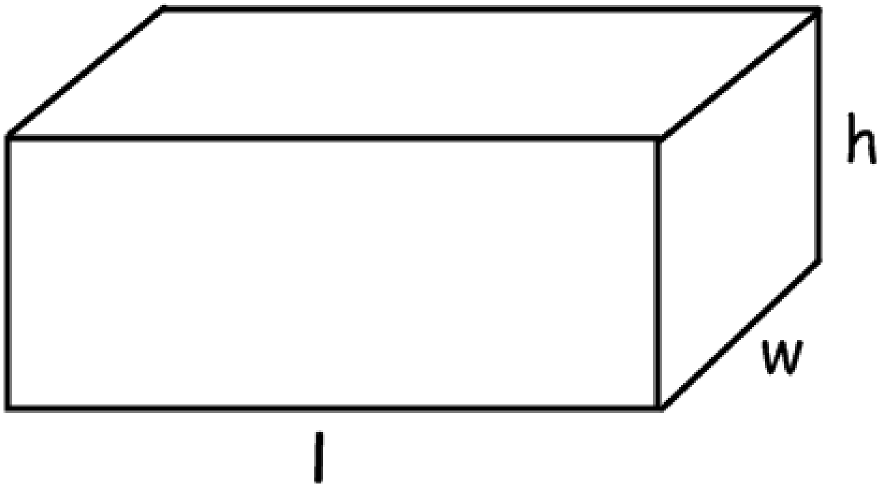


Figure 4-1 Decision variables associated to a typical shape of the module

Constraints are limitations that restrict the scope and extent of the optimization solution to make it viable and practicable. The decision variables have maximum and minimum constraints. Table 4-3 shows all constraints with the maximum and minimum boundary of each with units. Calculation of these maximum and minimum values defining all constraint is discussed later in the chapter. Depending on the optimization being performed, these constraints may or may not be used.

Table 4-3
Constraints with respective maximum and minimum limits

Constraints	**Minimum**	**Maximum**	**Units**
Length (L)	4	9.9	Feet
Width (W)	2	3.5	Feet
Height (H)	3	6	Feet
Weight(Z)	100	1000	Lbs

Objective functions define the purpose of optimization in term of function and equations. The objective needs to be either minimized or maximized for typical optimization results. The two objective functions that need to be maximized and minimized respectively for this research are:

- Volume/density
- Connection time of the module

Table 4-4 shows the objective functions with symbols. Values would be determined as result of the optimization process. Units of these values are also represented in a column of the table.

Table 4-4
Objective functions with to be determined optimal values and units

Objective	*Symbol*	Values	Units
Volume	*V*		cubic feet
Connection time of module	*T*		man hours

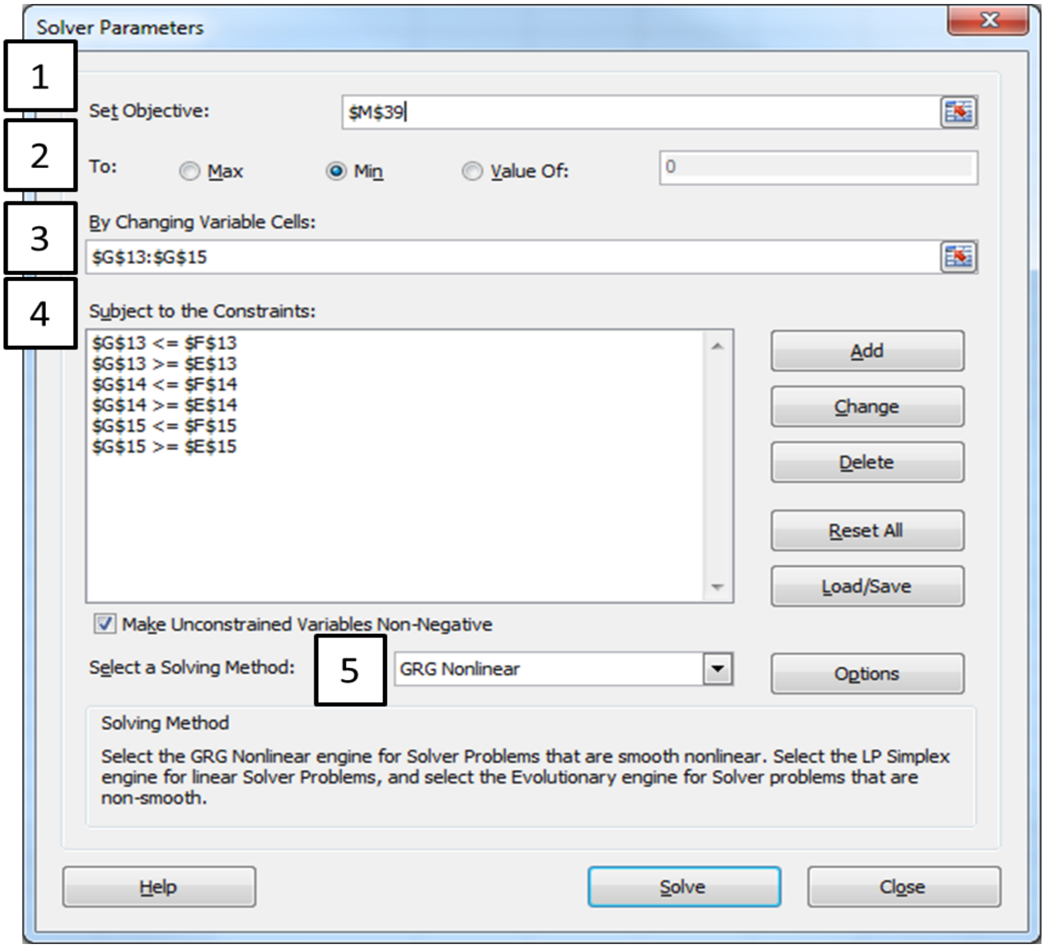
There are a variety of other variables used in the optimization model for defining the relationship between variables, defining constraint equations or the objective functions. These are called supporting variables. These variables are not decision variables or input variable but are still important to the process of optimization. Table 4-5 shows all such variables with respective symbols and units. These supporting variables will be used either directly or indirectly in the optimization.

Table 4-5
Supporting variables with symbols and units

Supporting Variables	***Symbol***	**Units**
Weight	*Z*	Lbs
Connection time of 1'*1' module	*MT*	Man hours
No of module in length	*NL*	No of Units
No of module in width	*NW*	No of Units
No of module in height	*NH*	No of Units
Number of modules in system	*N*	No of Units
Connection time for system	*TT*	Man hours

4.1.2 Optimization of the Model

The optimization of the model will be done using an Excel add-in called ‘Solver’. The add-in can be activated using the ‘Options’ menu in the ‘File’ tab. The solver can be accessed via the ‘Data’ tab. It can be used to solve linear, nonlinear and 3-D optimization problems. Figure 4-2 shows a screen shot of the interface for the Excel solver add-in used for optimization.



Set Objective: $M$39

To: ○ Max ● Min ○ Value Of: 0

By Changing Variable Cells: $G$13:$G$15

Subject to the Constraints:

$G$13 <= $F$13
$G$13 >= $E$13
$G$14 <= $F$14
$G$14 >= $E$14
$G$15 <= $F$15
$G$15 >= $E$15

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

Figure 4-2 Screen shot of the optimization solver.

Optimization of the model involves the following five steps that are also highlighted in Figures 4-2 with the numbers 1, 2, 3, 4 and 5. The following steps are actions required for each of these numbers:

- Step 1: ‘Set Target Cell’ defines the cell containing the optimization function with a choice to maximize or minimize the function.
- Step 2: Choose to maximize or minimize the function in order to receive an optimal solution for the objective function.

- Step 3: ‘Changing Cells’ refers to the decision variables of the function. These values of decision variables in the cell on the Excel sheet are subject to change depending on the optimization results.
- Step 4: ‘Subject to the constraints’ contains equations that define the boundary of optimization.
- Step 5: Choose the optimization method depending upon the constraint and objective equations.

4.2 Optimization Methods

There are three methods employed by Excel to perform the optimization:

1. Simplex linear programing (LP)
2. Generalized reduced gradient (GRG) nonlinear optimization
3. Evolutionary algorithm

4.2.1 Simplex Linear Programing

Simplex linear programing (LP) is the basic mathematical method used to determine the best possible solution for a problem. These problems are subject to linear solutions with a feasible region, possibly unbounded and open ended (Lemke, 1954). The standard form of simplex LP can be represented as following

Minimize or maximize: $f(x) = c * x$

Subject to: $a * x = b$

In the above equations, x is the variable, typically non negative in nature, c is the coefficient of the variable, while a, b represents a matrix or set of its columns. The ‘Subject to' equations correspond to the constraint equation and can be multiple equations. A solution is generated for $f(x)$ by examining the corner points of the feasible solution.

Solution of the LP model with a constraint of integer solution for decision variable or objective function is done using the branch and bound method. Using this method the solution set is divided into a range of small sets and the minimum/maximum value of the objective function is determined in each. This step is called branching. The next step, bonding, is when maximum/minimum values from different subsets are compared to determine the optimal solution.

4.2.2 Generalized Reduced Gradient Non-linear

Similar to simplex LP, the purpose of Generalized Reduced Gradient (GRG) nonlinear optimization is to find the best possible solution for a problem with the exception that either one of the constraints or the objective function is a non-linear equality or inequality. The standard form of nonlinear optimization problem could be represented as

Minimize or maximize: $f(x)$

Subject to: $g(x) \leq 0$ and $h(x) \geq 0$

In the above equations, x is the variable and $f(x)$ is a nonlinear function of x. The ‘Subject to’ equations $g(x)$ and $h(x)$ correspond to the constraint equations that can be linear or nonlinear in nature. Under nonlinear conditions, the solution might have a variety of ‘peaks’ (if maximizing) and ‘valleys’ (if minimizing) for a single problem. The GRG nonlinear method looks for these ‘peaks’ and ‘valleys’, thus giving out a solution when one of the following three conditions has been satisfied (Frontline solvers, 2013):

- “Solver found a solution” indicates all the constraints and optimality conditions are satisfied with the solution presented. This is typically a local optimal solution where a set of the values of the decision variables associated with the solution yields a better value of the objective as compared to any local value.
- “Solution has converged to the current solution” indicates all the constraints are satisfied without a ‘peak’ or ‘valley’ but the objective function value is changing very slowly in the last few iterations and trial solutions.
- “Solver cannot improve the current solution” indicates all the constraints are satisfied but the model has degenerated and the solutions are cycling with iterations. This generally occurs due to poor scaling of the model. “A poorly scaled model is on in which typical values of the objective and constraint functions differ by several orders of magnitude” (Frontline Solvers, 2013).

4.2.3 Evolutionary

The evolutionary algorithm or genetic algorithm is used to determine an optimal solution for non-smooth optimization problems. All problems correlated with a function that cannot be differentiated or has a continuous derivate is known as a non-smooth function. This method is progressive in character and uses results derived in a previous iteration and trial as a basis for determining the solution for the current trial.

4.3 Choice of Solver

The choice of the solver was based on the type of equation used in the objective and constraints. The optimization for the current objective function consists of three variables making it a nonlinear equation. Therefore the Simplex LP method was eliminated as possible solver choice. The functions for the current optimization are considered to be smooth functions therefore the Evolutionary algorithm was not needed. This leaves the GRG algorithm which is a good fit for the non-linear optimization

4.4 Constraints Calculations

As discussed earlier, the constraints of the decision variables to change would be governed by the method of transportation and restrictions associated to in-house movement of the module from one place to another. Lower bounds of the constraints in the particular case are not due to any restriction and thus are not calculated. Instead an approximation is used. Upper bounds of the constraints are calculated for weight, height, width and length.

Weight of the module was determined as to be a product of the volume and density. It is assumed that inside the building a material lift would be used to place the module in place. Weight of the module was set to have an upper limit corresponding to maximum capacity of these material lifts typically available and used for commercial construction. Thus, the upper limit bound for weight was determined to be 1000 pounds.

Height of the module would have an upper bound pertaining to the height of a typical ceiling for a room. It would be further bound by the height of the set of corridor and doors leading to a particular room. As per the information presented in the set of construction drawings, the height of the door sets the upper bound for the height constraints. The typical door in the facility has a height of 6’10”, thus the upper bound for height constraint was chosen to be six feet, leaving an allowance of ten inches. This allowance is for a cart and its wheels that is used for in-house movement of modules. These are commercially available and are usually referred to as ‘Material handling equipment: Appliance truck’.

Similar to the height constraint, the width of the module was also constrained at the upper limit by the width of the door. The upper bound for the width constraint was chosen to be three and half feet, based on information gathered from the set of construction drawings. The upper limit constraints for the length are maximized by analyzing the location that would constrain the module movement. For example, moving of the module around the corner. The constraining length based on the drawings was determined as detailed in the following section.

4.4.1 Differentiation of Upper Limit of the Length of the Module

The following equations and figures were used to deduce the value of upper limit constraint for the length of the module. Figure 4-3 shows the constraining point with the following variables

- Width of the corridor *T*'
- Length of the module $L = x + y$.
- Ɵ as the angle module makes with the wall of the corridor.

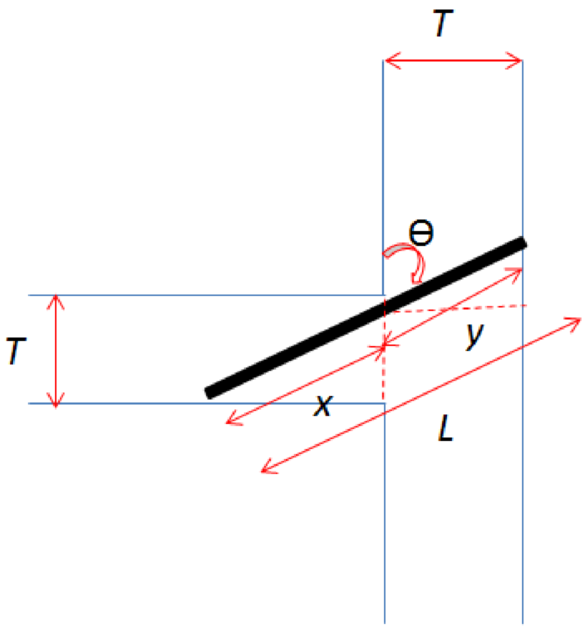


Figure 4-3 Constraining point for the 'Length of the Module'

Using trigonometry the following equations can be determined

$$x = \frac{T}{\cos \Theta}$$

$$y = \frac{T}{\sin \Theta}$$

Equation $L = x + y$ will undergo partial differentiation in terms of $dL/d\Theta$ using the equations derived above via trigonometry. The following equations show the results used to derive the upper bound for the length constraint. Details of the differentiation are presented in Appendix A.

$$L = x + y$$

$$L = \frac{T}{\cos \Theta} + \frac{T}{\sin \Theta}$$

$$\frac{\partial L}{\partial \Theta} = \left\{ \frac{\partial(\frac{T}{\cos \Theta})}{\partial \Theta} \right\} + \left\{ \frac{\delta(\frac{T}{\sin \Theta})}{\delta \Theta} \right\}$$

For maximum value of $dL/d\Theta = 0$, thus

$$\cos \Theta = \sin \Theta$$

From the above equation, $\Theta = \frac{\pi}{4}$. With $T = 3.5$, the length can be calculated to be $L = 9.899$ feet

4.5 Optimal Solution

The optimization model relevant to the research is a multi-objective optimization problem. As described earlier, it contains two objectives, maximization of the volume and minimization of time required for connection.

There are many methods available for multi objective optimization. For the research the Pareto optimal and tradeoff curves method is used based on the ease of application using Excel and its Solver. To develop solve the multi objective problem the following cases were used:

- Case 1: Maximization of Volume (Single Objective)
- Case 2: Minimization of Connection Time of the Module (Single Objective)
- Case 3: Maximization of Volume (‘Pareto optimal’ Method)
- Case4: Minimization of the Connection Time of the Module (‘Pareto optimal’ Method)

4.5.1 Pareto Optimal and Tradeoff Curve

Named after Vilfredo Pareto, Pareto optimal is a measure of efficiency. A variety of definitions have been given to the term and the process with respect to its application, but the following description given by Winston, & Goldberg, 2003, best applies to this research.

> “In a multi-attribute decision making situation in the absence of uncertainty, we often search for ‘Pareto optimal’ solutions. We will assume that our decision maker has two objectives, and that the set of feasible points under consideration must satisfy a given set of constraints. A solution (call it A) to a multiple objective problem is Pareto optimal if no other feasible solution is at least as good as A with respect to every objective and strictly better than A with respect to at least one objective.

> If we define the concept of dominated solutions as follows, we can rephrase our definition of ‘Pareto optimality. A feasible solution B dominates a feasible solution A to a multiple objective problem if B is at least as good as A with respect to every objective and strictly better than A with respect to at least one objective.”

The Pareto optimal solutions are the set of all un-dominated feasible solutions. The values of the objective function can be graphed on either axis and a curve is obtained. This curve is called a Trade-off curve that establishes a relation between optimal values of two objectives.

Figure 4-4 shops a typical trade-off curve with two objective functions in a plane coordinate system. In the curve presented, objectives on x-axis and y-axis are minimized and maximized respectively. The shaded region represents all the feasible solution while the points on the curve correspond to all of the ‘Pareto optimal solutions’ that are in the un-dominated feasible solution.

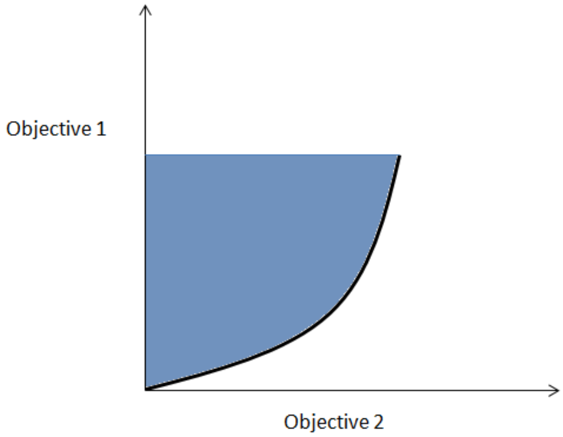


Figure 4-4 ‘Pareto optimal curve’

4.5.2 Functions and Relations

Before the optimization cases can be determined, definition of all relation used are necessary. These relations are standard in nature and will be used in all the above cases without any alteration. As mentioned before, assuming the module to be cube/cuboids in shape, the volume of module will be the product of its length, width and height. Equation 1 shows the volume of the module as a function of its length, width and height. This equation will be used an objective function in the optimization process. All the symbols used for the equation are the same as mentioned above in Table 4-2.

$$V = L * W * H \qquad \text{Equation 1}$$

Connection time of the module is the second objective and can be described as the product of width, height and time of connection for 1’x1’ module. This connection time is the total time required to freight, place and connect the module in place using the appropriate equipment. Based on the initial assumption that connections are made end to end only, it is implicit that there will be no connection along the width and height of the module. Equation 2 describes the connection time of a module as function of width, height and connection time for 1’x1’ module.

$$T = W * H * MT \qquad \text{Equation 2}$$

The connection time for a 1’x1’ module is known to be a function of weight. The smaller the module, the easier it is to handle. It also typically requires less equipment and/or lighter equipment, which results in quicker transition and assembly. As the size of the module increases, the module becomes more difficult to handle resulting in a higher transition time. The increased difficulty in connection leads to a requirement for additional equipment and labor hours. This relationship can be represented by a variety of equations depending upon the sector, type and various properties of construction. For the purpose of this research, the following equation was chosen it best suits the project and its constraining factors. Equation 3 represents time of connection for 1’x1’ module as a function of weight.

$$MT = \frac{\left(\frac{Z}{100}\right)^3}{100} \qquad \text{Equation 3}$$

Constraints used to bound and define the feasible solution region of the optimization model are simple equations providing maximum and minimum properties. These equations can be easily derived using Table 4-2 and Table 4-3. Equations 4, 5 and 6 describe the maximum and minimum for the length, width and height of the module. Equation 1 and Equation 2 would also be used as constraints because a multi-objective optimization is done using ‘Pareto optimal’ method.

$4 \leq L \leq 10$ Equation 4

$2 \leq W \leq 3.5$ Equation 5

$3 \leq H \leq 6$ Equation 6

The output from the optimization can be used to determine other variables for general information and ease of decision making process. These calculated variables include

- Number of modules along the length of the system

$NL = \frac{TL}{L}$ Equation 7

- Number of modules along the width of the system

$\mathrm{NW} = \frac{\mathrm{TW}}{\mathrm{W}}$ Equation 8

- Number of modules along the height of the system

$NH = \frac{TH}{H}$ Equation 9

Equation 10 describes the total number of modules in the system as a function of number of the modules along the length, width and height of the system.

$N = (NL - 1) * NW * NH$ Equation 10

4.5.3 Case 1: Maximization of Volume (Single Objective)

Case 1 is the optimal solution when Equation 1, volume, is maximized. The result is the maximum volume feasible with values of associated decision variables *L, W and H.* The connection time of the module was also calculated in order to perform the ‘Pareto optimal’ solution. These results obtained are tabulated and presented later in Chapter 5.

4.5.4 Case 2: Minimization of Connection Time of the Module (Single Objective)

Case 2 is the optimal solution when Equation 2, connection time of the module, is minimized. The result is the minimized connection time with the values of associated decision variables *L, W and H.* The volume of the module was also calculated in order to perform the ‘Pareto optimal’ solution. These results obtained are tabulated and presented later in Chapter 5.

4.5.5 Case 3: Maximization of Volume (Pareto Optimal Method)

Results from Case 1 are used and are considered to be a ‘Pareto optimal’ solution for Case 3. For the Case 1 solution not to be ‘Pareto optimal’, there would have to be a solution satisfying all the constraints that yields a higher value of volume and a lower value of connection time as compared to that obtained in Case 1. Since the solution obtained in Case 1 is a unique solution there is no other solution better than the solution from Case 1. However, a number of solutions can be determined that are as good as the solution obtained from Case 1 given a variation in connection time.

Case 3 presents the optimal solution of a maximized volume associated with a given set of connection time values. The total connection time is varied from the lower bound to the upper bound of connection time. A set of optimal volume solutions are generated for the given connection times resulting in multiple solutions that are graphed. For Case 3 the volume is graphed on the y-axis and connection times graphed on the x-axis. To derive these solutions a modified connection time equation is developed:

$$T\ (= W * H * MT) \leq Trial\ time \qquad \text{Equation 10}$$

A variety of values of *'trial time'* are used with the maximization of volume function represented by Equation 1. Equation 1 is constrained by Equations 4, 5, 6, and 10. These values of 'trial time' are assumed to be smaller than the values of connection time obtained in Case 1. A value of length, width and height associated to the each 'trial time' is calculated. The tradeoff curve is generated using these values. These values and graphs are tabulated in Chapter 5.

4.5.6 Case 4 Minimization of the Connection Time of the Module (Pareto Optimal Method)

Results from Case 2 are used are considered to be a 'Pareto optimal' solution for Case 4. For the Case 2 solution not to be 'Pareto optimal', there would have to be a solution satisfying all the constraints that yields a lower value of connection time and higher value of volume as compared to that obtained in Case 2. Since the solution obtained in Case 2 is a unique solution there is no solution better than the solution from Case 1. However, a number of solutions can be determined that are as good as the solution obtained from Case 2 given a variation in volume.

Case 4 presents the optimal solution of a minimized connection time of the module associated with a given set of assumed values of volume. The volume of the module is varied from the lower bound to the upper bound. A set of optimal solutions are generated for the given values of volume resulting in multiple solutions that are graphed. For Case 4 the volume is graphed on the y-axis and connection time graphed on the x-axis. To derive these solutions a modified connection time equation is developed:

$$V\ (= L * W * H)\ \geq Trial\ volume \qquad \text{Equation 11}$$

A variety of values of *‘trial volume’* are used with the minimization of the connection time function represented by Equation 2. Equation is constrained by Equation 4, 5, 6 and 11. These values of *‘trial volume’* are assumed to be greater than value of volume obtained in Case 2. A value of length, width and height associated to the each ‘trial time’ is calculated. Trade off curve is generated using these values. These values and graphs are tabulated in Chapter 5.

CHAPTER 5. RESULTS

This chapter deals with the set of results for the optimization presented in previous chapters. Results are compiled for the four different cases discussed in Chapter 4. Results for each case are tabulated with respect to the description of the process described in Chapter 4. The chapter also includes a discussion of the results.

5.1 Case 1: Maximization of Volume (Single Objective)

The following values were determined using the Excel solver for Case 1 in Chapter 4. Table 5-1 provides the values of all decision variables. Table 5-2 tabulates the value of the objective function. Table 5-3 presents the value of all other desired outputs.

Table 5-1

Values of decision variables corresponding to Case 1

Decision Variables			
	Symbol	Value	Units
Length	*L*	9.9	Feet
Width	*W*	3.37	Feet
Height	*H*	6.00	Feet

Table 5-2

Value of objective function corresponding to Case 1

Objective			
	Symbol	Values	Units
Volume	*V*	*200*	cubic feet
Connection time of module	*T*	*202.02*	man hours

Table 5-3

Value of other outputs variables corresponding to Case 1

Supporting Variables			
	Symbol	***Values***	**Units**
Weight	*Z*	*1000*	Lbs
Connection time of 1'*1' module	*MT*	*10*	Man hours
No of module in length	*NL*	*10.10*	No of Units
No of module in width	*NW*	*4.45*	No of Units
No of module in height	*NH*	*1.67*	No of Units
Number of modules in system	*N*	*75*	No of Units

The optimization results in the maximization of the module per the constraints. The module maximum volume is 200 cubic feet. Length and height of the module reaches the maxima while the width was constrained below the maximum. The binding constraints for these results are the upper limits for the height, length and weight of the module.

5.2 Case 2: Minimization of Connection Time of Module (Single Objective)

The following values were determined using the excel solver as per the description given for Case 2 in Chapter 4. Table 5-4 gives the values of all decision variables. Table 5-5 tabulates the value of objective function. Table 5-6 presents the value of all other desired outputs.

Table 5-4
Values of decision variables corresponding to Case 2

Decision Variables	*Symbol*	Value	Units
Length	*L*	4	Feet
Width	*W*	2	Feet
Height	*H*	3	Feet

Table 5-5
Value of objective function corresponding to Case 2

Objective	*Symbol*	Values	Units
Volume	*V*	*24*	cubic feet
Connection time of module	*T*	*0.10*	man hours

Table 5-6
Value of other outputs variables corresponding to Case 2

Supporting Variables/Equations	***Symbol***	***Values***	**Units**
Weight	*Z*	*120*	Lbs
Connection time of 1'*1' module	*MT*	*0.02*	Man hours
No of module in length	*NL*	*25*	No of Units
No of module in width	*NW*	*7.5*	No of Units
No of module in height	*NH*	*3.33*	No of Units
Number of modules in system	*N*	*625*	No of Units

The optimization results in minimization of the module per the constraints. The module minimizes at a volume of 24 cubic feet with a connection time of 0.10 man hours. Length, width and height were minimized to the lower limit.

These variables also acted as the binding constraints in the process of minimization.

5.3 Case 3: Maximization of Volume (Pareto Optimal Method)

The following values were determined using the Excel solver as per and optimization with the Pareto optimal method. As discussed in Chapter 4, different values of *'trial time'* were used to optimize Equation 1. Table 5-7 tabulates different values of '*trial time'* corresponding to the values of all the decision variables, objective functions and supporting variables.

Table 5-7

Different values of 'trial time' with corresponding values of all decision variable, objective function and supporting variables

Observed Values	***T-1***	**T-2**	**T-3**	**T-4**	***T-5***	**T-6**	**T-7**	**T-8**	***T-9***	**T-10**	**T-11**	**T-12**
Trial time (man hours)	0.1	0.2	0.5	1	2	5	10	20	50	100	150	200
Connection time for one module (man hours)	0.10	0.20	0.50	1.00	2.00	5.00	10.00	20.00	50.00	100.00	150.00	200.00
Volume (lbs/ft^3)	24.00	29.88	40.55	51.09	63.09	79.33	94.34	112.19	141.07	167.67	185.65	199.50
Length (feet)	4.00	4.98	6.76	8.51	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90
Width (feet)	2.00	2.00	2.00	2.00	2.01	2.30	2.53	2.65	2.82	3.06	3.31	3.49
Height (feet)	3.00	3.00	3.00	3.00	3.16	3.48	3.76	4.28	5.05	5.53	5.67	5.78
Weight (lbs)	120.0	149.3	202.7	255.4	315.4	396.6	471.6	560.9	705.3	838.7	928.2	997.4
Connection time of 1'*1' module (man hours)	0.02	0.03	0.08	0.17	0.31	0.62	1.05	1.76	3.51	5.90	8.00	9.92
No of module in length	25.00	20.08	14.80	11.74	10.10	10.10	10.10	10.10	10.10	10.10	10.10	10.10
No of module in width	7.50	7.50	7.50	7.50	7.45	6.51	5.92	5.67	5.31	4.90	4.54	4.30
No of module in height	3.33	3.33	3.33	3.33	3.16	2.88	2.66	2.34	1.98	1.81	1.76	1.73
Number of modules in system	625.0	502.0	369.9	293.6	237.7	189.0	159.0	133.7	106.3	89.41	80.80	75.19

Figure 5-1 is a plot of the variation of length, width and height versus connection time of the module. Figure 5-2 is a plot of the variation of the connection time of the module with the volume of the module. This curve is known as the optimal solution curve. Any point on the curve results in an optimal solution ratio of connection time of the module to the volume. Connection time is proportional to the volume and is directly proportional to the variation of length, width and height of the module. Figure 5-3 is a plot of the volume of the module versus the number of modules in the system.

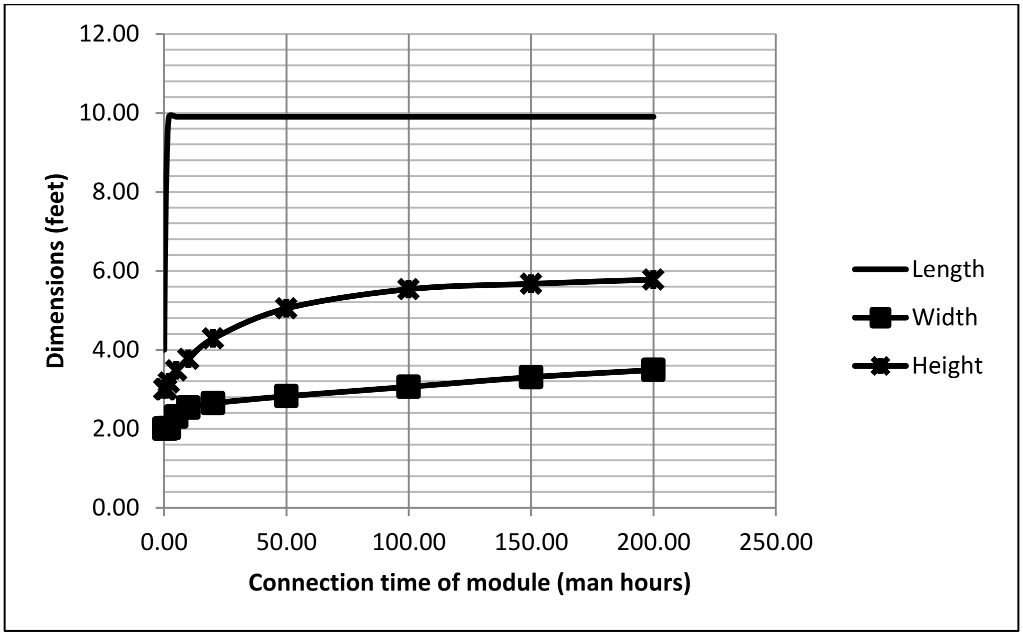


Figure 5-1 Graphs the variation of height, width and height of the module with the connection time of the module.

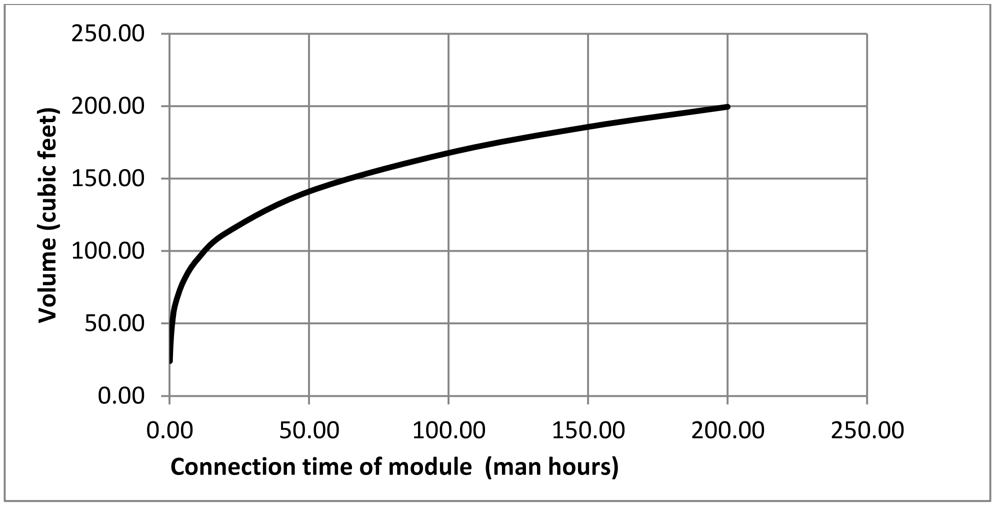


Figure 5-2 Graph representing curve of Volume to the connection time of the module

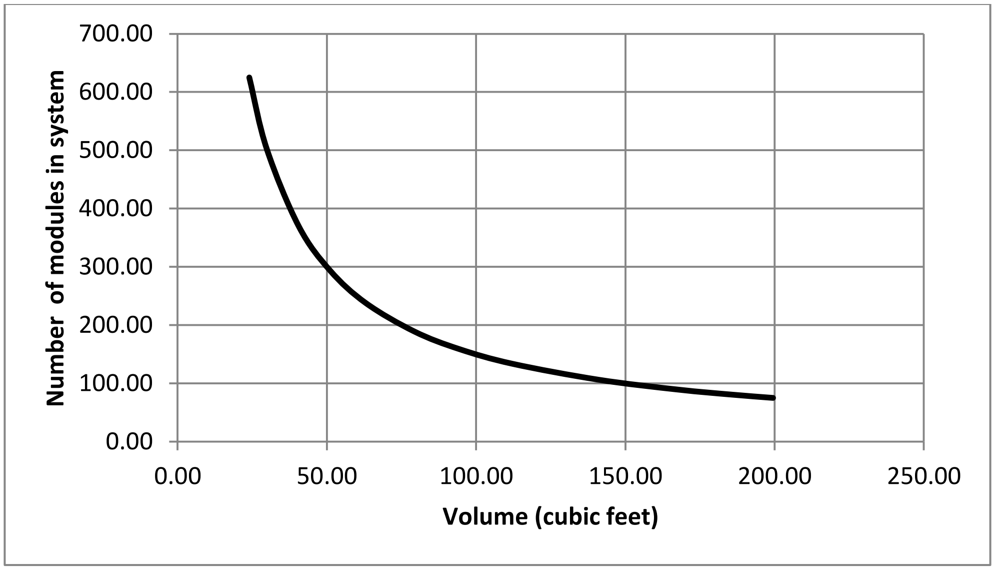


Figure 5-3 Graph representing the volume of the module versus the number of modules in the system.

As represented in Table 5-7 and Figures 5-1, 5-2 and 5-3 the connection time of the module increases with increases in volume at a variable rate. Initially, volume increases substantially with a small increase in the connection time. As the module becomes larger a substantial increase in connection time results in a small change in the module size. It can also be observed that during the optimization process, the length of the module reaches its maximum promptly and stays at this maximum for the rest of the process. Height of the module also maximizes at the beginning of the process. The width of the module rises more slowly and does not reach the maximum dimension.

At the end of the optimization process the 'Solver' can be used to generate the analysis report. This report is integrated in the solver and can be used to answer variety of question pertaining to the iterations and results. These reports provide with an insight on how the model operations. Analysis reports are of three types. Appendix B provides detailed reports generated by the solver.

5.4 Case 4: Minimization of Connection Time of Module (Pareto Optimal Method)

The following values were determined using the Excel solver for the maximum volume using the Pareto optimal method. As discussed in Chapter 4 different values of *'trial volume' were* used to optimize Equation 2. Table 5-8 tabulates different values of *'trial volume'* corresponding to values of all the decision variables, objective functions and supporting variable

Table 5-8

Different values of 'trial volume' with corresponding values of all decision variable, objective function and supporting variables

Observed Values	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10	T-11	T-12
trial volume (cubic feet)	24.00	27.00	30.00	36.00	45.00	60.00	80.00	100.0	125.0	150.0	175.0	200.00
Volume (cubic feet)	24.00	27.00	30.00	36.00	45.00	60.00	80.00	100.0	125.0	150.0	175.0	200.00
Connection time of module (man hours)	0.10	0.15	0.20	0.35	0.68	1.64	5.17	12.62	30.83	63.92	118.4	202.00
Length (feet)	4.00	4.50	5.00	6.00	7.50	9.90	9.90	9.90	9.90	9.90	9.90	9.90
Width (feet)	2.00	2.00	2.00	2.00	2.00	2.01	2.47	2.85	3.41	3.40	3.27	3.37
Height (feet)	3.00	3.00	3.00	3.00	3.00	3.00	3.27	3.55	3.70	4.46	5.40	6.00
Weight(lbs)	120.0	135.0	150.0	180.0	225.0	300.0	400.0	500.0	625.0	750.0	875.0	1000.0
Connection time of 1'*1' module (man hours)	0.02	0.02	0.03	0.06	0.11	0.27	0.64	1.25	2.44	4.22	6.70	10.00
No of module in length	25.00	22.22	20.00	16.67	13.33	10.10	10.10	10.10	10.10	10.10	10.10	10.10
No of module in width	7.50	7.50	7.50	7.50	7.50	7.45	6.07	5.27	4.40	4.42	4.58	4.45
No of module in height	3.33	3.33	3.33	3.33	3.33	3.32	3.06	2.82	2.70	2.24	1.85	1.67
Number of modules in system	625.0	555.5	500.0	416.6	333.3	250.0	187.5	150.0	120.0	100.0	85.71	75.00

Figure 5-4 is a plot of the variation of length, width and height versus connection time of the module Figure 5-5 is a plot of the variation of the connection time of the module with the volume of the module. This curve is known as the optimal solution curve. Any point on the curve results into an optimal solution ratio of connection time of the module and the volume. Connection time is proportional to volume. Volume is directly proportional to the variation of length, width and height of the module. Figure 5-6 is the plot of the volume of the module versus the number of modules in the system.

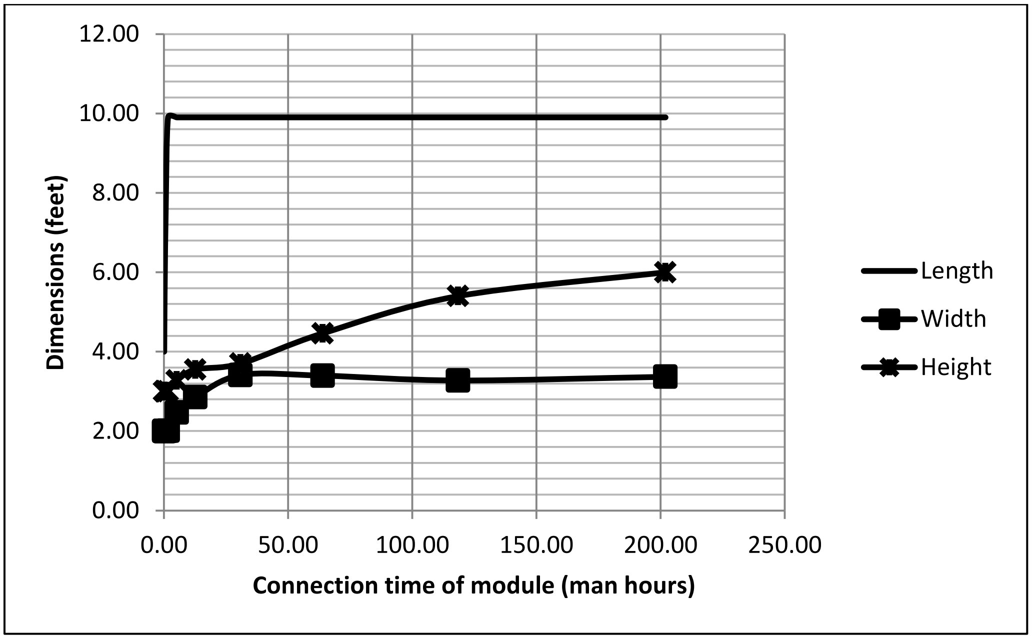


Figure 5-4 Graphs the variation of height, width and height of the module with the connection time of the module.

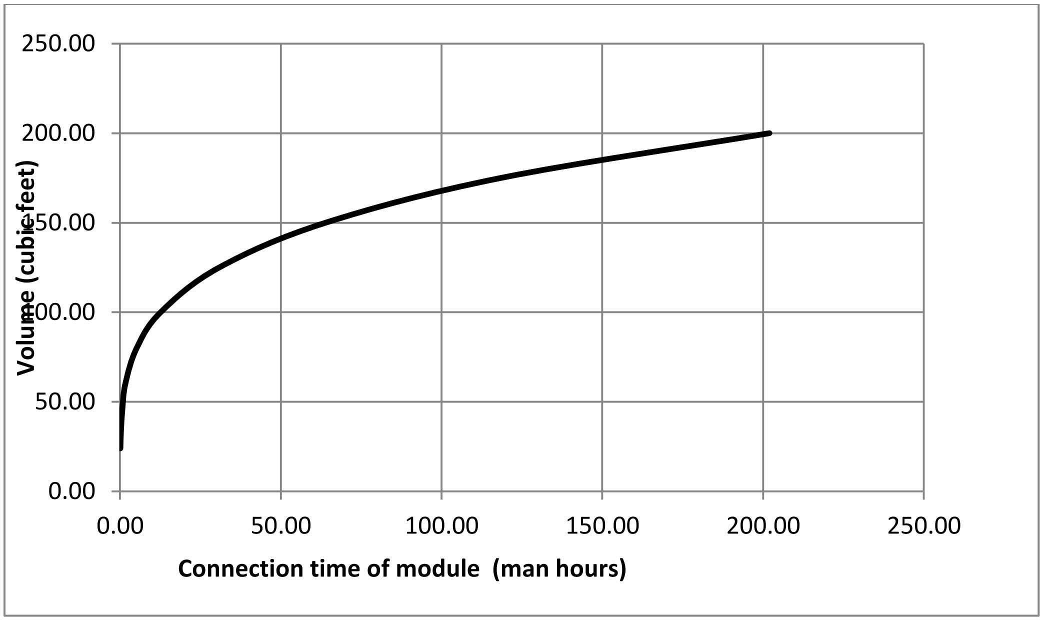


Figure 5-5 Graph representing curve of Volume to the connection time of the module

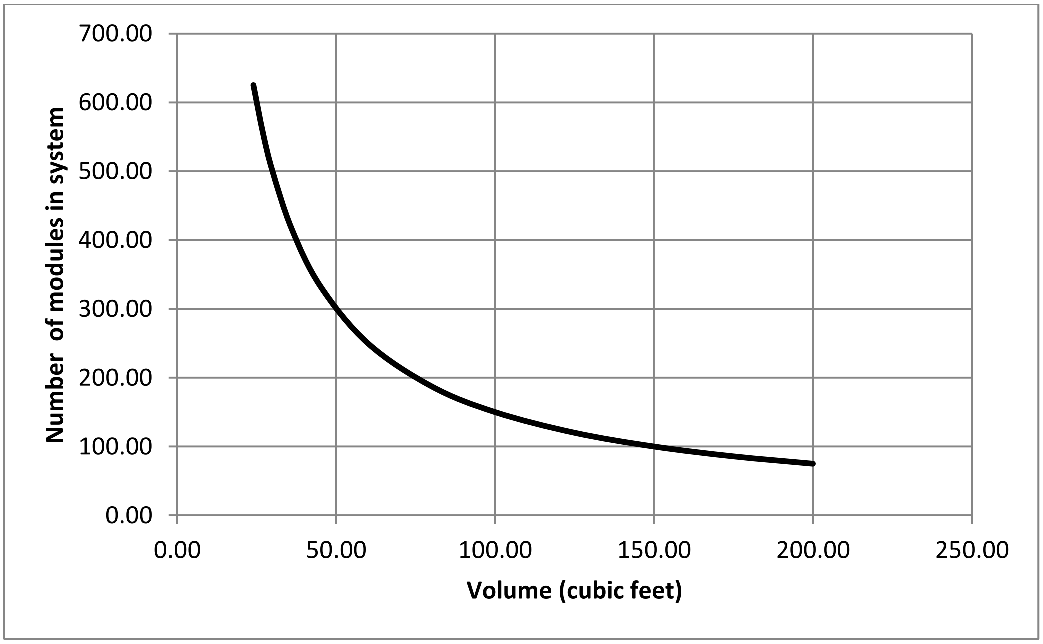


Figure 5-6 Graph represents the volume of the module versus the number of modules in the system

As represented in the table and associated graphs the results are similar to that derived in Case 3. Significance of Case 4 will be discussed in the following sections of the chapter.

5.5 Discussion of results

This section discusses all cases and results associated with the optimization performed. Each case is studied individually while evaluating its significance to the research and its inter-dependency with other cases.

5.5.1 Discussion of Case 1

This is a simple test of optimization that is performed for two reasons; the first is to test the Excel model developed for its accuracy and precision. The second is a basis for the Case 3 optimization. As expected, the Case 1 optimization maximized the volume of the module by maximizing the length, width and height of the module. The size of the module was only constrained by weight of the module. Since the optimization was governed by the size and weight constraints, it can be concluded that if there were no constraints this process would always maximize in a way that the entire system could be prefabricated offsite and put in to place with no onsite connections required. However, in real life conditions this is not feasible and thus constraints were added for an acceptable, practical and realistic result.

5.5.2 Discussion of Case 2

Similar to Case 1, this optimization is performed for primarily two reasons; the first is to test the Excel model developed for its accuracy and precision in the minimization mode. The second is that the result of Case 2 will serve as basis for the Case 4 optimization. As expected, the Case 2 optimization minimizes the volume of the module by minimizing the length, width and height of the module. This minimization process will not aid in the process of prefabrication. Therefore this result is not applicable for optimization of module size.

5.5.3 Discussion of Case 3

Case 3 presents the most applicable results of the optimization process. This case utilizes the ‘Pareto optimal’ method and presents optimization results using both the volume and connection time of the module as objective functions simultaneously. Volume was considered to be the primary objective while the other objective function of connection time of the module was converted to a constraint as described in the ‘Pareto optimal’ method. Various trials were performed and values associated with each of these trials were tabulated. Tabulated values were used to obtain a graphical curve between the two objective functions, connection time and volume. Connection time pertaining to each module could also be directly associated to productivity for each module. As presented in Table 5-7 and Figure 5-3 it was observed that volume increases substantially with a small increase in the connection time. As the module becomes larger a substantial increase in connection time results in a small change in module size. Thus it could be inferred that productivity is highest when the module is small and productivity decreases with an increase in module size. However as represented in Table 5-7 and Figure 5-4 as the volume decreases the number of modules in the system increases. Thus to develop the entire system it takes a higher number of small size module and a relative less number of large size modules. Thus an optimal scenario would be to determine the volume of the module using both connection time/productivity and the number of modules in the system. This is an important result and can be applied directly in the construction industry.

5.5.4 Discussion of Case 4

This optimization process was primarily performed to cross check the results for Case 3. Case 4 utilizes the ‘Pareto optimal’ method and presents optimization results using both the volume and connection time of the module as objective functions simultaneously. Connection time was considered to be the primary objective while the other objective function of volume of the module was converted to a constraint as described in the ‘Pareto optimal’ method. Various trials were performed and values associated with each of these trials were tabulated. Tabulated values were used to obtain a graphical curve between the two objective functions, connection time and volume. Results were obtained to be similar as presented in Case 3.

CHAPTER 6. CONCLUSIONS

This chapter presents analysis and discussion of the optimization based on the results presented in previous chapters. This chapter also discusses the future research that could be performed utilizing the optimization routine developed in this research.

6.1 Summary of Conclusions

Prefabrication is known as a technique to increase productivity in construction. The optimization routines developed through the research further increases the productivity of modularization by optimizing the size of the module. Renovation of a large commercial building was used to develop and validate the optimization software. The facility's entire HVAC system was completely replaced in the existing structure creating unique constraints for the prefabricated module size of the HVAC component.

Microsoft Excel was used as a tool to develop the optimization model. Length, width, height and weight of the module were assumed to be decision variable in the process. The objective was set as the maximization of the volume of the module size and the minimization of the connection time required in the field. Multi objective optimization was performed using the AsPareto optimal method based on the GRG nonlinear optimization model. A variety of cases were optimized and results were tabulated. Tabulated results were plotted to determine that optimum size of a prefabricated module is not necessarily the maximum or the minimum size possible.

One end of the curve represents a module with a small volume and small connection time leading to high productivity with a large number of total modules in the system. Other end of the curve represents a module with a large volume and long connection time leading to a low productivity with small number of modules in the system. Thus, optimal size of the module was determined to lie between the maximum and minimum volume of the module. Optimal size was not determined to be a fixed value in term of volume; rather it was determined to be a range of volumes that almost had similar productivity. For the project under consideration Figure 6-1 shows the desirable range of optimal size. This range was identified as the area where the curve is reaching the peak.

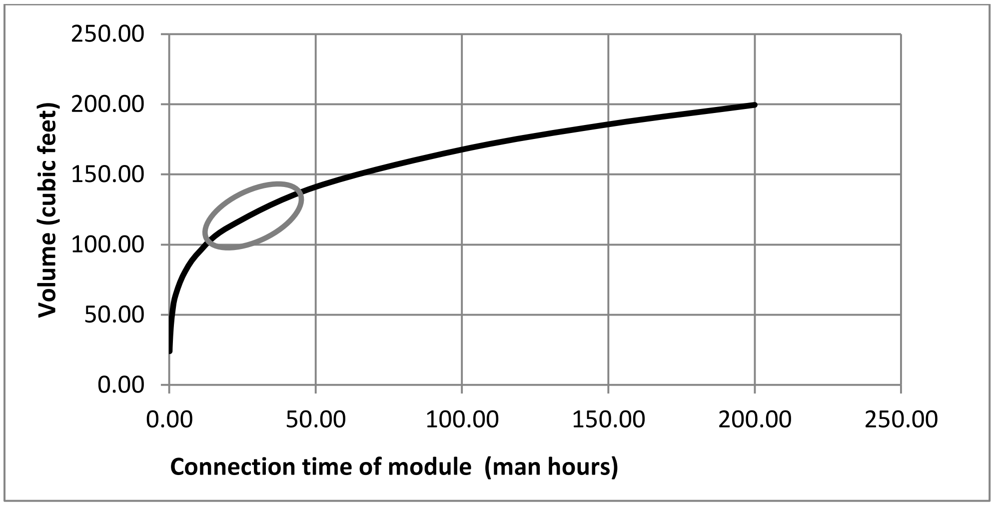


Figure 6-1 Optimal range of volume of the module

6.2 Future Research and Recommendations

The potential of this field of study is vast and diverse. This research could be expanded and further explored in many directions, including the following:

1. The present model could be further improved by using a 1’X1’ connection time function with weight derived from the data gathered by a productivity study.
2. Application of the optimization routine on a variety of different projects for different sectors, such as bathroom, kitchen, lab space etc. This could be done by analyzing the constraint equations for the individual project and running the optimization for each sector. Additional optimization would be used to further validate the model and its accuracy.
3. Introduction of the optimization routine and its parameter in the design phase of construction. This would lead improvised design of the module and further reduce labor hours.
4. Introduction of the quality parameter in the optimization process and analysis of optimal size with high quality as primary objective of optimization.
5. Associations of the optimization routine with BIM to improve project planning. The optimization routines coupled with a BIM model could be support software that deconstructs a design into the optimal factory assembled modules.

6. Ultimately the optimization routine could be used for standardization of construction modules on a supply chain in an industrial setting.

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APPENDICES

Appendix A: Differentiation for the Upper Limit of the Length of Module

The following equations and figures were used to deduce the value of upper limit constraint for the length of the module. Figure4-3 shows the constraining point with the following variables

- Width of the corridor ‘*T*’
- Length of the module $'L = x + y'$.
- ‘ϴ’ as the angle module makes with the wall of the corridor.

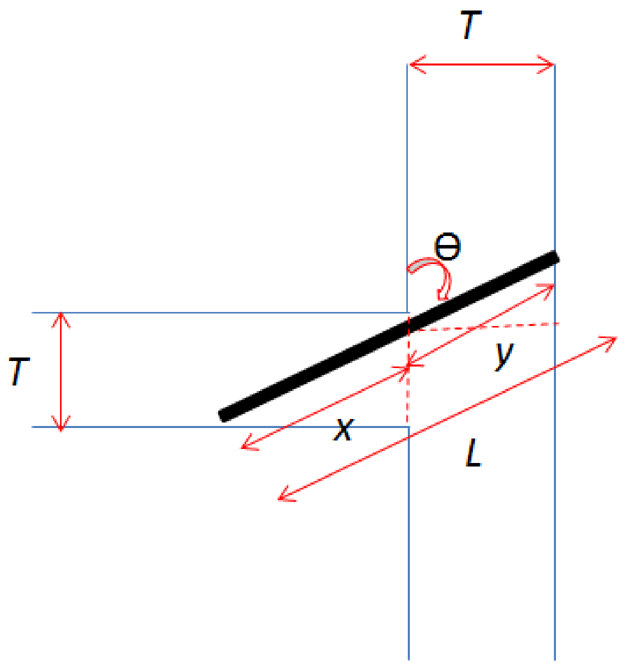

Figure A-1 Constraining point for the ‘Length of the Module’

Using trigonometry the following equations can be determined

$$x = \frac{T}{\cos \Theta}$$

$$y = \frac{T}{\sin \Theta}$$

Equation $L = x + y$.will undergoes partial differentiation in terms of $dL/d\Theta$ using the equations derived above via trigonometry. The following equations show the steps of differentiation with the final results.

$$L = x + y$$

$$L = \frac{T}{\cos\Theta} + \frac{T}{\sin\Theta}$$

$$\frac{\partial L}{\partial\Theta} = \left\{\frac{\partial(\frac{T}{\cos\Theta})}{\partial\Theta}\right\} + \left\{\frac{\delta(\frac{T}{\sin\Theta})}{\delta\Theta}\right\}$$

$$\frac{\partial L}{\partial\Theta} = T * \left\{\frac{\partial\left(\frac{1}{\cos\Theta}\right)}{\partial\Theta} + \frac{\delta\left(\frac{1}{\sin\Theta}\right)}{\delta\Theta}\right\}$$

$$\frac{\partial y}{\partial x} = T * \left\{\frac{\tan\Theta}{\cos\Theta} - \frac{\cot\Theta}{\sin\Theta}\right\}$$

For maximum value of $dL/d\Theta = 0$, thus

$$0 = T * \left\{\frac{\tan\Theta}{\cos\Theta} - \frac{\cot\Theta}{\sin\Theta}\right\}$$

$$0 = \left\{\frac{\tan\Theta}{\cos\Theta} - \frac{\cot\Theta}{\sin\Theta}\right\}$$

$$0 = \left\{\frac{\tan\Theta * \sin\Theta - \cot\Theta * \cos\Theta}{\cos\Theta * \sin\Theta}\right\}$$

$$0 = \tan\Theta * \sin\Theta - \cot\Theta * \cos\Theta$$

$$\cot\Theta * \cos\Theta = \tan\Theta * \sin\Theta$$

$$\frac{\cos\Theta}{\sin\Theta} * \cos\Theta = \frac{\sin\Theta}{\cos\Theta} * \sin\Theta$$

$$\cos^3\Theta = \sin^3\Theta$$

$$\cos\Theta = \sin\Theta$$

Thus from above equation, $\Theta = \frac{\pi}{4}$ when measured in radians. With $T = 3.5$, length can be calculated using the equations to be $L = 9.899$. Both *L* and *T* are calculated in feet.

Appendix B: Analysis Reports

The different type of analysis reports are

- Sensitivity reports
- Answer reports
- Limit reports

Sensitivity Report

Sensitivity analysis is the 'what-if' analysis for the optimization model and results. It can be used to check various scenarios that occurred in the model during the optimization process. Sensitivity analysis deals with the coefficients and the right hand side of the constraint equations which consist of variables and constraints. For the GRG nonlinear method sensitivity analysis measures the dual value as Reduced Gradient for the decision variables and measures dual values as Lagrange Multipliers for all constraints. Lagrange Multiplier measures Reduced Gradient is non-zero, only when the decision variable value is equal to its lower or upper bound, while Lagrange Multiplier has a non-zero value when corresponding constraint is binding Table 5-9 shows the sensitivity analysis tables for a particular trial of Case 3.

Table B-1

Sensitivity Report

Microsoft Excel 14.0 Sensitivity Report

Worksheet: [final model sheets v2.xlsx]Case3

Report Created: 2/3/2013 6:27:40 PM

Variable Cells

Cell	**Name**	**Final Value**	**Reduced Gradient**
$C$17	L Value	9.9	2.833008237
$C$18	W Value	2.102558409	0
$C$19	H Value	5.389587592	0

Constraints

Cell	**Name**	**Final Value**	**Lagrange Multiplier**
$C$49	Z Values	560.9301744	0
$C$49	Z Values	560.9301744	0
$C$41	T Values	20.00000077	1.402322306

Answer Report

Answer report summarizes all the values the entire optimization process. It gives details about the solver used and solver setting while running the optimization. Report also tabulates the final values for all the decision variables and the objective function. It also represents all the constraints with characteristic of each in the optimization solution as binding or not binding. Table 5-10 shows answer report of a particular trial for Case 3.

Table B-2

Answer Report

Microsoft Excel 14.0 Answer Report

Worksheet: [final model sheets v2.xlsx]Case3

Report Created: 2/3/2013 6:27:38 PM

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: GRG Nonlinear

Solution Time: 1.825 Seconds.

Iterations: 6 Subproblems: 0

Solver

Options

Max Time 100 sec, Iterations 100, Precision 0.000001

Convergence 0.0001, Population Size 100, Random Seed 0, Derivatives Forward,

Require Bounds, Max Subproblems Unlimited, Max Integer Sols Unlimited, I

Integer Tolerance 5%

Objective Cell (Max)

Cell	Name	Original Value	Final Value
$C$40	V Values	199.50	112.19

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$C$17	L Value	9.9	9.9	Contin
$C$18	W Value	3.488193251	2.102558409	Contin
$C$19	H Value	5.777009243	5.389587592	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$C$49	Z Values	560.93	$C$49<=$C$30	Not Binding	439.07
$C$49	Z Values	560.93	$C$49>=$B$30	Not Binding	460.93
$C$41	T Values	20.00	$C$41<=$C$31	Binding	0.00
$C$17	L Value	9.90	$C$17>=$B$27	Not Binding	5.90
$C$18	W Value	2.10	$C$18>=$B$28	Not Binding	0.10
$C$19	H Value	5.39	$C$19>=$B$29	Not Binding	2.39
$C$17	L Value	9.90	$C$17<=$C$27	Binding	0.00
$C$18	W Value	2.10	$C$18<=$C$28	Not Binding	1.40
$C$19	H Value	5.39	$C$19<=$C$29	Not Binding	0.61

Limit Report

Limit report deals with all the decision variable with upper and lower bound constraints associated to these variables. This report accounts for the value of the decision variable as well as value of the objective function with respect to upper and lower bound of each decision variable. Table 5-11 shows answer report of a particular trial for Case 3.

Table B-3
Limit Report

Microsoft Excel 14.0 Limits Report

Worksheet: [final model sheets v2.xlsx]Case3
Report Created: 2/3/2013 6:27:40 PM

Objective

Cell	Name	Value
$C$40	V Values	112.19

Variable

Cell	Name	Value	Lower Limit	Objective Result	Upper Limit	Objective Result
$C$17	L Value	9.90	4.00	45.33	9.90	112.19
$C$18	W Value	2.10	2.00	106.71	2.10	112.19
$C$19	H Value	5.39	3.00	62.45	5.39	112.19