Applicability of a Platform-Based Approach To Design and Construction of New Buildings

by

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B.S.B.A, Georgetown University, 1998
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Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of

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BARKER
Abstract

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ABSTRACT

This research was performed in order to assess the possible efficiencies that could be gained in the construction industry through the application of the platform manufacturing concept to the design and development of new buildings. A “product platform” is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced to target various market segments\(^1\). The methodology employed considers five primary systems of a prototype residential building with 10 innovative alternatives overall, then examines the extent to which these innovations can lead to significant cost advantages, especially when applied to a series of derivative buildings.

Results indicated that the application of such a concept to the construction of a new building could lead to at least 10% savings in labor and material costs, allowing us to conclude that as an approach, the concept clearly has demonstrable benefits. When we consider that only 10 alternatives were evaluated, we may conclude that, clearly, expanding the number of alternatives and systems could yield additional potential benefits. Thus, the concept of platform manufacturing does lead to significant efficiencies and advantages in construction, at least for a residential building of this type with the particular innovations assessed in this dissertation.

Thesis Supervisor: John B. Miller
Title: Associate Professor of Civil and Environmental Engineering

\(^1\) Meyer, 1997.
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Chapter 1: Introduction

1.1 Background

For senior managers around the world, the advent of the twenty-first century has brought forward a need to develop better products faster, more effectively and more efficiently than ever before. Three main forces over the past two decades: fierce global competition, the proliferation of fragmented markets with increasingly demanding customers, and rapid technological revolution, are driving a new industrial transformation.

The construction industry, as the most encompassing and sizeable industry in the world, has lagged behind other industries that manufacture products in its capacity to adapt and conform to this transformation\(^1\). For instance, almost every residential and office building in the United States today is custom-built to the exact specifications of an owner, entailing immense relative costs and heightened risks that are unique to each project.

Attempts at industrialization in the building industry have been generally unsuccessful to date. Modular construction, factory-built housing, and pre-engineered solutions on a large-scale basis have all failed to address the real forces and particular desires of a community, in addition to the distinctiveness required by owners and users of building spaces\(^2\). Individuality, choice, evolution, and the continued life and growth of buildings have traditionally come in conflict with the attempt to produce planned, regulated, and secure building processes. Few, if any, builders have been able to successfully pin down the optimal trade-off between standardization and distinctiveness, or between mass production and mass customization\(^3\).


It then seems as though the only way to build products faster and more efficiently without adding workers and resources or diminishing quality is to change the basic structure of product development. In attempting to innovate production processes in construction, the industry must accelerate its adoption of “technology transfer”. This term refers to the passing along of information, prototypes, processes, and innovations from one specialized industrial sector to another for the purpose of commercialization and expansion to a larger customer base\(^4\). Manufacturing principles from the car industry, for instance, can be successfully implemented to produce attractive, customized and affordable housing. The term does not mean, however, that housing must be produced in factories!

The most innovative and timely concept to address this transformation and restructuring of the construction industry lies in the successful implementation of a platform-manufacturing model, one that best addresses the setbacks of previous attempts at industrialization. A “product platform” is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced to target various market segments\(^5\). In construction, this concept could refer to a limited set of common building systems and processes that are shared amongst projects with similar or different uses and whose commonality leads to decreased costs and lead times.

This platform-based approach to product design and development has allowed automotive, computer, electronics, aerospace and hardware manufacturers, among others, to lower their lead times and to significantly reduce design, materials, labor and equipment costs. These manufacturers have created value for their firm and their customers by restructuring the process of designing and developing their products. As a result, they are able to pass on savings to consumers while creating a more profitable long-term business model.

The concept of product platforms in the construction industry best addresses the ideology of “mass customization”, a term commonly used to describe the production and distribution of customized goods and services on a mass basis. Mass customization achieves the mass production of goods with differing individual specifications through the use of components that may be assembled in a number of different configurations. In the case of residential development and construction, for example, a series of common subsystems (i.e. structure, services) may be shared by projects targeting various market segments, such as the middle-income and high-income segments. Different exterior and interior finish packages, varying space distributions, and limited façade modifications and “themes”, might all address the optimal need for distinctiveness that industrialization has failed to provide, while ensuring that economies of scale and scope are achieved through systems commonality.

Furthermore, platform architectures capable of accommodating new technologies and variations in components and subsystems make it possible for firms to create derivative products at relatively minor incremental costs relative to initial investments in the platform itself. This is so because the fundamental subsystems and interfaces of the platform are carried forward across derivative products. Thus, in general, the more comprehensive and exhaustive the design of the platform is initially; the more advantages that can be gained in the long-run from a platform-based approach to building construction.

1.2 Thesis Objective

The main goal of this dissertation is to assess the applicability and impact of a platform-based approach to the design and construction of new buildings. In doing so, this research will partially develop a platform building system that enables a firm to build

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Chapter 1: Introduction

residential and office buildings at a significant cost and schedule advantage, utilizing first-class quality architecture. The thesis aims to demonstrate that a platform-based approach to designing and constructing one or a series of occupied buildings may offer considerable advantages vis-à-vis the traditional custom-designed building method.

1.3 Thesis Approach

It is imperative that the design of product platforms and the analysis of its subsystems and interfaces be based on available facts, and not merely on a designer’s personal hunches. Composite design refers to a process methodology that seeks to optimize product platform architecture through the analysis of alternatives and the design of its subsystems. This process includes the definition, cost and functional analysis, selection and integration of subsystems and their interfaces into a “family” of products that optimize the operation of the overall system. The result is referred to as a unique platform architecture: the particular combination of subsystems and interfaces between subsystems that constitute a common product structure or platform for a series of derivative products. A product platform architecture that is designed using this methodology has the potential to achieve true cost-value leadership.

In applying the composite design process to building design and construction, this exposition will first gather data about the process of platform design and manufacturing in various industries, mainly the automotive industry. It will then identify alternatives for seven subsystems of a prototype building and apply a value analysis to each in order to arrive at the best possible alternative. Consequently, the interfaces between ideal alternative subsystems will be examined in order to optimize the form and function of the overall system (i.e. the building).

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The research will also consider the extent to which prefabricated components can be incorporated into the platform architecture of new occupied buildings (e.g. offices or residential units). For instance, with widespread use of computer technology in the past decade, the automotive industry has responded to the concept of mass customization with a modular system of production. In this case, the role of suppliers has changed from simply delivering parts to factories to assembling collections of parts (i.e. instrument panels, doors and HVAC units) off-site and delivering them “just-in-time” for installation on the assembly line. This modular system has often resulted in reductions of labor costs by a third and reduced concept-to-release times (58 months to 38 months in the past decade alone), in addition to better quality and increased customization.\footnote{Hart, 2001.}

Borrowing from the innovations in the automotive and aerospace industries, with computer technology playing an increasing role in the expansion of the mass customization concept, the primary framework for the analysis of each subsystem alternative will be a recently introduced simulation software package named MOCA Build\textsuperscript{TM}. Developed by a former professor at the Massachusetts Institute of Technology (MIT), MOCA Build simulates the actual performance of work in a construction site in order to objectively evaluate the cost and schedule impact of various building alternatives and new technologies, as well as the complexity of various processes and optimal labor utilization rates on a project. MOCA Build provides unparalleled simulation capabilities that will enable the accurate analysis of cost and schedule implications of various subsystem alternatives, facilitating the composite design process of a robust platform architecture.\footnote{Forsman, 2000.}

The platform-based approach will be examined in the context of a high-end mid-rise residential building with 19 apartment units and parking spaces that will serve as a prototype for further development of the platform architecture concept. The prototype will be located at a residential development in the Caribbean and is planned for actual deployment, representing an example application of the methodology.
Chapter 1: Introduction

1.4 Thesis Significance

The contribution of this research to project planning and execution can be evaluated in two dimensions. First, we seek to understand whether or not a platform-based design approach can be applied to non-mass produced units. Consequently, we will then examine whether a platform approach to design and construction can lead to durable and sustainable savings in large scale complex systems and processes, specifically the building design and construction processes.

1.5 Organization of Thesis

Chapter 2 is a survey of the most relevant literature gathered on the concept of design platforms and its application to the construction industry. It first explores a platform-based approach as a source of efficiency in manufacturing, as well as its advantages and challenges. The composite design process for a product platform is then explained. The next topic identifies the two or three most important lessons from the automobile industry as they relate to platforms and the extent to which those lessons can be replicated in the construction industry. An overview of previous attempts at industrialization in construction is presented, with arguments for and against the concept of mass production considered. Finally, the concept of systems building as well as the role of technology and the extent of their application to a platform-based approach are briefly examined.

Chapter 3 provides a synopsis of the research methodology utilized in the research. The chapter first explains the composite design method and then considers it in the context of the prototype building that is being employed for this thesis. The advantages of utilizing the MOCA Build software as a framework for subsystem evaluation are presented. The chapter also lists all criteria used to evaluate the impact of various subsystems on the overall platform architecture. Sources of data, collection
means and methods, as well as measures taken to ensure the reliability and verifiability of the data are herein described.

Chapter 4 provides a detailed explanation of the major results. These include the definition of building systems and subsystems for a platform architecture, the testing via simulations of the various subsystem alternatives, as well as the value analysis applied to each of the subsystems to arrive at the optimal alternative. Various innovations in pre-assembled components are examined and the effect of subsystem optimization on the overall system identified.

Chapter 5 summarizes the research work, and examines the major implications of using such an approach in the design and construction of occupied buildings.
Chapter 2
Topic Background

2.1 Introduction

In this chapter, we seek to examine the relevant literature and current lines of thought regarding the concept of product platforms and its potential application to the construction industry. In doing so, we will first discuss the concept and definition of platforms and how it developed. Secondly, we will explore the application of the concept to the automotive industry to draw parallels that could shed some insights into the applicability of a platform approach to a complex process such as construction. Thirdly, we draw some conclusions about the extent to which the platform concept of product development and manufacturing can be applied to construction, including its advantages and disadvantages, as well as similarities and differences. Finally, we will consider the process of platform design and its critical role in the development of a unique and robust platform architecture.

2.2 The Concept of Product Platforms

A platform approach to product development has represented a critical success factor in many markets. The sharing of components and processes across a platform of products has enabled companies to develop differentiated products efficiently, increasing the flexibility and responsiveness of their processes, and thus capturing market share from competitors that develop only one product at a time\(^1\). The platform approach is also a viable way to achieve successful mass customization – the high-volume manufacturing of products that are tailored to meet the needs of individual customers\(^2\). Under mass customization, highly differentiated products can be brought to market without consuming excessive resources that would otherwise be consumed through customization of each product to particular customers. In other words, a customer’s need for

individualism in a particular product and the costs involved in delivering it can be balanced against a certain degree of standardization which limits the amount of resources required to deliver the exact product that the customer wants. This occurs, in part, because product platforms that are set in place to deliver mass customization share many, if not most development and production assets. We will see how mass customization is addressed through a platform-based approach later in this chapter.

We must note that platform manufacturing is much more than parts-standardization. Even though platform products share many development and production resources, parts-standardization amounts to not much more than the sharing of a reasonable set of components that are not necessarily considered a platform. In their article *Planning for Product Platforms*, Robertson and Ulrich state that:

"...parts-standardization efforts across products may lead to the sharing of a modest set of components, but such a collection of shared components is generally not considered a product platform..." 

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In their paper published in the *Sloan Management Review*, Robertson and Ulrich identify four main elements or assets which comprise a platform: components, processes, knowledge, and people and relationships\(^5\). The **components** are the parts that comprise a product, the tools and equipment used to make them, and the product design of the derivatives. In the case of a software platform, for example, the components include the programs burned into programmable chips or stored on disks. **Processes** include the equipment used to assemble components into products, as well as the design of the appropriate production processes and supply chain. **Knowledge** is the know-how, the application and limitations of technology and the production techniques employed in production. This element also includes testing methods and proprietary models used in the platform. Finally, *people and relationships* refer to the teams, relationships within team members and the larger organization, and relationships with suppliers. The presence of these four elements is precisely what distinguishes a platform from the mere standardization of parts.

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2.3 Lessons from the Auto Industry

In the early 1990s, Kodak’s platform approach to the development of its Quicksnap 35mm single-use camera allowed it to capture over 70 percent of the market, even when it introduced the product later than its main competitor, Fuji, and was originally unprepared when the market took off. Likewise, Palm Inc. has been able to offer several derivatives of Personal Digital Assistants (PDAs) to target various market segments, with color or black-and-white screens and various exterior enclosures. Palm is the leader in the PDA market with more than 40 percent market share.

But the industry that most resembles the building and real estate industry for the purpose of platform manufacturing concept analysis is the automobile manufacturing industry. Platform manufacturing was developed, in fact, by vehicle manufacturers in response to the inability of mass production to respond to consumer’s growing call for distinctiveness and customization. It is imperative that we consider the lessons learned from the approach utilized by these manufacturers in applying the platform concept to their own industry.

Cars and buildings are often compared because they are both extremely sophisticated and complex products. That car manufacturing can be made affordable, attractive and efficient from the complex assembly of over 20,000 parts is a marvel in itself. Depending on how parts are counted, a small building may be constructed from as many as 200,000 components, yet in most instances these buildings are unique in design and manufacturing requirements.

First, there are many attributes shared by cars and buildings: (a) affordability, (b) complexity in systems and interfaces, (c) owner involvement, (d) weather-tight construction, (e) economical operation, (f) durability over a certain period of time without

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9 Gann, 1996.
10 Gann, 1996.
major maintenance, (g) integrated mechanical and electrical systems, and (h) an appropriate level of safety. Also, both are characterized by a high percentage of the cost of construction representing field labor. At the same time, differences such as the immobility factor of buildings, site specificity and regulatory impact have been utilized to criticize the use of the automotive industry as a model of efficient construction methods.

One such critic of the comparison between building and car manufacturing is Richard Bender, author of *A Crack in the Rear-View Mirror*, who alleges that:

"Much of the problem of industrializing the building industry has grown out of the mistaken image of the automobile industry as a model: a view which focuses on the house and the housing project as products and the factory as a tool for making them. But the house as a manufactured product and the factory as a tool for house making are concepts in conflict with real forces and desires in the community, such as individuality and choice…"

Such critics base their opinions on the overall failure of factory-built housing and other standardized building techniques, and that particular arena’s application of the lessons from the automotive industry\(^\text{11}\). These generally would not apply to the concept of platform manufacturing in construction because the platform approach aims specifically to address the issue of uniqueness and commonality that is the main impediment to the success of industrialized building. Platform design in a building context seeks to balance the trade-off between distinctiveness and commonality of real estate products and the quest for economies of scale and mass customization in building construction. *It only promotes the factory production of a limited set of prefabricated components and subsystems that still facilitate the achievement of certain predetermined parameters of customization.* This is a key point in that a platform approach might include the mass production of parts, and not the mass production of the whole product.

The most important issue in both building (especially housing) production and car manufacturing is that of balancing the trade-off between standardization (in order to

\(^{11}\) Bender, 1973.
facilitate the efficient use of production lines) and flexibility (to ensure that products are marketable to customers who value choice among a wide range of customized options). This trade-off is being met in both (house and building) construction and car manufacturing through the use of standard subassemblies and platform design approaches combined with computerized subsystem optimization, all topics that will be discussed in this research.

2.3.1 Evolving Manufacturing Concepts in Automobile Production

Auto manufacturers had historically employed concepts of mass production to deliver affordable and attractive products. Mass production used narrowly skilled professionals to design products made by unskilled workers with thousands of common parts using expensive single-purpose equipment that churned out high volumes of standardized products. The result were lower costs for consumers at the expense of variety and by means of work processes that most employees found boring and discouraging.

As customers began demanding ever-increasing levels of uniqueness and differentiation, the manufacturing process became overly complicated with a wide array of trim levels, option packages, and stand-alone options that lacked an overall cohesive and long-term manufacturing strategy, significantly impacting the efficiency of car manufacturers. As a result, automakers turned to “lean production”, which, according to John Everett, Professor of Civil and Environmental Engineering at University of Michigan, is called “lean” because it:

“...required less of everything: less labor, less investment in manufacturing space and equipment, less inventory on site, and less design and development time...”

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Although not related to a platform-based approach, optimum lean production is one of the precursors of the concept. Manufacturers achieved higher profits through optimum lean production in two main ways: speed and economies of scale. Time was saved in two stages: development and assembly. In terms of development, a small team was brought together to coordinate the development of a platform. For example, in the past, functional divisions within the manufacturer and major suppliers constructed models of components from clay, wood and plaster. Under optimum lean production, manufacturers utilized computer software instead. Finally, low inventory levels were kept at all times.

Lean production caused the automobile industry to shift into a pattern of fewer, larger companies, capable of dominating production around the world, not just in one country.

In addition, instead of smaller parts and components, suppliers sent entire systems, such as complete instrument panels, with knobs, gauges and padding already installed. Rather than assembling full bodies made from individual parts, vehicle manufacturers now weld together stamped body panels at the final assembly plant.

This transformation led the platform concept to evolve into what it is today. Under lean production, a new product shared as many components as possible with other platforms, as well as with previous generations of platforms. Individual models shared many basic components with other models, but were fitted with distinctive sheet metal, trim, and interior finishes in order to attract different types of customers. For example, faced with high development costs because of limited sales of its Lincoln luxury cars, Ford was able to share highly profitable luxury-brand platforms among Jaguar, Lincoln and Volvo at the end of the 1990s. By increasing speed and economies of scale, manufacturers achieved higher profits through lean production\(^\text{14}\).

Chapter 2: Topic Background Review

2.3.2 Platform Design in the Automotive Industry

What had been a mark of pride in mass production – designing an entirely new model from scratch in four years – was replaced in the 1990s with cost-saving measures to take advantage of older models when possible and lower the concept-to-reality time to two years. The answer became the most recognized feature of lean production: platform design and development. The platform team played a key role in helping lean manufacturers break the traditional inefficiencies of design for manufacturing. Under mass production, a new project moved slowly from one function to another; marketing to engineering to factory operations. Decisions were made within each function based on limited criteria specific to that function. Designers sought sleek styling, marketers required features that consumers wanted, and salespeople preferred competitive prices, while engineers desired high-performing engines. If a problem were encountered, the appropriate function would go back and solve it by itself because the issue fell under a specific function’s responsibilities. There appears to be plenty of similarities with the design process of buildings in this case.

Modern automotive design, on the other hand, is collaborative, integrated throughout the entire manufacturing process\(^{15}\), unlike the fragmented nature of construction design, with each subsystem treated as a separate layer of the overall system. Under lean production, a small team is brought together to coordinate the development of a platform. Design and engineering are integrated into virtually one system, which facilitates fast communication among the various specialists working on a new project without them having to work in the same location. With team members working simultaneously, designers do not have to wait a considerable time while engineers confirm the workability of designs.

For example, the increasingly complex patterns of communication among team members and functional specialists were facilitated by the concept of co-location, which integrated design and engineering into virtually one system and facilitated rapid

\(^{15}\) Rubenstein, 2001.
communication among the diverse group of specialists working on a new project, without
them having to work in the same place. In this case, designers and engineers could view
the same prototype at the same time when in different locations through a high-definition
television linked via satellite broadcast. Full-color laser holography provided a 3D
appearance in which the vehicle seemed to hover behind the screen. Designers then
developed a product based mainly on market research. Engineers made certain that
designs could be mass-produced precisely and that all components fit together without
excessive gaps.

Also, under this new development concept, die designers and body designers, for
example, worked together on the same team, so die production could begin at the same
time as the start of body design, thus shaving off development time.

Another great difference now in automobile design and manufacturing is the
evolution from a systems-based approach to design, production and assembly, to
“chunks” produced under controlled conditions and inserted into the final product. These “chunks” are built in a controlled facility, and then delivered Just-In-Time (JIT) for
rapid final installation. This idea of “chunks” is derived from the concept of
prefabrication and pre-assembly, which can play important roles in platform design and
development. It is in this area where many of the lessons of the automotive industry can
be replicated in the building process.

2.4 Construction Applications for a Platform Approach Solution

The next logical question to ask is whether the concept of platform design and
development is applicable to the construction industry. Let us first examine three
definitions of the word construction by the Merriam-Webster Online Dictionary:

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Chapter 2: Topic Background Review

1. **Construct**: to make or form by combining or arranging parts or elements

2. **Build**: to form by ordering and uniting materials by gradual means into a composite whole

3. **Build**: to develop according to a systematic plan, by a definite process, or on a particular base

In the context of the construction industry and this thesis, the composite whole represents the built facility and the ordering and uniting of materials as the construction process. Thus, we can combine all definitions and define *construction* as nothing more than,

“**the process of forming by ordering and uniting materials into a built facility according to a systematic plan.**”

Note the reference to a “systematic plan”, a means which hints at the crucial role played by Systems Design in the design and development process in construction. This concept will also play a large role in the process of platform design and manufacturing, which arranges these systems in a way that can reap benefits and create efficiencies in the construction process.

It is now imperative that we consider the peculiarities that characterize construction and the ways in which a platform approach can mitigate and partially address those, including the differences between auto manufacturing and construction:

A. **Scale**: Buildings don’t have to be produced in quantities of 25,000 units in order to be profitable. Also, the *physical* scale is different, with buildings able to hold a vast amount of cars, in some instances.

B. **Site specificity and one-of-a-kind nature of projects**: Like in the automotive industry where no car exists that fits all customer uses, platform-designed buildings have limitations in use. Site specificity is one such limitation. Structural designs, connections to main water and electrical systems, and the character of surrounding architecture are all examples of factors to be considered when
erecting buildings and evaluating a platform approach. Also, each project, can be argued, has different requirements that must be reckoned with, such as capital facilities, offices, residential habitat, while the goals of cars are very much aligned: transportation, driving experience, etc. In short, all cars share one singular objective, which is that of transportation, while buildings are characterized more by its specific usage: hospital, condominium, school or office, for example.

C. Project specific organizational affiliation: Supplier contracts are usually renegotiated and managers and construction staff (including subcontractors) are usually restructured for each project. The geographical location factor has much to do with this peculiarity.

D. Regulatory intervention: The process of getting approvals for a design solution is often unpredictable and varies with different uses of real estate and amongst various projects, as well as local codes and regulations. Cars are more easily approved as fulfillment of clear safety standards entails a more structured process subject to less uncertainty. Also, more common national standards exist in the automobile industry, making it easier to fulfill expectations in that industry.

E. Longevity: Buildings must operate and last for much longer than cars (i.e. over 100 years for buildings compared to 4-5 years for automobiles). In addition, the manufacturing process of buildings is much more complex and time consuming than that of automobiles.

Furthermore, the size and immobility of the product mean that buildings are assembled at the point of consumption, setting construction apart from many manufacturing industries, in which finished products are transported to the market. Unlike cars, which can be built on a controlled environment such as a manufacturing facility, buildings cannot be shipped to other locations. This means that economies of
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labor, machinery, and transport of parts need to be considered in a different light from those in the manufacture of typical consumer products.

2.4.1 Advantages and Challenges of a Platform Approach to Product Design and Development in Construction

Companies in the construction and real estate sectors that engage in successful building platform planning can achieve benefits on several levels\textsuperscript{17}:

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<table>
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<tr>
<td>1. <strong>Customization:</strong> Greater ability to tailor real estate products to the needs of various market segments</td>
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<td>2. <strong>Product Attributes:</strong> Reduction in development costs, time and efficiency</td>
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<tr>
<td>3. <strong>Profitability:</strong> Reduction in manufacturing costs</td>
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<tr>
<td>4. <strong>Less investments:</strong> Reduction in production investment</td>
<td></td>
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<tr>
<td>5. <strong>Simpler systems:</strong> Simplification of systemic complexity</td>
<td></td>
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<tr>
<td>6. <strong>Risks minimization:</strong> Lower risks associated with construction</td>
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1. **Greater ability to tailor real estate products to the needs of various market segments.** The platform approach can reduce incremental costs associated with addressing specific needs brought about by a market segment or individual customers, thus enabling a firm to meet market needs more closely. With consumer tastes and needs changing more and more rapidly, real estate and construction firms that can respond to these needs more efficiently and expeditiously with the use of platforms can tap new markets and outpace the competition for limited housing and commercial space growth. In a way, these firms can stretch demand horizontally (across market segments – office and residential, for example, and geographic locations) and adjust more quickly to emerging market demands.

\textsuperscript{17} Adapted to the construction industry from an article by Robertson, David & Ulrich, Karl. *Planning for Product Platforms.* Sloan Management Review, Summer 1998. pp. 19-31
2. **Reduction in development costs and time.** Parts, assemblies, and processes developed and tested for one product model do not have to be developed and tested for other models. This benefit may apply to platform derivative products, as well as updated products\(^{18}\). Monetary investments in design per building can also be significantly reduced throughout a series of derivative products, even if up-front design costs can increase significantly in the initial stages of platform design.

3. **Reduction in manufacturing costs.** As manufacturers that produce larger volumes of common parts can achieve higher economies of scale, purchasing of these parts by construction firms in higher volumes can lead to lower unit costs and manufacturing costs. Other ways in which firms can reduce manufacturing costs include:

   a. **High-volume materials procurement:** savings achieved from procuring materials in large quantities to be distributed and utilized over a whole series of products that comprise a platform.

   b. **Waste minimization:** When one considers that 15-37\% of construction dollars are essentially wasted\(^{19}\), reduction of field waste becomes a significant cost savings advantage. Waste is minimized as systems are pre-assembled and productivity increases.

   c. **Repetition and pre-assembly** cause productivity to increase and manufacturing times to decrease\(^{20}\).

   d. **Economies of scope:** Firms employing a building platform that can accommodate various uses can apply their extensive knowledge of optimal systems in order to squeeze economies that stem from stretching the scope of their product mix. Elements of a platform can be replicated in various market segments in order to standardize parts and processes, and lower risks.

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4. **Reduction in production investment.** Equipment and tooling, and the engineering time needed to develop building products can be shared among higher production volumes, lowering fixed costs per unit. Furthermore, a reduction in interest expenses must be considered, as less investment is required to start-up a project.

5. **Simplification of systemic complexity.** Lowering the amount of parts required for a building system lowers the costs of materials management, inventory control, purchasing, logistics and maintenance\(^\text{21}\). In addition, workflows are more systemized and clear-cut, so there is less confusion on site.

6. **Lower risks associated with construction.** The lower investment in a product that derives from a platform means that financial risks on new products are decreased, even though market and technical risks may still exist. Because systems and subsystems of buildings that derive from a platform have been meticulously designed and tested (and in some cases proven), better cost and schedule estimates may be completed and the benefits of removing uncertainty may be attested. Moreover, as more systems of a platform have addressed Uniform Building Code restrictions that encompass a national implementation, local permitting and compliance issues can be minimized.

At the same time, there are four major challenges facing companies that select a platform approach to product development, in construction and in other industries\(^\text{22}\):

<table>
<thead>
<tr>
<th>Four Major Challenges in a Platform Approach to Construction and other Industries (Adapted from Robertson &amp; Ulrich, 1998)</th>
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<tbody>
<tr>
<td>1. Coordination and integration of organizational capabilities throughout design</td>
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<tr>
<td>2. Balancing commonality and distinctiveness</td>
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<tr>
<td>3. Design process can get caught up in details</td>
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<tr>
<td>4. Constraints in land utilization are created</td>
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\(^{21}\) Ulrich, Sartorius, Pearson, and Jakiela, 1993, pp. 429-447.

1. **Coordination and integration of organizational capabilities throughout design.**
Building companies that utilize platforms need to meet the needs of a particular market segment while conserving development and production resources. On one hand, planners and marketing staff address the issue of what markets to enter and what customers in each segment want, as well as the product attributes that will satisfy such markets, sometimes disregarding the ability of the firm to engineer particular product attributes perceived as needed to deliver a competitive product. On the other hand, designers and engineers deal with the problem of developing a platform architecture which delivers differentiated products that still share parts and processes and thus sacrifices some product attributes for the sake of meeting cost and price restrictions. This creates challenges because building products are inherently complex and because completion requires an *integrated* approach to development combining the expertise of marketing, design, and manufacturing disciplines *together*. The fact that such disciplines are not always used to working with each other in design and construction of non-custom buildings (platform-based buildings) may create conflicts related to assumptions, goals, and frameworks. A challenge of a platform-based approach is how to shift to a common design approach to be used across buildings and over time.

2. **This possible organizational hindrance leads to the most important challenge in platform design: balancing commonality and distinctiveness.** Design and manufacturing engineers can provide cost data to argue that creating distinctive products can be unfeasibly expensive, a theory that leads to products that are too similar in the minds of the customer. On the other hand, marketers may argue that only products that are *perceived* as unique in the minds of the consumer will appeal to the various market segments that a product platform aims to target. In designing a product platform for a series of residential buildings that utilizes the mid-rise prototype in consideration, this challenge will be constantly addressed and evaluated, as will be seen throughout the rest of this exposition.

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3. Even after achieving integration and a balance of commonality and uniqueness, the process of platform design can get caught up in details, resulting in the process stalling or on products having no unique attributes.

4. Constraints in land utilization are created when platform products are developed in real estate. Usually, buildings are designed to fit the offerings and limitations of a particular site. In contrast, using a platform-approach means that derivative building products will only be able to be erected in some sites and not in others. The scope of the platform is determined in the design process in order to determine ways in which derivative products can be reconfigured to fit a maximum number of sites.

2.4.2 Prefabrication and its Impact on Platform Design and Development

Prefabrication refers to the production of components under factory conditions\(^{24}\). Pre-assembly, a related term, is the process of putting together parts off-site or on-site to form components that are then assembled on-site to create a whole\(^{25}\). This type of modularized construction actually preempted the adoption of the concept by the auto, aerospace and shipbuilding industries. The use of prefabricated components reduces essential problems of on-site production because a minimum amount of activities are carried out on site. The erection and assembly of prefabricated components also results in less materials wastage on sites than that which occurs with on-site fabrication. There are two types: those that are produced without prior knowledge of the specific design or type of building, and those that are produced for a specific building only after the design has been completed.

The Federal Operation Breakthrough Program in the late 1960s and early 70s, sponsored R&D in order to increase the use of industrialized mass production tools and techniques in the homebuilding industry. Though it was not successful in establishing a

\(^{24}\) Allen, 1999.

\(^{25}\) Allen, 1999.
sustainable and profitable number of industrialized housing units, this initiatives helped
develop and refine the process of off-site prefabrication of components such as:
integrated shower/bathtubs, windows and pre-hung doors, roof trusses and pre-cut
framing systems, cabinet and millwork, floor, roof and wall panels, and even complete
wall systems.\footnote{Moavenzadeh, 1991.}

There are certain limits to prefabrication that might render the concept
inappropriate in some instances: size limits imposed by transportation requirements,
monetary investments required to develop such a system, coordination and interface
difficulties, and other challenges such as the ability of the object to adapt to specific site
circumstances and to address the uniqueness requirement by owners. Also, the costs of
land, site development, foundations, maintenance and taxes are not mitigated by
prefabrication.

Nevertheless, the huge potential savings from pre-fabrication, referred in trade
lingo now as “panelization”, makes it likely to gain sway in the industry. For instance,
Pulte Homes, the largest U.S. homebuilder, says it is now saving $3,000 to $4,000 per
house using premanufactured parts.\footnote{Perez, 2002.} The company owns a firm which manufactures
components such as entire walls, including the studs, framing, and drywall, with some
walls even pre-wired for electricity before being trucked to the homesite for final
assembly. Other components include staircases, exterior walls, and structural beams. This
manufacturer supplied about 2,800 of the nearly 5,000 homes that Pulte built in 2001,
leading to tens of million of dollars in savings. The builder says that in the Philadelphia
area, homes that sell for about $550,000 can employ panelization and lead to $17,000 in
cost reduction. In addition, Pulte officials say factory-built parts have helped cut about 10
days out of average 110-day construction time for its homes. They hope to cut another 10
days by using even more prefabricated parts.
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The Center for Construction Research and Education at MIT, for one, has found that construction practice will move toward off-site prefabrication of larger and more integrated products, components and even subsystems. The advantages of off-site work include: lower costs, improved quality control, better working conditions, less need for expensive skilled workers, and shorter on-site building time. These benefits are accelerating the adoption of this trend, with homebuilders such as Pulte (mentioned above), Beazer Homes USA Inc., Toll Brothers and NVR increasingly adopting such manufacturing techniques to increase their margins. The main limitation at this point – a need for high volume production of standardized components – may be countered by the increasing availability of large global markets and by the proliferation and adoption of flexible manufacturing and prefabrication techniques. The main challenge for building manufacturers, then, becomes the search for innovative ways to improve performance in the final-assembly stages on site, possibly through new approaches to project management.

2.4.3 Previous Related Attempts at Industrialization in the Building Industry

During the first half of the twentieth century, influential architects such as Le Corbusier believed passionately in the idea of the mechanization and industrialization of construction. Their aim was to increase efficiency by rationalizing the process and applying the scientific method. Le Corbusier’s Domino House, a pilot model house designed in 1914, became one of the most influential representations of industrialization with a simple, standardized frame, slab floors, flexible floor layouts independent of structure, lightweight changeable internal walls, and an external non-load bearing shell. He argued that,

“...houses must go up all of a piece, made by machine tools in a factory, assembled as Ford assembles cars, on moving conveyor belts.”

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29 Perez, 2002.
30 Bender, 1973.
31 Gann, 1996.
This idea of Le Corbusier and others resulted in new methods of construction and a profound impact in design and construction philosophy into the 1960s with the evolution of systems building.

Except in low-cost, mass-produced housing and schools, attempts at industrialization in the building industry in the United States to date have had mixed results. In addition to the aforementioned concept of prefabrication of components, three ideas have come to define industrialization in buildings during the last half a century: (a) modular unit construction, (b) factory-built buildings and components, and (c) systems building.

Production of modular unit construction is based on modules of transportable size. Materials are processed and subassemblies manufactured in factories and brought to assembly lines to produce modules. About 30% of the value of module-based buildings is built in factories. In modular unit housing production, it must be noted, the reductions in costs of manpower associated with lower on-site construction activities have been countered to a certain extent by increased costs of design and sales staff as well as advertising and transportation.

The housing “factory” can utilize many of the production methods developed in automobile production systems. One rare success in factory-built housing lies in the Sekisui House Company in Japan. The largest industrialized housing producer in Japan, Sekisui makes prefabricated steel or timber-framed housing panels in five factories. The company controls the whole value chain from design to final assembly on site, providing a high degree of customization to buyers, using the Information Technology-based Sekisui’s Flexible Planning System.

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32 Sweden and Russia have built profitable modular housing models employed by both governments and private entities.
33 Gann, 1996.
34 Gann, 1996.
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Factory-produced elements of each house typically include around 30,000 items, comprising 700 different component types, and more than 2 million different kinds of parts to satisfy all permutations of design options in its catalogues. Between 20 and 25% of the value of Sekisui Houses are produced in the firm’s factories. These factories produce and assemble frames, wall panels, insulating materials, floors, partitions and doors, as well as component kits of windows and doors to be installed on site. About 30% of house value is produced by suppliers of services, fixtures and furnishings. These assemblies are usually sent directly to the site and installed by trained subcontractors. Site work accounts for about 20% of the value, while sales, marketing and management overhead accounts for 25%. Sekisue House’s warehouses are automated and occupy 70% of the factory area. Transportation per home occurs with about six to eight 4-ton trucks.

Sekisuki claims that labor costs were reduced from 50% of total costs of the house to 25% using the modular system. In addition, assembly time is claimed to come down by nearly half\footnote{Gann, 1996.}.

Despite the unusual success of Sekisui and a handful others, sales of modular and factory-produced building products have not grown significantly in the United States because the specifications and high degree of standardization required to make them economically viable have not satisfied the American consumer’s need for individuality and freedom of choice.

The third manifestation of industrialized building techniques is referred to as Systems Building. It plays a substantial role in platform development and will be examined in a later section.
2.5 The Process of Platform Design

The long-term success of an enterprise hinges on a family of value-rich products targeting growth markets rather than on a single product\textsuperscript{36}. The process of platform design determines those products that a company introduces into the market during the following five to ten years or beyond. In the introductory chapter (section 1.3), we defined composite design as a process methodology that seeks to optimize product platform architecture through the analysis of alternatives and the design of its subsystems. This process includes the definition, cost and functional analysis, selection and integration of subsystems and their interfaces into a “family” of products that optimize the operation of the overall system. Applying composite design involves six main tasks and processes:

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<td>A. Establishing the goals of the system in terms of performance and price</td>
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<td>B. Classifying and analyzing the subsystems of a design and those of competitors.</td>
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<tr>
<td>C. Measuring the design complexity of the platform and that of competitor’s products.</td>
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<tr>
<td>D. Marking the design and those of competitors against a function and cost baseline.</td>
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<tr>
<td>E. Building opportunities for product line expansion into the platform.</td>
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<td>F. Integrating manufacturing processes to achieve cost advantage</td>
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A. Establishing the goals of the system in terms of performance and price. No design journey can be successful without identifying the destination. Thus, product developers must identify the aim of the overall system and its critical forms, features and functions, which then become the drivers of the design process. Most times, the goal of the system is based on a market need. More important is the recognition that one cannot optimize a subsystem and ignore others. Instead, one must consider the system as a whole and be prepared to make trade-offs. This

\textsuperscript{36} Meyer and Lehnerd, 1997.
is the underlying assumption behind the optimization of the system in question, which in the case of construction, is the built facility.

B. **Classifying and analyzing the subsystems of a design and those of competitors.**
The entire platform must be considered a “system”, comprised of subsystems and the interfaces between them. One of the early pioneers of the concept of Systems Design who applied the concept to manufacturing, W. Edward Deming defines a system as “a network of interdependent components that work together to try to accomplish the aim of the system.” System and subsystem analysis is the fundament of composite design in the sense that we attempt to understand the extent of optimization required for each subsystem and its related interfaces to produce an overall optimized system, achieving a desirable product and cost-value leadership. An “optimized” system in this case is one in which all subsystems taken as a whole create the greatest output performance for the least amount of inputs.

We must note that the interfaces between subsystems are of critical importance to the optimization of the overall system. And the design phase is the most important one in solving possible interface problems before they are encountered on site. In fact, a great extent of an architect’s time, as well as that of the engineer, builder and inspector, is based on this problem of incompatible interfaces.

C. **Measuring the design complexity of the platform and that of competitor’s products.** Superior designs usually minimize needless complexity. As a result of doing so, direct and indirect costs are reduced. This stage is critical, then, in order to design an effective platform that translates into cost and time savings over a series of derivative products.

Scientifically, complexity can be measured using three factors (per Boothroyd and Dewhurst, of the University of Rhode Island): the number of parts, the number of types of parts, and the number of interfaces of each of the parts. Each of these sums are multiplied, and the cube root of the product of this multiplication is calculated to determine the complexity factor.

D. **Marking the design and those of competitors against a baseline of function and cost.** Present designs should be indexed or rated against those of competitors in terms of functionality and cost. Once each individual subsystem in indexed, one can then aggregate those indices into an overall index of function and cost for the design as a whole. From this process, a clear understanding of the best subsystems from across the industry can be derived. One need not be superior in every single subsystem and not all subsystems need to be optimized to deliver superior performance.

E. **Building opportunities for product line expansion into the platform.** It is in this stage where opportunities arise to single out one or several areas where tremendous leverage can be created by building degrees of freedom into the design of a platform. Designers must consider ways in which a platform can accommodate future derivative products based on market needs. In construction, relevant questions can include: Can this high-end residential building platform accommodate a low-end product? Can an office building platform accommodate various classes of real estate (i.e. Class A vs. Class B)?

F. **Integrating manufacturing processes to achieve cost advantage.** Once an optimal design has been developed, this stage seeks to answer the question: What is the one best way to produce it? This is where having manufacturing personnel (i.e. builders, construction managers, etc.) can be critical in the eventual success of a platform. These people understand better than anyone what it takes to build products that derive from a platform. In the construction industry, one example of
a decision made at this stage is whether to use subcontractors for part of the building job.

When the process of building construction is seen through a platform approach, one notices that there are several components and processes that can and are standardized throughout a series of buildings. After all, the difference in the structural elements, to take an example, of affordable versus middle-high income condominium buildings is very limited. Thus, the cost is highly comparable. The key-differentiating factor is the quality and level of finishes. In building construction, perception can be a key determinant of value. The environment of buildings and the perception of owners are created from what owners can see. Users of building spaces can see spaciousness, exterior facades and looks, internal finishes and amenities. Other systems that cannot be seen, such as services (i.e. HVAC, electrical, plumbing) and structural systems, are more prone to be standardized over a series of products. Minor modifications in exterior enclosure systems and interior finishes could possibly create what are perceived to be completely different and unique buildings even when the percentage of common parts is above 70% and the structure and services are essentially identical.

In the process of designing occupied buildings, an apparent indifference to innovation in other industries, as well as the decentralized nature of the design and construction industries, have adversely affected architects’ creativity and kept builders lagging decades behind other industries that manufacture products\textsuperscript{41}. While a materials scientist will work with a number of product engineers, or an architect will closely coordinate with a construction manager, there is not typically an integrated flow of communications between all entities. At the moment, the process of designing and planning occupied spaces in residential construction is fundamentally decentralized and fragmented. For instance, the practice of coordinating between an architect’s construction drawings and the installation of a trade’s work relies on a “systematic” process of superfluous drawing, checking, redrawing and rechecking designed to catch mistakes before they occur in installation. A typical project design process might flow like this:

\textsuperscript{41} Hart, 2001.
Figure 2: Typical Project Design and Installation Process Flow

Architect & engineer submits construction documents (CDs) to a contractor

Contractor passes the CDs to fabricator of choice

Fabricator hires a company to execute the shop drawings or does it in-house

Based on interpretation of architect's CDs, the detailer drafts series of shop drawings indicating exact scope, spec. fabrication info., and installation details

Shop drawings are passed back through the fabricator to the contractor and on to the architect/engineer for review

After reviewing and checking the shop drawings to see if they comply with the intent of the CDs, they will be passed back down the line.
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Unless it is contracted with Design-Build responsibility for each subsystem, and depending on project complexity, shop drawings may be passed through several hands back and forth before they are approved. Then the fabricator proceeds with the shop fabrication based on the drawings and always subject to human mistakes.

The integration of knowledge from the main disciplines involved in construction (architecture, construction, product engineering and marketing/sales functions) becomes tantamount to the development of a successful product platform. This concept is referred to as an integrated approach to product design and development. Many industries have created design teams that are integrated throughout the process or at strategic points in it in order to promote the exchange of design-manufacturing collective knowledge.

Instead of the typical design/construction model, which is a linear process where each source of expertise operates independently before passing the work to the next expert, the platform design process utilizes the shared expertise of many sources throughout the entire design and manufacturing period. The impact of one design decision (say the prefabrication or installation choice, or the location of mechanical ductwork) is immediately analyzed by the whole design team, leading to optimal solutions that are then incorporated into the rest of the subsystems, so long as the design process is well-managed. Examples might include modifications to space distributions so that all risers are grouped together and distributed efficiently. Although this kind of decision might be made without the presence of an integrated design process, it can take much longer and works a lot less efficiently than using the composite design process.

This innovation in the design and development of platforms implies that real estate development and construction firms that are vertically integrated are better prepared to tackle the challenge of platform design. Developer-owners who have plentiful experience working with a specific architect and who own the construction process and sales organization can be more efficient in integrating the various disciplines involved in the design of platforms.

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The key design advantage of platforms is the opportunity presented to spend more time on architectural and planning problems rather than on detailing of design and communication of instructions to the builder. And more importantly, innovation occurs early in the design process rather than as a builder’s substitute to a conventional design parameter. Therefore, the design process sets the pace and plan for the execution of the whole building project.

2.5.1 The Role of Systems Design in Platform Development

Recall that a product platform comprises a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced to target various market segments. The composite design process seeks to identify, analyze on a function and cost basis, select and integrate those subsystems and interfaces into products that optimize the function of the overall system. Thus, the use of a “systems approach” to the design and development of platforms is imperative.

“Systems building” is an approach to industrialization in the building process that utilizes the basic problem solving strategy of general systems theory. In this case, particular systems or alternatives are analyzed in terms of the “whole”, and then considered in terms of the particular parts. Applying this type of thinking usually involves an initial stage of systems definition where the whole system is defined in terms of its interacting subsystems and components. Such type of thinking will be applied to our mid-rise building prototype in the Methodology section of this thesis.

Systems design is the application of the scientific method to selection and assembly of components or subsystems to form an optimum system to attain a specified set of goals and objectives while subject to certain constraints. A “systems approach”

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offers the possibility of significant improvement in the construction of buildings. Studies
done in the 1970s in Europe, for instance, show that the number of man-hours spent by
European builders to produce a given unit of housing has been cut in half by the use of
systems building. This occurs primarily because unskilled workers can be introduced
where craftsmen were once needed. Also, the Studies for Educational Facilities (SEF)
project, which involved the development of a series of school buildings and was a testing
ground for the systems approach to construction, required 10 ½ months for the design and
construction of its first series of schools. The 10 schools of the second phase of the
program had reduced the required design and construction time down to 8 ½ months, and
represented a 40 to 60% cost savings in design and construction over traditional methods.

A building system has been called a “kit of parts”. It consists of a group of
components and subsystems, which can be put together in a great array of configurations
to provide a large number of solutions to any given problem. It is based on the belief that
mass production processes are best utilized when a wide variety of designs can be
developed from a minimum number of different parts.

Systems design is a key component of a platform approach because subsystems or
a limited set of them are commonly shared amongst products in a platform. For example,
in another test of systems design of U.S. schools in the early 1970s, titled School
Component Systems Development (SCSD), system components comprised about 50% of
the total building. While the architects who designed the individual buildings were
required to use the four pre-determined SCSD subsystems, they were free to adapt the
building to the site and to design the exterior using conventional materials and
construction methods.

In terms of customization and uniqueness, consider that for the school program, a
definition of 10 subsystems with four acceptable proposals per subsystem would be
capable of generating 1,048,576 possible wholes (or schools), each one somehow unique

45 Bender, 1973.
from any other, yet still complying with the overall parameters of the initial performance specifications defining the original 10 subsystems.

This approach is particularly applicable in the development of a potential platform in residential buildings. For example, the structural system sets the pace for the building construction; enclosing, supporting and providing stability for mechanical equipment, enclosure, finishes and furnishings. This subsystem can be standardized over a series of buildings using a grid or modular method of design. Major subsystems would be shared amongst this series of buildings. Architects would be familiar with the specifications of such systems and would design a building and customize it to incorporate the required set of subsystems while making each building unique. Some in systems building, in fact, have argued that it is possible to produce buildings of the highest architectural quality from a highly restrictive selection of materials.\(^{47}\)

2.5.2 The Process of Systems Design

The concept of standardization has been given a new impetus by the systems approach through the design of buildings on a grid, or modular basis.\(^{48}\) The aim is to coordinate the size of factory-made components and subsystems with the design of buildings. Widely used major components, such as trusses, stairs, heating and air conditioning packages, and kitchen equipment, are then inserted into the modules. The systems design approach is utilized to determine the optimal subsystems. It involves three main parts:\(^{49}\)

A. **Analysis** is the process of providing designers (architects and engineers) with an understanding of the requirements of the system and what it should accomplish.

\(^{47}\) Bender, 1973.

\(^{48}\) Bender, 1973.

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This part includes the collection of data, identification of the objectives and restrictions, and establishment of performance specifications.

B. **Synthesis** is the process of selecting components to form the system that meets the design objectives while subject to restrictions.

C. **Appraisal** is the process of evaluating system performance. Data obtained in the appraisal process is used to improve the system, through feedback of information and resulting analysis. In the end, a system must be continually updated and evaluated to improve the platform and subsequent derivative products.

One approach to the synthesis and appraisal stages of the systems design approach is to conduct a value analysis. Characteristics required of a particular subsystem are listed and assigned a relative importance. Then each alternative is assigned a number 1-10 that reflects the ability of the alternative to address the criteria. All resulting weighted values are added up and matched with the cost, to come up with a ratio of value to cost. This makes the process of deciding between alternatives a systemized process, using the scientific method as a backbone.
Table 1: Value Analysis: Comparison of Alternative Partitions

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Relative Importance</th>
<th>Alternatives</th>
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<tr>
<td></td>
<td>Relative</td>
<td>1 All Metal</td>
<td>2 Glass and metal</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Value</td>
<td>Weighted</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Value</td>
<td>Value</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction Cost</td>
<td>8</td>
<td>10</td>
<td>80</td>
<td>8</td>
<td>64</td>
</tr>
<tr>
<td>Appearance</td>
<td>9</td>
<td>7</td>
<td>63</td>
<td>9</td>
<td>81</td>
</tr>
<tr>
<td>Sound Transmission</td>
<td>5</td>
<td>5</td>
<td>25</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>Privacy</td>
<td>3</td>
<td>10</td>
<td>30</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Visibility</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>80</td>
</tr>
<tr>
<td>Movability</td>
<td>2</td>
<td>8</td>
<td>16</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Power outlets</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Durability</td>
<td>10</td>
<td>9</td>
<td>90</td>
<td>9</td>
<td>90</td>
</tr>
<tr>
<td>Low maintenance</td>
<td>8</td>
<td>7</td>
<td>56</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>Total weighted values</td>
<td></td>
<td>360</td>
<td></td>
<td>397</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td>$12,000</td>
<td></td>
<td>$15,000</td>
<td></td>
</tr>
<tr>
<td>Ratio of values to cost</td>
<td></td>
<td>0.0300</td>
<td></td>
<td>0.0265</td>
<td></td>
</tr>
</tbody>
</table>

* Source: Building Engineering and Systems Design.

A systems design approach will be incorporated into the composite design process for the platform in consideration. Alternatives will be considered in the context of subsystem interfaces and optimization of the overall building.

2.6 The Role of Information Technology in Platform Development

The rapidly developing advancement of information technology is significantly affecting present-day industries where success lingers on the ability to quickly and efficiently process sizeable amounts of information.

The most prevalent technology-related trend in production techniques of car manufacturing and industrial building is that both are developing component selection and optimization techniques using IT systems. In car manufacturing, computers have played an important role in product development for many years without transforming the fundamental process of development. In addition to the use of computers for traditional

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initiatives such as reduction of lead times and improvement in productivity, manufacturers are expanding the range of activities in which computers play a role. In the 1970s and 1980s, the focus of computer use was on digitization of engineering drawings and performance analysis. In the 1990s, the role of computers expanded into adjacent activities such as testing, advanced engineering and styling. Sophisticated simulation programs enabled by supercomputers now enable the precise testing of car model dynamics without physical prototypes, providing a wider range of alternatives and substantial savings in development time and costs. Using designer’s CAD data, car engineers can even simulate factory operations and do a virtual assembly. Also, realistic styling models generated by advanced computer graphics may now substitute clay, plaster and wooden models, and the digitization of quality management tools improves product quality and allows for the sharing of engineering know-how amongst platforms.

Car manufacturers have outpaced the building construction industry in its ability to successfully deploy computer-integrated manufacturing techniques (CIM), linking CAD and CAM (Computer-Aided Manufacturing), a tool that building producers have just begun exploring. 4D CAD or 4D modeling in the building industry incorporates existing CAD modeling techniques with scheduling, estimating, sequencing, fabrication, delivery, and installation information to give an unprecedented ability to track a project from design through construction. Other tools, such as the MOCABuild™ construction simulation software, allow builders to evaluate the cost and schedule impact of various building alternatives to an overall project. MOCA Build will be explored at length in Chapter 3: Methodology.

In building platform development, such software products can be immensely useful by enabling a manufacturer to: consider the impact of various subsystems and interfaces, better manage work processes on site so that platform development is feasible, and to assess the viability of certain trade-offs between uniqueness and commonality, one

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of the most important challenges faced by developers of a platform architecture in construction. These products can also facilitate the evaluation of the long-term impact of various alternatives over a series of buildings so that a consistent product can be brought to market at significant cost advantages.

The Internet is also proving an immensely useful mechanism in materials procurement and information sharing. As in car manufacturing, sales of generic parts and even pre-assembled components are increasingly being conducted through Internet auctions\(^{52}\). The Internet is especially valuable in procurement of materials for building platforms. High volume parts quantities needed in various locations across the country, for example, can be more efficiently managed from a central planning office and procured through various distributors in the specific areas where derivative buildings are erected. In addition, local prices can be compared with national prices and indexes accessible through the Internet in order to determine the best available cost.

In the end, computer technology by itself can barely lead to sustainable competitive advantage for a firm or group of firms. Acquisition of hardware by one company is likely to be quickly followed by others as the cost of computer hardware comes down considerably and new software becomes available to the whole industry. The critical element becomes the extent to which organizational arrangement and processes, philosophies, and know-how support technology advancement. Face-to-face communication will continue to complement computer technology. Competitive advantage will lie in the organizational capability of a builder or real estate/construction organization to develop or acquire proprietary software that best addresses its processes and to coherently integrate software, hardware and human capital and knowledge into an overall effective system.

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\(^{52}\) Kieran Timberlake Associates Research, 2002.
Chapter 2: Topic Background Review

2.7 Applying the results of composite design to a building platform

Let us now consider how efficiencies gained in composite design can combine with others to create value through a platform-based approach to design and construction.

Table 2: Potential impact of capital efficiency through a platform-based approach, in percentages

<table>
<thead>
<tr>
<th>Initial project portfolio cost</th>
<th>Design Platforming*</th>
<th>Time to market</th>
<th>Accelerated production ramp-up</th>
<th>Surplus cost of standard</th>
<th>Final portfolio cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>8-10</td>
<td>3-8</td>
<td>1-2</td>
<td>2-5</td>
<td>85-90</td>
</tr>
</tbody>
</table>

* Includes materials, manufacturing, basic and order-specific engineering, and transport, commissioning, and warranty.

Consider this McKinsey & Company model of potential cost savings based on the application of a platform-based approach to a series of capital projects, be those residential buildings, industrial plants or buildings with a similar use. First, the savings in manufacturing are accompanied by significant savings in engineering and architectural design costs and time, as designs executed for one building can be replicated for a series, thus lowering the percentage that design costs constitute out of the total project cost.

All of these are effects of efficiencies in platform design that lead to savings in materials, manufacturing, basic and order-specific engineering, and transport, commissioning, and warranty, and are thus referred to as savings based on “Design Platforming”. The expected percentage savings in our prototype building, which should supports the figure

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that McKinsey includes in the model (8-10%), will increase as a series of buildings is rolled out. The aforementioned platform-related advantages (i.e. volume procurement, productivity gains, quicker reaction to potential on-site problems, and the positive effects of process optimization) can all be quantified within this 8-10% cost savings.

Next, we consider that the time to market may be significantly shortened based on this approach, thus leading to a 3-8% cost savings, which may be more like 3-5% for a residential-type building platform due to location factors, particular market requirements, demand for uniqueness in the product, and others. Potential benefits include first-mover advantage, and earlier commencement of operations, including cash flow generation. The latter is especially valuable in capital projects. It also concerns the time value of money and savings in the cost of capital.

Also, the effects of ramping up quickly minimizes down time of resources and lower costs by about 1-2%. Finally, the surplus cost of similar sizing in everything from materials to productivity can achieve savings of 2-5%, such as throughout a series of buildings.

When added up, a platform approach to the design and development of a series of buildings can lead to 15% cost savings across the board. This figure goes even higher as the value of a project increases and costs are spread out amongst derivative products.

Now let us attempt to quantify the potential savings from platforming, as established in this exposition:
Table 3: A common design saves money*

<table>
<thead>
<tr>
<th>PERCENT</th>
<th>POTENTIAL SAVINGS FROM PLATFORMING</th>
<th>COST REDUCTION LEVERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic engineering</td>
<td>5</td>
<td>-50</td>
</tr>
<tr>
<td>Order-specific engineering</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Parts, components</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Systems</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Raw materials</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Transport, commissioning, warranty</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Overhead</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

Breakdown of design cost structure

*This table has been adapted from an original by McKinsey & Company\textsuperscript{54} to reflect potential savings from a residential building platform.

The design side of the equation is the most important facilitator of all types of savings in a platform approach. Before these can be achieved, an understanding must be clear in that the costs of basic engineering and architecture can increase by 50% when designing for a platform. The process is more complicated and involved, as decisions made during this time will affect a whole series of derivative products. In this research, a hint of how overly complex the process will be easily perceivable.

\textsuperscript{54} Hoare & Seiler, 2001.
Chapter 2: Topic Background Review

However, the efficiencies start with manufacturing, where savings can reach 15% through designing particularly for ease of assembly throughout a series of derivative products. Learning curve benefits also contribute to these savings, but the design part of the development process will either facilitate or inhibit the acquisition of these benefits.

Consequently, designing for a platform ensures that parts, components and systems are carefully studied and selected. This selection plus the benefits of high-volume procurement can lead to a 5% savings in materials that are employed in a building series.

Overall, the platform-based approach to designing a series of buildings could therefore lead to an average 15% cost savings over the traditional custom-built approach to real estate product development.
2.8 Summary and Conclusions

To summarize the insights of this chapter, let us briefly review the various topics we have addressed thus far. First, the platform approach to product design and development was originally developed by auto manufacturers in response to their inability to address the growing demand for uniqueness desired by customers. In this chapter, we considered the ways in which the implementation of a platform approach in the automotive industry helped address particular inefficiencies and peculiarities that inflicted the sector at the time. We then examined some of the advantages and the challenges faced by real estate and construction companies that aim to implement such an approach in their manufacturing processes. Thirdly, we examined the process of composite design in platform development, which incorporates a systems approach and prefabricated components, and the impact that technology asserts in the development process of platforms, both in the auto industry and in building construction. Fourthly, we exposed previous attempts to industrialize the building industry and considered a series of reasons why the efforts have been less than successful to this day. Finally, we looked at ways in which platform design and development addresses most of the peculiarities found in the construction trade.

A platform approach to construction in many ways answers some of the peculiarities of construction that have been presented in ways that the traditional custom-designed building method does not. First, because a platform consists of a series of derivative products, economies of scale are increased, specifically by realizing gains in materials procurement, productivity, and efficiencies in manufacturing that cannot be achieved through the standard custom-designed building method. Second, a platform is designed with the constraints of site specificity in mind, so that derivative products can better accommodate themselves to particular site demands. Also, because specifications of derivative products are known to the owner, only sites that meet the requirements of the derivative products can be selected.
Furthermore, an organization that utilizes a platform approach can develop detailed process manuals and extensive parts and processes knowledge that enables it to better manage on-site workers and their trade. As the percentage of common parts increases within a series of platform products, greater leverage can be gained in the manufacturer-supplier relationship as material volume increases and a global perspective to procurement is adopted. To the extent that off-site pre-assembled units are incorporated into the building design, these can be manufactured for many different buildings and shipped to individual locations. Finally, the design of common subsystems and components that appropriately meet the national scope of the Uniform Building Code alleviates the meticulous evaluation of completely unique and custom-designed building products and minimizes the potential inconsistencies that can occur when erecting platform-designed buildings in several locations across the United States. Standard practices in installation make building processes more secure and less open to regulatory conflicts.

These concepts are all critical to the fundamental understanding of the platform manufacturing concept. A profound understanding of the impact of platform design and development in the construction industry cannot be achieved without a thorough review and a solid grasp of these topics. In addition, the rest of this thesis will draw from the concepts discussed in this chapter to prove that a platform approach to the design and construction of occupied buildings provides considerable advantages to both development firms and owners.
3.1 General Methodology

Recall that a composite design approach aims to optimize the overall product platform architecture through the analysis and design of its subsystems and components, and the resulting interactions between them. In order to assess the extent to which a platform-based approach is applicable to the construction of built facilities, this thesis will apply the composite design approach to the design and development of a particular building, referred to in this dissertation as the “prototype building”. Theoretically, this prototype building will be the first in a series of derivative buildings that will together form a product platform.

Furthermore, one of the key advantages of a platform-based approach that can also be proven through a scientific means such as a graduate-level thesis is the cost and duration savings that can be gained through the application of such a manufacturing approach. Thus, we aim to identify ways in which a platform approach can lead to cost and duration efficiencies in the prototype building as well as in derivative buildings going forward. The goal is to determine whether the savings usually garnered by application of a platform-based approach in the automobile and consumer products industries, among others, can be replicated in the construction industry.

3.2 Prototype Building Description

The prototype building in consideration is a high-end mid-rise residential building with 19 apartment units and parking space located in the Dorado Beach area of Puerto Rico (about 15 miles east of San Juan) in the Caribbean. The high-end market represents approximately the top 3% of the market in the local area in terms of volume of units sold at a particular price point. Each of the five different unit types is a fully contained
Chapter 3: Methodology

residential apartment, with bedroom(s), kitchen, bathroom(s), living/dining room, utility room, closet(s), and external loggia and gardens. The basement level will comprise the parking area, which is accessible in car via two entrances at each end of the building. On top of the basement, four levels of residential units will be in place. Access to the units will be available through elevators and open-air walkways on one side of the structure.

Figure 3: Units Diagram

Figure 4: Sample Layout of Two Prototype Building Units
Units will range in size from 2,000 ft\(^2\) to 4,000 ft\(^2\), with one or two floors. The architectural theme of the building will be contemporary Mediterranean-Caribbean, with a tall roof structure and outside "loggias" or patios in most apartment units. The composite design process will assume that the building requires a structural steel structure with exterior enclosure. An architect’s artistic rendering of the prototype building appears in the following page.
Figure 6: Artist’s Rendering of Prototype Residential building, March 2001.
Chapter 3: Methodology

The particular prototype building design was selected for a number of reasons. First, it represents a viable application of a real estate product that could be derived from a residential building platform. Second, the building is replicable in many different sites and locations, and is fairly representative of a large segment of the residential real estate market. Third, being a mid-rise building with only 19 apartment units, the complexity of the building systems and components are simple and straight-forward enough to facilitate an in-depth analysis that falls within the scope of this research. Fourth and last, the author is fairly knowledgeable about the subsystems that make up the building and has access to the managers within the organization that is planning to develop it.

3.3 Industry Professionals Who Have Been Consulted for this Dissertation

The following is a table listing some of the industry professionals that were consulted about the topic of this research:

<table>
<thead>
<tr>
<th>Name</th>
<th>Function</th>
<th>Contact Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Donald Burkett</td>
<td>Sales Manager</td>
<td>ICS 3-D Panel Works, Inc.</td>
</tr>
<tr>
<td>John Macomber</td>
<td>MIT Professor</td>
<td>MIT</td>
</tr>
<tr>
<td>Osvaldo Marcano</td>
<td>Mechanical Engineer</td>
<td>Self-employed</td>
</tr>
<tr>
<td>Orlando Mendez</td>
<td>Program/Project Manager</td>
<td>Dorado Beach Resort Homes</td>
</tr>
<tr>
<td>John Miller</td>
<td>MIT Professor</td>
<td>MIT</td>
</tr>
<tr>
<td>Hans Moll</td>
<td>Architect</td>
<td>PRISA, S.E.</td>
</tr>
<tr>
<td>Rafael Morales</td>
<td>Construction Manager</td>
<td>Dorado Beach Resort Homes</td>
</tr>
<tr>
<td>Don Murphy</td>
<td>Procurement Manager</td>
<td>Sommerville Hardware</td>
</tr>
<tr>
<td>Ricardo Puig</td>
<td>Mechanical Engineer</td>
<td>Self-employed</td>
</tr>
<tr>
<td>Franco Rigamonti</td>
<td>Civil Engineer, Consultant</td>
<td>MOCA Systems, Inc.</td>
</tr>
<tr>
<td>Sarah Slaughter</td>
<td>Civil Engineer, Consultant</td>
<td>MOCA Systems, Inc.</td>
</tr>
<tr>
<td>Friedel Stubbe</td>
<td>Developer</td>
<td>Dorado Beach Resort Homes</td>
</tr>
</tbody>
</table>
3.4 Systems Definitions and Alternatives

The first step in the composite design process is to classify and analyze the subsystems of a particular product platform to be developed. This ought to be done so that alternatives for each subsystem can be identified and evaluated. Thus, we began by organizing all building systems into five different classifications based on three sources: the HIS trade classifications, analysis of automobile systems, and the construction system for residential buildings as a whole. In addition, Systems Building concepts were studied and applied to the building project, and industry professionals were consulted, as noted above.

Once all building systems were classified, extensive research was conducted and various industry professionals consulted in order to identify current innovations that could be applied to the product platform design of this particular prototype building. The extent to which pre-fabricated components could be incorporated was also considered at this stage. Finally, a subset of alternatives was selected based on three criteria:

A. **Feasibility**: the extent to which the alternative met the goals of the product, can feasibly be installed in such a building and is available in the local market (includes Environmental Impact: the extent to which the alternative caused positive or negative impact on the surrounding environment)

B. **Economies**: the extent to which the system can provide economic benefits and efficiencies in cost and duration

C. **Organizational competency**: the extent to which the builder or developer possesses competencies by which use of the system alternative creates efficiencies (i.e. knowledgeable, competent labor force).

The following table presents the five system classifications, with the corresponding subsystems and components and the results of a brainstorming session in which we considered various subsystem alternatives appropriate for each application (with the ones selected for consideration in bold):
# Table 5: Platform System Classifications with Considered Alternatives

<table>
<thead>
<tr>
<th>PLATFORM BUILDING SYSTEMS CONSTRUCTION</th>
<th>Sub-Systems</th>
<th>Alternatives considered (selected for testing are in bold)</th>
</tr>
</thead>
</table>
| Systems | A. Sub-structure | • Pre-cast walls for foundation  
• **Standard**  |
| No. 1 – STRUCTURE | B. Super-Structure | • Structural Steel Frame:  
1. Pre-welded beam stub to column, with in-place bolted beam connection to beam stub (“Column Tree”)  
2. In-place welded beam-to-column connections  
• Four options for Unit separation walls:  
1. **Concrete Masonry Units**  
2. Extra Heavy Gypsum Partition with particular sound attenuation  
3. **Sprayed-on Concrete (Gunite)** wall  
4. Prefabricated Wall Panels  
• Fire Protection:  
1. Spray-on  
2. Board for beams **not** under a masonry wall  
3. Paint  
4. Cemeticous Plaster  
• 4 cast-in-place concrete walls as load-bearing center structure  
• Pre-fabricated Stairwells  
1. Metal option  
2. Pre-cast Concrete  
3. Cast-in-place |
| No. 2 – EXTERIOR ENCLOSURE | A. Walls | • Pre-cast Panels (depending on lifting loads):  
1. With installed windows  
2. Without installed windows/apertures  
• Different sizes of pre-cast concrete panels  
• Concrete masonry walls  
• Sprayed-on Concrete (Gunite) walls  
• Cast-in-place concrete |
| | B. Roof | • Current design  
• Pre-assemble like Trusses  
  o Small trusses  
  o Larger trusses |
| | C. Apertures | • Doors  
• Windows  
  o Hurricane resistance windows (impact glass)  
  o Installed with Pre-cast concrete panels  
  o Custom installed |
### No. 3 – INTERIOR SPACE DIVISION

| A. Walls | • Pre-assembled Gypsum Wall panels that slide into tracks and include:  
|          | o Light-switch high chases for wiring, which are then finished, or  
|          | o Floor-high chase for wiring, which can then be covered with Trim, or  
|          | o One side finished with studs, surface, electric/telecom wiring and plumbing piping, and connected to each other by slots on the side of each wall panel  
|          | • Standard tracks-studs-wiring and ducts-then surface installation  
|          | • CMU Walls  
|          | • Spray-on Concrete (Gnite) Walls  
| B. Ceilings | • Standard suspended ceiling  
|            | • Pre-assembled ceiling panels (7 per module, could require plumbing/HVAC redesign) |

### No. 4 – SERVICES

| A. Plumbing | • Pre-assembled plumbing trees  
|             | • Pre-assembled plumbing wall  
|             | • Standard installation/current design  
|             | • Material  
|             | o PVC drain pipe  
|             | o Cast Iron drain pipe  
| B. HVAC Piping | • Pre-cut piping  
| C. HVAC | • Current/standard design (rigid metal with insulation)  
|         | • All flexible ductwork (sometimes noisier)  
|         | • Flexible/fixed ductwork combination  
|         | • Wall-mounted AC units  
|         | • Solar water heating  
|         | • Split-system  
| D. Electrical | • Modular zone distribution (pre-assembled wiring with zone connections)  
|             | • Wireless fixture switches  
|             | • Wireless units that would allow readings from ground level  
|             | • Homeruns with rigid conduits with pulled wiring  
|             | • Homeruns with Electrical Metal Tubing (EMT)  
| E. Telecom | • Standard  
| F. Fire Protection | • Common areas and hallways fire protection  
|             | • Fire protection in common areas and units  
|             | • Pre-cut piping  

### No. 5 – FINISHES

| A. Floors | No alternatives for Finishes were considered at this time because of limited standardization and application to a platform concept.  
| B. Wall Finish |  
| C. Ceiling Finish |  
| D. Casework and Millwork |  

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Chapter 3: Methodology

The following table maps out the various alternatives that were selected and evaluated, and assigns a system classification to each. Shaded items are those that are uniquely evaluated in each simulation.
Table 6: SIMULATION DETAILS FOR PLATFORM APPROACH METHODOLOGY

<table>
<thead>
<tr>
<th>Simulation Number</th>
<th>Description</th>
<th>Structural Steel Frame</th>
<th>Unit Sep. Walls</th>
<th>Interior Partition</th>
<th>Exterior Enclosure</th>
<th>Other Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Super-Structure Column Trees; first baseline</td>
<td>In-place welding</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>New Baseline with Column Trees</td>
<td>Column Trees</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Pre-cast concrete panels (LARGE)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Large Panels</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Pre-cast concrete panels (SMALL)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Small Panels</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>New Baseline with Column Trees and Large Precast Concrete Panels</td>
<td>Column Trees</td>
<td>CMU</td>
<td>Drywall</td>
<td>Precast Panels</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Prefabricated spray-on concrete panels for unit separation walls</td>
<td>Column Trees</td>
<td>Spray-on</td>
<td>Drywall</td>
<td>Precast (interior drywall)</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Prefabricated spray-on concrete panels for all interior partitions and unit sep. walls, as well as interior of precast panels (only mesh and spray-on)</td>
<td>Column Trees</td>
<td>Spray-on</td>
<td>Spray-on</td>
<td>Precast (interior drywall)</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Quickwire push-in innovation</td>
<td>Column Trees</td>
<td>CMU</td>
<td>Drywall</td>
<td>Precast (interior drywall)</td>
<td>Quickwire Push-in</td>
</tr>
<tr>
<td>9</td>
<td>Rigid conduits for branches from Junction to Receptacle</td>
<td>Column Trees</td>
<td>CMU</td>
<td>Drywall</td>
<td>Precast (interior drywall)</td>
<td>Rigid Conduit for Branches</td>
</tr>
<tr>
<td>10</td>
<td>CMU walls with exterior finish and interior drywall</td>
<td>Column Trees</td>
<td>CMU</td>
<td>Drywall</td>
<td>CMU with plaster finish (interior drywall)</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>Pre-assembled Wall Panels for Interior</td>
<td>Column Trees</td>
<td>CMU</td>
<td>Pre-assembled wall panels</td>
<td>Precast (interior drywall)</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>Pre-assembled plumbing trees with pre-cut piping</td>
<td>Column Trees</td>
<td>CMU</td>
<td>Drywall</td>
<td>Precast (interior drywall)</td>
<td>Pre-assembled plumbing trees</td>
</tr>
<tr>
<td>13</td>
<td>Best Case</td>
<td>Column Trees</td>
<td>Spray-on</td>
<td>Spray-on</td>
<td>Pre-cast</td>
<td>Quickwire, Plumbing Trees</td>
</tr>
<tr>
<td>14</td>
<td>Best of Structure and Exterior, Worst from Interior and Services</td>
<td>Column Trees</td>
<td>CMU</td>
<td>Drywall</td>
<td>Pre-cast</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>Worst of Structure and Exterior, Best from Interior and Services</td>
<td>In-place welding</td>
<td>Spray-on</td>
<td>Spray-on</td>
<td>CMU Wall</td>
<td>Plumbing Trees &amp; Quickwire Push-in</td>
</tr>
</tbody>
</table>
In Chapter 2, we discussed evidence suggesting that we cannot optimize one subsystem while ignoring the others (fundamental consideration in systems design practice). Instead, we must examine the *interfaces* between subsystems in order to optimize the overall system (the building as a whole).

In many instances, the results of a particular alternative on one system may be different from the impact that this alternative may have on the construction duration and cost of the building as a whole. This is why alternatives must be considered from the perspective of the net effect it may have on the overall building. These observations force designers to consider the impact that one alternative may have on the duration and cost of all other systems. For example, plumbers can work faster installing plumbing trees, but we may still see the costs of the plumbers’ idle time while the next assignment commences. Also, efficiencies in one system may mean that another system will require more expensive materials and installation costs because the new system interferes with another one. Thus, system alternatives should never be evaluated by themselves.

In devising a plan to conduct simulations, the best case and worst-case scenario (standard components) simulations were run in order to evaluate the impact of subsystem *interfaces*. The selection process can be visually represented in the diagram on the following page, which will serve as a decision map for the analysis of subsystems.

The aim was to determine the extent to which a combination of ideal alternatives could lead to higher cost and time savings than those attributed to the aggregate or sum of the savings of each individual alternative. In other words, we sought to answer whether:

\[
\text{SAVINGS (A) + SAVINGS (B) + SAVINGS (C) < or > SAVINGS \{A, B, C\}.}
\]

For this reason, we also decided to combine the best alternatives from structural and exterior systems, with those of interior systems and services, as well as the worst from structural and exterior systems, with the best of interior systems and services. Both
Chapter 3: Methodology

Simulations would allow us to consider the impact of various interfaces and the extent to which they allow for a more efficient operation in the construction stage.
Figure 7: DECISION MAP FOR SUBSYSTEM ANALYSIS (B = Best Case Scenario, W = Worst Case Scenario)
Chapter 3: Methodology

Each simulation yielded four pieces of data relevant to our analysis:

1. Activity-based labor cost of subsystem
2. Subsystem installation duration
3. Activity-based labor cost of overall building
4. Construction duration for overall building

We define activity-based costs as those that account for the actual work that has to be performed installing a subsystem, not including idle time. This type of cost is critical when comparing manufacturing alternatives. At the end, the resulting activity-based cost and duration will enable the more precise determination of the ranges in material costs for which a particular system option is more or less attractive than its alternatives.

The activity-based costs listed in the tables on the Results section of this research include subcontractor labor costs and overhead/profit only, assuming work efficiency at 70%. Also, tables for overall building costs and duration (versus costs and duration for a particular system alternative) have a darkened top row for easy identification.

3.5 Measures and Means

3.5.1 Measures: Criteria for Analysis of Alternatives

Three key criteria have been considered when evaluating the impact of each construction alternative on the baseline results:

A. Cost and duration impact on particular system
B. Cost and duration impact on overall building
C. Other attributes (i.e. quality, market segment, material costs)
Chapter 3: Methodology

A. Cost and duration impact on particular system:

A baseline model which includes the typical construction procedure for a building such as the prototype has been utilized to evaluate the potential cost and time savings of a particular alternative. The costs and duration for the systems in both the baseline model as well as the alternative model will first be considered in the context of the impact that the alternative has on the cost and duration of only that particular system. For example, when considering the impact of having all interior partitions constructed with spray-on concrete and foam panels, the relative cost difference on the Interior Walls & Ceilings system will first be considered.

B. Cost and duration impact on overall building:

The next key analysis has been performed on the impact that a particular alternative may or may not have on the overall cost and duration of the whole building construction. For example, an innovation which involves a preassembled component may prove to be a less expensive system and/or a quicker system to install. However, the same option may require a more complex and/or costly procedure for installing a system that is interdependent with the original alternative. Such interactions are key to understanding the systems approach to platform design and construction.

As discussed previously, understanding such interfaces between systems will become increasingly important, especially when we perform a sensitivity analysis by comparing various groups of systems selected together for evaluation.

C. Other attributes:

The particular alternatives in question must be finally considered in the context of the quality standards of the subsystem and its applicability to a particular market segment. Also, the impact of increases or decreases in the cost of materials related to each system need to be juxtaposed against increases or decreases in labor costs to determine the extent
Chapter 3: Methodology

to which each alternative is advantageous or disadvantageous. Only in cases where material costs were not available for the local market, we utilized an assumption of 40% indexed cost over the means, which accounts for more expensive materials sold in PR (taken from R.S. Means and applied to alternative).

3.5.2 A Note on Time-Costs Tradeoff in Analysis of Subsystem Alternatives

In some instances, a system may cost more to install than the alternative, but can be completed in much less time. The cost-time tradeoff of the particular alternative will vary based on the particular needs of the owner/constructor/developer. An especially important factor in this case would be the time value of money and the cost of capital. Both are concepts that ought to be considered when assessing the value of duration efficiencies caused by one subsystem alternative.

3.5.3 Means: Use of MOCA Build Software

As discussed in Chapter 1, the primary framework for the analysis of each subsystem alternative and interface will be a proven and commercially available software named MOCABuild™. Developed by former MIT professor Sarah Slaughter, MOCA Build allows users to simulate the actual construction of a building in order to assess the cost and schedule impact of various building alternatives.

MOCABuild software will be an instrumental tool in evaluating each of the alternatives that comprise our unique product platform. By analyzing the cost and schedule impact of each subsystem alternative, and by examining the interfaces between them, we can select subsystems that can test the changes in terms of labor, material, and operating costs over a series of buildings. We attempt to demonstrate that a platform-based approach to design and construction, aided by the selective use of pre-fabricated
components, is viable in delivering a certain type of real estate product with higher quality, faster and cheaper than could be delivered without application of this approach.

To ensure reliability, the data utilized for simulation comes from time-motion studies and interviews at more than 200 construction sites, which concentrated on the physical components in buildings and the tasks required to transform and aggregate these into finished building systems. The information gathered was used to develop simulation models that can be utilized mostly in the early design stage, but also in all other phases of construction, to evaluate design and construction alternatives, examine opportunities for innovation, improve resource utilization, evaluate the viability of construction methods, and consider cost/time and standardization/uniqueness factor tradeoffs.

All in all, the models in the software allow users to simulate the actual construction of a building from the foundation up, as it would actually be completed in the field. The software represents a system with the ability to run controlled experiments. Not only can it be used to produce cost and schedule estimates, but users can also experiment with alternative techniques and their impact on duration and cost, thus reducing risk and uncertainty for a project or series of projects.

This innovative software was selected for this analysis over other software programs such as Primavera because it:

A. Measures the interdependencies between systems,
B. Is based on real data, and
C. Captures the performance of work by the various trades on a construction site.

MOCABuild is a particularly useful tool for this type of assessment, especially when new innovations that might not be proven in a certain market need to be evaluated. By conducting time-motion studies of particular tasks involved in installing such

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innovations, models can be adjusted to reflect actual task time in the real world construction site. This enables an objective evaluation of the viability of such innovations and alternatives. In addition, by inputting current production rates for tasks that are performed on-site for other types of products, one can come up with a largely reliable cost and schedule estimate for new products, especially when builders have no experience with the particular type of product in question.

3.5.4 Labor Rates Assumptions

The labor costs utilized in the simulation model include the base hourly wages plus overhead, workers compensation, and subcontractor profit markup observed in the area where the prototype building is located. They also reflect current labor cost rate conditions as of the time of this study*. Labor costs were 25-33% of those costs in Boston and other Northeastern U.S. urban centers. All costs reported in this thesis use hourly labor costs reported for Puerto Rico.

### Table 7: Labor Rate Assumptions by Trade

<table>
<thead>
<tr>
<th>Labor Trade Name</th>
<th>PR Labor Hourly Rate</th>
<th>Boston Labor Hourly Rate</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIP Carpenters</td>
<td>$25</td>
<td>$68.39</td>
<td>Observed</td>
</tr>
<tr>
<td>CIP Ironworkers</td>
<td>$20</td>
<td>$89.55</td>
<td>Observed</td>
</tr>
<tr>
<td>CIP Laborers</td>
<td>$15</td>
<td>$53.99</td>
<td>Observed</td>
</tr>
<tr>
<td>CIP Finishers</td>
<td>$20</td>
<td>$60.45</td>
<td>Observed</td>
</tr>
<tr>
<td>Steel Ironworkers</td>
<td>$25</td>
<td>$101.87</td>
<td>Avg. Steel welders and riggers</td>
</tr>
<tr>
<td>Crane</td>
<td>$70</td>
<td>$279.00</td>
<td>Assumed ~ ¾ New England - Urban</td>
</tr>
<tr>
<td>Carpenter (drywall)</td>
<td>$25</td>
<td>$53.42</td>
<td>Assumed same as CIP carpenters</td>
</tr>
<tr>
<td>Masons</td>
<td>$25</td>
<td>$64.98</td>
<td>Assumed same as CIP carpenters</td>
</tr>
<tr>
<td>Sheet Metal</td>
<td>$20</td>
<td>$60.71</td>
<td>Assumed ~ 1/3 New England - Urban</td>
</tr>
<tr>
<td>Steamfitters</td>
<td>$25</td>
<td>$59.62</td>
<td>Assumed ~ 1/3 New England - Urban</td>
</tr>
<tr>
<td>Plumbers</td>
<td>$25</td>
<td>$50.14</td>
<td>Assumed ~ 1/3 New England - Urban</td>
</tr>
<tr>
<td>Electricians</td>
<td>$25</td>
<td>$64.13</td>
<td>Assumed ~ 1/3 New England - Urban</td>
</tr>
<tr>
<td>Telecom Installers</td>
<td>$20</td>
<td>$64.13</td>
<td>Assumed ~ 1/3 New England - Urban</td>
</tr>
<tr>
<td>Sprinklerfitters</td>
<td>$20</td>
<td>$59.70</td>
<td>Assumed ~ 1/3 New England - Urban</td>
</tr>
<tr>
<td>Window Installers</td>
<td>$20</td>
<td>$60.75</td>
<td>Assumed ~ 1/3 New England - Urban</td>
</tr>
</tbody>
</table>

* The labor costs assumed for the local Puerto Rico area include subcontractor overhead and profits and satisfy the R.S. Means Location Factors figures for Puerto Rico (29.1% of the average in the mainland United States).
Productivity rates were assumed to be those of the Boston area, since our aim is only to compare alternatives and not yet generate an accurate idea of the duration of this particular prototype building construction.

Labor and Hoisting Equipment Resources have been assigned in the following manner in accordance with local practice:

**Table 8: Number of resources assigned by labor trade in simulations**

<table>
<thead>
<tr>
<th>Labor Trade Name</th>
<th>Number of Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIP Carpenters</td>
<td>10</td>
</tr>
<tr>
<td>CIP Ironworkers</td>
<td>10</td>
</tr>
<tr>
<td>CIP Laborers</td>
<td>10</td>
</tr>
<tr>
<td>CIP Finishers</td>
<td>4</td>
</tr>
<tr>
<td>Steel Ironworkers</td>
<td>10</td>
</tr>
<tr>
<td>Crane</td>
<td>2</td>
</tr>
<tr>
<td>Carpenter (drywall)</td>
<td>10</td>
</tr>
<tr>
<td>Masons</td>
<td>8</td>
</tr>
<tr>
<td>Sheet Metal</td>
<td>4</td>
</tr>
<tr>
<td>Steamfitters</td>
<td>4</td>
</tr>
<tr>
<td>Plumbers</td>
<td>10</td>
</tr>
<tr>
<td>Electricians</td>
<td>10</td>
</tr>
<tr>
<td>Telecom Installers</td>
<td>2</td>
</tr>
<tr>
<td>Sprinklerfitters</td>
<td>2</td>
</tr>
<tr>
<td>Window Installers</td>
<td>x</td>
</tr>
</tbody>
</table>

The figures explain the low labor costs found throughout the simulation results. However, the real figure used in our analysis will be the percentage change (ΔT) in construction costs and duration in both the particular system that the alternative belongs to, and the overall building.
3.5.5 Reliability and Verifiability of the Input Data and Models

The platform design process requires that analysis of common and alternative subsystems and interfaces be based on available facts. Thus, we employed Puerto Rico resource numbers and wage rates in the mode, as well as production rates from the Northeast United States. These production rates are based on time-motion studies, supplemented by estimates provided by aforementioned construction managers currently involved with the labor pool that is intended to work on the prototype building. For instances in which innovations were evaluated, professionals that have experience installing such systems were consulted to generate a relevant production rate, resources and wage rates. Production rates were applied to each task within the simulation model to arrive at the schedule impact of the various alternatives, as well as total activity-based costs.

3.6 Summary

In this chapter, we have outlined the methodology that this thesis will undertake in attempting to demonstrate that the concept of platform manufacturing can be applied to built facilities, delivering significant efficiencies that can be replicated throughout a series of derivative products. We will utilize a systems approach to determine the best alternatives to various subsystems of a prototype building, using a construction simulation software package titled MOCA Build. In the next chapter, we examine the alternatives in more depth and outline the results of all simulations as well as possible cost and duration impacts of each on the subsystem and on the whole.
4.1 Alternatives Considered in Baseline Model Definition

The model employed to compare the positive or negative impact of the various alternatives considers the traditional installation and material costs of constructing the aforementioned prototype building in Puerto Rico. This model will be referred to as the “baseline model” from this point forward. Several baseline models were developed throughout the process. Early in the testing stage, two alternatives were considered separately in order to determine whether to incorporate them into the first baseline model. Let us discuss both of these before outlining the selection of system alternatives for the baseline model.

4.1.1 Column Trees Alternative to Super Structure Connections

The structural steel frame requires strong connections at the beam to column connection point to meet the wind and seismic load requirements of the Puerto Rico building code. The traditional method employed in the area involves erecting each steel beam with a minimum number of erection bolts, and then welding the required plates to the columns and beams in the field. The proposed alternative, referred to as Column Trees, allows the pre-welding of beam stubs to the columns (onsite on the ground or in a separate shop), which then requires only a bolted beam to beam-stub connection on site.

An early-on test of structural steel frame system alternatives resulted in 50% labor cost savings and 13% time savings as depicted in the following table:
Chapter 4: Results

Table 9: Structural Steel Erection Duration and Labor Cost

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Steel Erection Duration</th>
<th>Steel Erection Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welded Beam-Col</td>
<td>Structural Steel Frame with full moment connection (plates and in field welds for beam-column connection)</td>
<td>96 days</td>
<td>$190,780</td>
</tr>
<tr>
<td>Column Tree</td>
<td>Pre-welded beam stub to column, with in-field bolted beam to beam stub connection</td>
<td>83 days (-13%)</td>
<td>$96,113 (-50%)</td>
</tr>
</tbody>
</table>

In this case, the material requirement is the same, so no extra material cost ought to be considered. On the other hand, the extra costs of pre-welding and extra bolting on the field must be considered. Since a typical field welder can deposit about 1.8 to 2 pieces of weld rod per hour manually (assuming each rod is 12 inches long), and we need 329 inches of pre-welding on the ground (27.42 feet)\(^1\) for all “column trees”, then the extra labor costs incurred by implementation of the alternative would be $381.00 (assuming $25 for welder/ironworker per hour labor rate for 15.24 hours). However, this figure assumes no idle time and no time to handle materials. Thus, we will assume 70% work efficiency, and a 40% idle time for materials handling, which brings the figure to $1,360.73. This is still much less than the 50% reduction in labor costs, so the alternative will be considered further in our analysis.

The considerable savings in cost and duration of column trees installation confirms the efficiencies that can be gained from prefabricated connections of beam stub to column in the structural system. In fact, such connections can provide even more savings and efficiencies if spread throughout a whole building series.

It is easier to perform high-quality welding in a controlled environment when workers are not hanging high up in the air. Quality control can also increase when beam-to-beam connections are prefabricated in a controlled environment, with a dedicated labor force.

Organizationally, a construction firm can lower risks, increase worker safety, and achieve cost economies through the use of such an alternative.

---

\(^1\) Per MOCA Build simulation take-offs.
4.1.2 Pre-cast Concrete Panels for Exterior Enclosure

One other decision that was tackled early on and that was incorporated into the baseline model, is the choice of pre-cast concrete exterior panels for the building’s exterior enclosure (pre-cast panels were originally thought to constitute the most efficient exterior enclosure system. The decision to consider and simulate other alternatives was done later). Two general scenarios were considered based on the particular configuration of the prototype building units and the ensuing layout and size of exterior wall areas. The first alternative consisted of roughly rectangular panels with maximum side lengths of 21’ X 6’. This alternative increased the number of panels but reduced the number of connections per panel. The second alternative consisted of larger panels, including window and/or door openings, but required a higher number of connections per panel.

Preliminary analysis indicated that the use of the larger panels resulted in a reduction of panel erection time and cost of approximately 50%.

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Panel Erection Duration</th>
<th>Panel Erection Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular Panels</td>
<td>Precast concrete panels that are smaller and rectangular</td>
<td>63 days</td>
<td>$275,216</td>
</tr>
<tr>
<td>Larger Panels</td>
<td>Larger precast concrete panels with windows and doors</td>
<td>38 days (-40%)</td>
<td>$139,030 (-49%)</td>
</tr>
</tbody>
</table>

Thus, the use of larger panels was incorporated into the baseline model.

The other systems and alternatives for the baseline model include the following:

- The unit separation walls are those that divide all apartment units from each other and are about 66 to 76 linear feet long. They have been considered as a distinct and separate system due to its particular sound attenuation and strength requirements. The baseline will assume these walls to be constructed from Concrete Masonry Units (CMU). These are cinder blocks approximately 12” long
by 5” wide by 6” high. Each block contains two cavities that are filled with grout to control sound attenuation. They are placed on top of one another during installation and plastered on both sides for finishing.

- Interior partitions have been assumed to consist of two 5/8” Gypsum Boards on each side of a 3 5/8” 20-gauge 24 O.C. stud with unfaced batt, which satisfies a 52-54 Sound Transmission Class rating ideal for a high-scale residential application. The system includes humidity-minimizing panels and sheetrock in areas such as bathrooms and kitchens.

- The services assumed for the baseline model consisted of the standard mechanical, electrical, and plumbing installation procedures for a mid-rise residential building. These standards will be discussed when alternatives for such services are examined in detail.

One must note that the impact of increases or decreases in the cost of materials related to each system need to be juxtaposed against increases or decreases in labor costs to determine the extent to which each alternative is advantageous or disadvantageous. However, the process may be simplified by taking the savings in labor costs for a particular alternative and determining if any increase in material costs of the alternative is less than the labor cost savings, so that the net effect is still a savings amount that is positive (S > 0). This procedure will be considered in evaluating the net effects of each alternative.

Thus, we can now designate a new baseline model from which we can compare the impact of various alternatives on the particular subsystem cost and duration, as well as on the cost and duration of the whole building. Both column trees and pre-cast concrete panels were incorporated into the original baseline because it was not worthwhile to continue to analyze all alternatives against a baseline that was extremely different from preferred initial alternatives. Both systems’ selections occurred while trying to determine which subsystems were ideal for the baseline model.
The new baseline cost and duration is represented in the following table:

### Table 11: Projected Overall Building Construction Cost and Duration for Baseline Model

<table>
<thead>
<tr>
<th>Description</th>
<th>Project Duration</th>
<th>Activity-Based Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL BLDG</td>
<td>153</td>
<td>$903,087</td>
</tr>
<tr>
<td>25% OH</td>
<td>180,617</td>
<td></td>
</tr>
<tr>
<td>Labor Subtotal</td>
<td>153</td>
<td>722,470</td>
</tr>
<tr>
<td>Cast-In-Place Concrete</td>
<td>80.7</td>
<td>66,773</td>
</tr>
<tr>
<td>Electrical</td>
<td>102.5</td>
<td>141,053</td>
</tr>
<tr>
<td>Equipment-Cranes</td>
<td>103.8</td>
<td>40,007</td>
</tr>
<tr>
<td>Fire Protection</td>
<td>31.8</td>
<td>2,433</td>
</tr>
<tr>
<td>Glass Curtain Wall</td>
<td>106.3</td>
<td>10,894</td>
</tr>
<tr>
<td>HVAC</td>
<td>81.4</td>
<td>12,739</td>
</tr>
<tr>
<td>HVAC Piping</td>
<td>50.2</td>
<td>15,860</td>
</tr>
<tr>
<td>Interior Walls &amp; Ceilings</td>
<td>76.3</td>
<td>77,808</td>
</tr>
<tr>
<td>Plumbing</td>
<td>97.6</td>
<td>120,464</td>
</tr>
<tr>
<td>Precast Concrete Panels</td>
<td>37.9</td>
<td>139,030</td>
</tr>
<tr>
<td>Other</td>
<td>17.8</td>
<td>1,245</td>
</tr>
<tr>
<td>Structural Steel</td>
<td>73.8</td>
<td>96,113</td>
</tr>
<tr>
<td>Telecom</td>
<td>72.7</td>
<td>2,548</td>
</tr>
</tbody>
</table>

As we discuss the various alternatives, we will be referring to a Decision Map for Simulation Analysis in five stages:

<table>
<thead>
<tr>
<th>Decision Map for System Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
</tr>
<tr>
<td>In-place welding</td>
</tr>
<tr>
<td>Column Trees</td>
</tr>
<tr>
<td>Exterior</td>
</tr>
<tr>
<td>Large Pre-cast Panels</td>
</tr>
<tr>
<td>CMU Wall</td>
</tr>
<tr>
<td>Interior</td>
</tr>
<tr>
<td>STD Walls, CMU Party</td>
</tr>
<tr>
<td>Spray-on, Spray-on</td>
</tr>
<tr>
<td>Rigid Conduit/EMT</td>
</tr>
<tr>
<td>Quickwire</td>
</tr>
<tr>
<td>Plumbing</td>
</tr>
<tr>
<td>Standard</td>
</tr>
<tr>
<td>Wall Panel, CMU</td>
</tr>
<tr>
<td>STD Walls, Spray-on</td>
</tr>
<tr>
<td>STATUS</td>
</tr>
<tr>
<td>I</td>
</tr>
<tr>
<td>II</td>
</tr>
<tr>
<td>III</td>
</tr>
<tr>
<td>IV</td>
</tr>
<tr>
<td>V</td>
</tr>
</tbody>
</table>

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The shaded subsystem alternatives are those that have been selected as ones that can lead to a significant cost and duration advantage (also, those that will be later considered for the best case scenario). This table serves as a visual representation of the procedure which we are utilizing to test our hypothesis. Testing will occur in five stages, representing the five major systems for which we will consider alternatives.

4.2 Analysis of Alternatives

4.2.1 Concrete Masonry Unit Walls with Plastered Finish for Exterior Enclosure

One of the trickier alternatives to model was the CMU exterior enclosure option in place of precast concrete panels (i.e. baseline). Because masons are known for being very efficient in the local area of the prototype building, the alternative was worth exploring.

The problem becomes the fact that a considerable amount of masons will be needed for the exterior enclosure given the surface area, and this enclosure can only be started after a certain amount of tasks are completed. This means that in order to finish the building as expediently as feasible, a number of masons that is too large (above 80) and unrealistic would be needed. Over 35,000 square feet of exterior walls had to be built in CMUs, with plastering and finishing on top of it, including an 8 hour cure time between CMU installation and plaster hand trowel finish.

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Exterior Enclosure Duration</th>
<th>Exterior Enclosure Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precast Concrete Panels</td>
<td>Large Precast Concrete Panels that include door/window openings</td>
<td>38 days</td>
<td>97,100</td>
</tr>
<tr>
<td>CMU</td>
<td>CMU Exterior with Plastering, and Drywall Interior</td>
<td>47 days (+24%)</td>
<td>1,362,451 (+1,300%)</td>
</tr>
</tbody>
</table>
In order to find a realistic way of completing the business in a time that was acceptable, the number of masons had to be significantly increased, a cost which is much higher than the extra cost of precast concrete panels. The difficulty in managing such a large group of masons, especially if delays occur between installations in the platform series of buildings, is a crucial aspect of this alternative.

Material costs for pre-cast concrete panels come to be around 45% more expensive than CMU materials, which is still not enough to warrant full consideration of the CMU alternative as a viable alternative to the exterior enclosure system.

As evident in these results, this alternative is not worth considering for a best case scenario going forward. With this decision, we complete Stage II and the Exterior Enclosure system in our decision map:

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Complete Building Duration</th>
<th>Complete Building Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precast Concrete Panels</td>
<td>Large Precast Concrete Panels that include door/window openings</td>
<td>153 days</td>
<td>$903,087</td>
</tr>
<tr>
<td>CMU</td>
<td>CMU Exterior with Plastering, and Drywall Interior</td>
<td>152 days (-1%)</td>
<td>$2,441,292 (+171%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decision Map for System Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel In-place welding CMU Wall</td>
</tr>
<tr>
<td>Column Trees Wall Panel, CMU</td>
</tr>
<tr>
<td>Completed COMPLETED STATUS</td>
</tr>
</tbody>
</table>
Chapter 4: Results

4.2.2 Prefabricated Foam Panels with Spray-on Concrete for Unit Separation Walls

The first alternative we evaluated was the use of prefabricated foam panels with spray-on concrete for the unit separation walls. According to various manufacturers (primarily ICS 3-D Panel Works, Inc.) as well as industry professionals (see listing in the Methodology section), the technique has been growing in popularity especially due to cost and time savings that can be achieved as the system is rolled out through a series of buildings, and as crews gain productivity efficiencies, and the area of system installation grows larger.

The components of this system are the following: a core of modified expanded foam, flanked by wire mesh on each of its two sides, connected with galvanized truss wires, and field-coated with concrete (see diagram).

Placed over slab embedded steel dowels, a first group of masons fastens panels (made up of insulation and truss wires with welded wire fabric) to one another and reinforces seams and corners with wire mesh. Window and door openings are quickly cut to accommodate any type of frame material. The space between the core and wire mesh allows for rapid placement and routing of electrical conduit and plumbing. Another group of masons applies wet or dry shotcrete to the desired thickness, producing a monolithic
A concrete structure that accepts any type of interior and exterior surface texture treatment. A third set of masons plasters and finishes both surfaces of the panels.

Manufacturers mention flexibility, ease of installation, versatility of application, and impressive strength as the system's core advantages. The system was selected for testing because these advantages can lead to reduced construction times, excellent sound and thermal control properties, reduced on-site heavy equipment, and lower maintenance costs. In addition, organizational competencies in the local area are such that masons can be reasonably expected to become more productive and efficient installing the system over a series of buildings. On the other hand, material costs can be slightly higher but easily available.

We then ran a simulation of the labor cost and duration for just the building unit separation walls (which separate the units) out of pre-fabricated foam panels with spray-on concrete and compared it to the baseline model, which assumes that the same walls are built using CMU installation. Assumptions for the remaining systems were those employed for the baseline model, as we sought to evaluate only the impact of this particular alternative.

<table>
<thead>
<tr>
<th>Description</th>
<th>Structural Steel Frame</th>
<th>Unit Sep. Walls</th>
<th>Interior Partition</th>
<th>Exterior Enclosure</th>
<th>Other Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefabricated spray-on concrete panels for unit separation walls</td>
<td>Column Trees</td>
<td>Spray-on</td>
<td>Drywall</td>
<td>Precast (interior drywall)</td>
<td>-</td>
</tr>
</tbody>
</table>

The results were as follows:

**Table 14: Prefabricated spray-on concrete panels for unit separation walls only**

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Interior Walls &amp; Ceilings Duration</th>
<th>Interior Walls &amp; Ceilings Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMU (Standard)</td>
<td>Cement Masonry Unit throughout unit separation walls</td>
<td>76 days</td>
<td>$77,808</td>
</tr>
<tr>
<td>Spray-on</td>
<td>Foam with steel grid on each side for unit separation walls</td>
<td>75 days (-2%)</td>
<td>$77,793 (0%)</td>
</tr>
</tbody>
</table>
Chapter 4: Results

As was expected, initial results indicate that the installation cost impact of using prefabricated spray-on concrete panels to replace the typical concrete masonry unit walls is minimal. A 2% reduction (one day) in system installation duration is also small. In addition, a reported 66% ($3/ft^2$ for foam panels versus $1.81$ for CMU wall materials) increase in material costs with the use of foam concrete panels vis-à-vis a CMU unit separation wall makes the option less attractive.

Thus, there appears to be a small impact in the cost of installing unit separation walls in the prototype building using pre-assembled spray-on wall panels. This is so because of the relatively low area (in square feet) of unit separation walls relative to all interior walls in the building. One can assume that the larger the square footage of spray-on walls, the lower greater the impact on the specific system of interior walls, and overall.

In addition, the apparent complexity involved with spray-on concrete panels may cause delays especially early in the construction process as workers are trained in the procedure. It appears that such an alternative cannot be recommended for use strictly in unit separation walls of a platform building.

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Complete Building Duration</th>
<th>Complete Building Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMU (Standard)</td>
<td>Cement Masonry Unit throughout unit separation walls</td>
<td>153 days</td>
<td>$998,350</td>
</tr>
<tr>
<td>Spray-on</td>
<td>Foam with steel grid on each side for unit separation walls</td>
<td>152 days (-1%)</td>
<td>$994,141 (-1%)</td>
</tr>
</tbody>
</table>

When reviewing the impact of such an alternative in the context of building cost and duration as a whole, we find that the same can be said in this case: the impact of using prefabricated foam panels for unit separation walls is small. However, a 1% decrease in the overall building labor costs might be sufficient to pursue this option for a building platform.
Now, in this example, the positive difference between the materials cost of the prefabricated foam panels and those of a CMU wall have to be less than the difference in labor costs of the total building, which is $4,209. For an explanation of the material costs assumptions, please see the following table:

<table>
<thead>
<tr>
<th>Linear Ft. CMU Wall</th>
<th>Height of Unit Separation Wall</th>
<th>Total Square Footage</th>
<th>Finished CMU Cost</th>
<th>Total Material Cost</th>
<th>Spray-on Foam Panel Material Cost</th>
<th>Material Cost Difference</th>
<th>Labor Cost Difference</th>
<th>Net Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,345 ft</td>
<td>12 ft</td>
<td>16,140</td>
<td>$2.76/ft2</td>
<td>$29,213</td>
<td>$48,420</td>
<td>$19,207</td>
<td>-$4,209</td>
<td>$14,998</td>
</tr>
</tbody>
</table>

Because the material costs are 45% more expensive for the alternative and the difference between those costs is more than $4,209 (they amount to $1,460), then the use of the alternative provides by itself does not provide valid efficiencies.

This is an example of a case in which the impact on the particular system is almost negligible, but the impact on the overall building is more significant. Most probably, a 1% reduction in duration advances the critical path to project completion and perhaps alleviates a subsequent bottleneck in the construction process.

Because the duration difference is so negligible, it is unnecessary to discuss a cost-time tradeoff. We will consider the applicability of the concept to a platform design in the next analysis of alternatives, since it applies this innovation to all interior walls.

### 4.2.3 Prefabricated Foam Panels with Spray-on Concrete for All Interior Partitions

The next simulation included the use of these foam panels across all interior partitions, substituting the drywall component that is standard in high-end apartments. All other systems remained the same as the baseline.
Chapter 4: Results

As expected due to the increase in area where the system could be applied, the results proved more substantial:

Table 16: Prefabricated spray-on concrete panels for all interior partitions

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Interior Walls &amp; Ceilings Duration</th>
<th>Interior Walls &amp; Ceilings Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drywall</td>
<td>Gypsum Board partitions with CMU Unit Separation Walls</td>
<td>76 days</td>
<td>79,053</td>
</tr>
<tr>
<td>Spray-on</td>
<td>Foam with steel grid on each side and spray-on concrete</td>
<td>56 days (-27%)</td>
<td>163,532 (+107%)</td>
</tr>
</tbody>
</table>

The cost of installing such a system almost doubles from that of the typical drywall partition, largely because of the higher number of laborers needed to complete installation. More resources are needed since three crews take part in installing this system, versus both CMU walls and Gypsum Board partitions. However, 20 days are shaved from the project completion, representing a 27% decrease. When combined with this considerable decrease in project completion, the unmeasured advantages of the system, which include greater strength, sound and thermal attenuation, flexibility, and structural integrity, could make it worth the extra cost. For now, we have chosen it as a viable alternative and will consider it further in our analysis.

Table 17: Prefabricated spray-on concrete panels for all interior partitions

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Complete Building Duration</th>
<th>Complete Building Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drywall</td>
<td>Gypsum Board partitions with CMU Unit Separation Walls</td>
<td>153 days</td>
<td>$998,350</td>
</tr>
<tr>
<td>Spray-on</td>
<td>Foam with steel grid on each side and spray-on concrete</td>
<td>134 days (-13%)</td>
<td>$1,074,109 (+8%)</td>
</tr>
</tbody>
</table>

The impact on the whole building cost and duration is significant. An 8% increase in costs ends up buying a 13% reduction in project completion time. In addition, an increase in material costs of 66%, or $67,288.20, accompanies the execution of this alternative. Even though the total labor and material costs of this alternative add up to an additional $143,047.20 versus the traditional CMU and drywall partitions, the time-cost savings, local market pressures that question the quality of drywall, as well as technical
advantages and organizational competencies, all suggest that this alternative should be considered further.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2,862 ft Gypsum/ 1,345 ft CMU</td>
<td>12 ft</td>
<td>34,344/16,140 Gypsum/ CMU</td>
<td>$1.60/ft2 Gypsum: $1.81/ft2 CMU</td>
<td>$84,163.80</td>
<td>$151,452</td>
<td>$67,288.20</td>
<td>$75,759</td>
</tr>
</tbody>
</table>

If this statistic were to be evaluated as a trade-off for a specific building, all costs or savings implied by the earlier completion need to be incorporated (including costs of borrowing, interest earned on cash received earlier, opportunity costs of capital, as well as the harder to measure monetary value to the end user in early occupancy of real estate space). The specifics of these costs fall beyond the scope of this dissertation.

4.2.4 Pre-assembled Wall Panels for Interior Partitions

Pre-assembled wall panels have been traditionally used in office settings, and have proved convenient due to its flexibility, low installation costs, and functionality. Recent advances have brought about the consideration of such panels for use in residential construction\(^2\). The alternative merited an evaluation and application to the current prototype building for platform design. The other systems were assumed to remain the same from our baseline model.

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These pre-assembled wall panels come custom designed and built to the exact specifications of a particular building (or in the case of a platform approach, a series of buildings). In some instances, these panels have electrical and plumbing ducts already installed. They are prefabricated in a specialized facility and transported to the site. The ease of installation can be countered by the costs of preassembly as well as transportation. One would think that the material costs of pre-assembled wall panels will hinder the evaluation of such an alternative and will fail to provide significant efficiencies on the particular prototype building in consideration. However, one can expect the gap to narrow as a series of buildings in a relatively surrounding locality adopt the use of a similar pre-assembled panel.

Table 18: Interior Walls System Cost and Duration

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Interior Wall Installation Duration</th>
<th>Interior Wall Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drywall</td>
<td>Interior Drywall Partitions</td>
<td>76 days</td>
<td>77,808</td>
</tr>
<tr>
<td>Wall Panels</td>
<td>Prefabricated wall panels for residential use</td>
<td>54 days (-29%)</td>
<td>14,617 (-82%)</td>
</tr>
</tbody>
</table>

According to preliminary research and based on figures from R.S. Means Book, prefabricated, 5” thick, bare (no pre-wiring) wall panels can run anywhere from $5.75 to $7.75 per square foot in material costs, which is about 4.22 times the material costs of a drywall partition (assumes the average within the range, which is $6.75/ft² material costs of prefabricated wall panel versus $1.60/ft² material costs of drywall partitions). Let us consider the aggregate cost of materials in this case:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2,862 ft</td>
<td>10 ft</td>
<td>28,620 ft</td>
<td>$1.60/ft²</td>
<td>$45,792</td>
<td>$193,185</td>
<td>$147,393</td>
<td>-$63,191</td>
<td>$84,202</td>
</tr>
</tbody>
</table>

The net effect on the alternative installation is an increase in costs of $84,202. This may or may not be worth paying in order to get a 29% reduction in the system
installation duration. We will have to examine the complete building cost and duration in order to determine whether this alternative should be considered further.

Table 19: Interior Walls Prefabrication Impact on Overall Building Cost and Duration

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Complete Building Duration</th>
<th>Complete Building Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drywall</td>
<td>Interior Drywall Partitions</td>
<td>153 days</td>
<td>$903,087</td>
</tr>
<tr>
<td>Wall Panels</td>
<td>Prefabricated wall panels for residential use</td>
<td>131 days (-15%)</td>
<td>$928,232 (+3%)</td>
</tr>
</tbody>
</table>

The total net increase in costs for the use of prefabricated wall panels is about $109,347.00, including labor and materials. Based on the time value of money, costs of borrowing, higher prices paid by customers for early delivery, and others, it might be worth implementing since it leads to a 15% reduction in building completion time. However, the value of intangible characteristics, such as sound attenuation and quality, are such that we selected not to include the alternative in the best case scenario for this thesis going forward.

All in all, the concept of pre-fabricated wall panels provides interesting implications to platforming. As we discussed in Chapter 2, the use of prefabricated parts reduces essential problems of on-site production because a minimum number of activities are performed on site. Less material wastage results, installation costs are significantly reduced, and overall system costs can be more accurately predicted.

Even though the application of such an innovation might not make sense for this particular prototype building because the panels have to be transported from the mainland United States and are thus very costly materials, a derivative building which is in closer proximity to the production facility of the panels could also render this alternative attractive (in addition to the duration savings).
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At this point, our Decision Map for our analysis can be depicted as follows:

<table>
<thead>
<tr>
<th>Decision Map for System Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
</tr>
<tr>
<td>In-place welding</td>
</tr>
<tr>
<td>Column Trees</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>COMPLETED</td>
</tr>
</tbody>
</table>

4.2.5 Quickwire Electrical Installation

A small innovation in electrical outlet installation is the Quick-wire receptacle. This component allows a “clamp-like” connection of wires into the wall receptacle via two small apertures in the back of the receptacle that immediately grasp the dual electrical cable runs. This innovation reduces receptacle installation times from 8 minutes using a standard connection (cut wires, twist into each screw, etc.) to 2 minutes using the Quickwire Push-In connection (source: field tests and hardware expert).

The item came about while researching ways to make the electrical installation in buildings more efficient. All the other systems remained as in the baseline model.
Chapter 4: Results

The results on the electrical system installation costs came to the following:

<table>
<thead>
<tr>
<th>Description</th>
<th>Structural Steel Frame</th>
<th>Unit Sep. Walls</th>
<th>Interior Partition</th>
<th>Exterior Enclosure</th>
<th>Other Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quickwire push-in innovation</td>
<td>Column Trees</td>
<td>CMU</td>
<td>Drywall</td>
<td>Precast (interior drywall)</td>
<td>Quickwire Push-in</td>
</tr>
</tbody>
</table>

The results on the electrical system installation costs came to the following:

**Table 20: Quickwire push-in innovation**

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Electrical System Duration</th>
<th>Electrical System Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard connection</td>
<td>Standard wire connection to receptacle</td>
<td>102.5 days</td>
<td>141,053</td>
</tr>
<tr>
<td>Quickwire</td>
<td>Clamp-style installation procedure at power receptacle</td>
<td>102 days (-1%)</td>
<td>138,882 (-2%)</td>
</tr>
</tbody>
</table>

The impact of the Quickwire push-in receptacle was small, but noticeable. The use of this alternative leads to a 2% decrease in the cost of electrical system installation and a 1% decrease in duration.

**Table 21: Quickwire push-in innovation**

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Complete Building Duration</th>
<th>Complete Building Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard connection</td>
<td>Standard wire connection to receptacle</td>
<td>153 days</td>
<td>$903,087</td>
</tr>
<tr>
<td>Quickwire</td>
<td>Clamp-style installation procedure at power receptacle</td>
<td>152 days (-0.7%)</td>
<td>$900,370 (-0.3%)</td>
</tr>
</tbody>
</table>

Although almost negligible at both the individual system level and the overall building system level, the alternative still leads to a 0.3% reduction in the overall building cost and thus remains one that, though very small, we should consider going forward.

The material costs for the Quickwire push-in have been determined at 8% above standard receptacle outlet cost of $1.86 (R.S. Means). With 1,015 electrical outlets in the prototype building, the material cost of the alternative comes to $2,040.40. The 8% additional material cost of the alternative comes to $163.24, which means that the net impact of the Quick-wire innovation alternative on the electrical system represents a
Chapter 4: Results

savings $(S)$ of $2,553.76$. Since savings are positive $(S>0)$, then the alternative makes
sense to execute.

<table>
<thead>
<tr>
<th>Number of Electrical Outlets</th>
<th>Cost per Standard Outlet</th>
<th>Total Material Cost</th>
<th>Material Cost Difference</th>
<th>Labor Cost Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,015</td>
<td>$1.86 unit</td>
<td>$2,040.40</td>
<td>$163.24</td>
<td>-$2,717</td>
</tr>
</tbody>
</table>

Even though the innovation accounts for limited impact in the installation process, it represents but one of various small innovations that together can create significant impact not only in one building, but especially in a series of derivative buildings.
4.2.6 Rigid Conduit versus Electrical Metal Tubing for homeruns

Next, an alternative to the typical material for homeruns (the horizontal connections between central equipment in systems and the end connection to the built space), rigid conduit, was examined. The baseline electrical wiring material is a rigid metal conduit with pulled wiring for homeruns and flexible plastic coating branch wiring for fixtures. Electrical Metallic Tubing has proven to be more flexible with pre-installed wiring, with significant ease of installation. In addition, material costs are only slightly higher.

<table>
<thead>
<tr>
<th>Description</th>
<th>Structural Unit Sep.</th>
<th>Interior Partition</th>
<th>Exterior Enclosure</th>
<th>Other Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMT Test</td>
<td>Column Trees</td>
<td>CMU</td>
<td>Drywall</td>
<td>Precast</td>
</tr>
</tbody>
</table>

The results are as follows:

**Table 22: Electrical System Installation Duration and Labor Cost**

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Electrical Erection Duration</th>
<th>Electrical Erection Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Conduit for homeruns</td>
<td>Standard residential electrical system, using rigid conduit with pulled wiring</td>
<td>106 days</td>
<td>190,929</td>
</tr>
<tr>
<td>EMT for homeruns</td>
<td>Electric Metallic Tubing (EMT) for homeruns wiring</td>
<td>89 days (-16%)</td>
<td>140,932 (-27%)</td>
</tr>
</tbody>
</table>

The results of our simulation for the whole building was as follows:

**Table 23: Electrical System Impact on Overall Building Duration and Labor Cost**

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Complete Building Duration</th>
<th>Complete Building Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Conduit for homeruns</td>
<td>Standard residential electrical system, using rigid conduit with pulled wiring</td>
<td>156 days</td>
<td>$1,069,592</td>
</tr>
<tr>
<td>EMT for homeruns</td>
<td>Electric Metallic Tubing (EMT) for homeruns wiring</td>
<td>140 days (-11%)</td>
<td>$998,350 (-7%)</td>
</tr>
</tbody>
</table>

Uses of EMT resulted in both a 27% reduction in installation costs of the electrical system, and a 16% reduction in electrical system installation time. In addition, the overall labor cost of the building came down by as much as 7% with the use of EMT. In terms of material costs, Electrical Metal Tubing is generally about 39% less expensive per linear foot than rigid galvanized steel conduit (per R.S. Means, and two hardware
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store quotes). Therefore, the specific material costs increase the advantages and add to the decision on whether to adopt this alternative or not.

Once again, this alternative is worth pursuing further as we consider the various systems that will optimize our platform-design approach to construction of the prototype building.

4.2.7 Pre-assembled Plumbing Trees with Pre-cut Piping

In searching for ways of adding another several percentage points to the cost and/or duration savings of the building platform, the use of pre-assembled plumbing trees have been considered. A source of efficiency can be thought to be found in having a dedicated plumber on a section of the site pre-cut all pipes and assemble them into plumbing trees. These trees can then be hoisted into place on site and welded. Once again, all other systems remain as assumed in the baseline model.

<table>
<thead>
<tr>
<th>Description</th>
<th>Structural Steel Frame</th>
<th>Unit Sep. Walls</th>
<th>Interior Partition</th>
<th>Exterior Enclosure</th>
<th>Other Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-assembled plumbing trees</td>
<td>Column Trees</td>
<td>CMU</td>
<td>Drywall</td>
<td>Precast (interior drywall)</td>
<td>Pre-assembled plumbing trees</td>
</tr>
</tbody>
</table>

The plumbing trees alternative leads to a 3% savings in the costs of installation of the plumbing system. There is no perceived change in installation duration since plumbing installation activities are not in the critical path to building completion.

Table 24: Plumbing System Installation Costs and Duration

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Plumbing Installation Duration</th>
<th>Plumbing Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-site standard</td>
<td>On-site standard installation of tubing</td>
<td>98 days</td>
<td>180,546</td>
</tr>
<tr>
<td>Trees</td>
<td>Pre-assembled plumbing trees with pre-cut piping</td>
<td>98 days (0%)</td>
<td>175,579 (-3%)</td>
</tr>
</tbody>
</table>
When considering the cost of the building as a whole, the plumbing trees seem to extend the cost of the building perhaps because of additional labor required to prepare pre-cut piping, as well as hoisting it to the site already assembled. Nevertheless, this is an alternative that will be considered during the interdependency analysis and whose interface will be closely watched. It is only by doing so that the true interoperability of all systems can be tested.

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Complete Building Duration</th>
<th>Complete Building Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-site standard</td>
<td>On-site standard installation of tubing</td>
<td>153 days</td>
<td>$998,350</td>
</tr>
<tr>
<td>Trees</td>
<td>Pre-assembled plumbing trees with pre-cut piping</td>
<td>153 days (0%)</td>
<td>$1,000,919 (+1%)</td>
</tr>
</tbody>
</table>

The material costs are not relevant to the decision of employing this alternative since the amount of materials required is the same in both instances. The additional costs of pre-assembly can be considered part of the labor costs of the system and building.

Because the impact to the costs of the overall building is positive (increase in costs) while the impact on the plumbing system is significantly more negative (3% reduction or three times the impact on the overall building), we will explore this option as a possibility for the best case scenario simulation which we will perform next.
Chapter 4: Results

4.2.8 Summary of Alternatives Analysis

By now, we have selected those alternatives that we intend to consider for a best case scenario. The decision map now stands in the following manner:

<table>
<thead>
<tr>
<th>Steel</th>
<th>Exterior</th>
<th>Interior</th>
<th>Electrical</th>
<th>Plumbing</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-place welding</td>
<td>Large Pre-cast Panels</td>
<td>STD Walls, CMU Party</td>
<td>Rigid Conduit/EMT</td>
<td>Standard</td>
</tr>
<tr>
<td>Column Trees</td>
<td>CMU Wall</td>
<td>Spray-on, Spray-on</td>
<td>Quickwire</td>
<td>Trees</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wall Panel, CMU</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMPLETED</td>
<td>COMPLETED</td>
<td>COMPLETED</td>
<td>COMPLETED</td>
<td>COMPLETED</td>
</tr>
</tbody>
</table>

The alternatives that result in the higher cost and time savings, accompanied by advantages inherent in technical advances and organizational competencies, have been selected as subsystems that will be further tested to determine interdependencies between subsystems. Again, the goal of the composite design approach is to select a group of subsystems that are optimal by themselves will not always optimize the overall system. Thus, an interdependency analysis will evaluate these interfaces to ensure that the overall system is optimized and maximum benefits of a platform approach can be extracted.

4.3 Interdependency Analysis

In order to evaluate the best case scenario, the selected systems will be those with the most probable impact according to initial results. Again, the selection is not only based on the impact of the alternative on the cost and duration of both the system installation and the total building construction. It shall take note of the relative cost and time tradeoffs inherent to each alternative as well as the possibility of further cost and duration efficiencies based on the rollout of a series of derivative applications.
Chapter 4: Results

After careful analysis of all alternatives, the following are those that constitute the Best Case Scenario:

<table>
<thead>
<tr>
<th>Description</th>
<th>$\Delta$ on System Installation Duration</th>
<th>$\Delta$ on System Installation Cost</th>
<th>$\Delta$ on Building Construction Duration</th>
<th>$\Delta$ on Building Construction Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column Tree Connections with Precast Concrete Panels</td>
<td>-13%</td>
<td>-50%</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>CMU Exterior Enclosure</td>
<td>+24%</td>
<td>+1300%</td>
<td>-1%</td>
<td>+171%</td>
</tr>
<tr>
<td>Prefabricated foam panels Unit Separation Walls</td>
<td>-2%</td>
<td>0%</td>
<td>-1%</td>
<td>-1%</td>
</tr>
<tr>
<td>Prefabricated foam panels for all interior partitions</td>
<td>-27%</td>
<td>+107%</td>
<td>-13%</td>
<td>+8%</td>
</tr>
<tr>
<td>Pre-assembled Wall Panels for Interior Partitions</td>
<td>-29%</td>
<td>-82%</td>
<td>-15%</td>
<td>-3%</td>
</tr>
<tr>
<td>Quick-wire Push-In</td>
<td>-1%</td>
<td>-2%</td>
<td>-0.7%</td>
<td>-0.3%</td>
</tr>
<tr>
<td>Electrical Metallic Tubing</td>
<td>-16%</td>
<td>-27%</td>
<td>-11%</td>
<td>-7%</td>
</tr>
<tr>
<td>Pre-assembled plumbing trees</td>
<td>0%</td>
<td>-3%</td>
<td>0%</td>
<td>+1%</td>
</tr>
</tbody>
</table>

After careful analysis of all alternatives, the following are those that constitute the Best Case Scenario:

<table>
<thead>
<tr>
<th>Description</th>
<th>Structural Steel Frame</th>
<th>Exterior Enclosure</th>
<th>Unit Sep. Walls</th>
<th>Interior Partition</th>
<th>Other Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Column Trees</td>
<td>Pre-cast</td>
<td>Spray-on</td>
<td>Spray-on</td>
<td>Quickwire, EMT, Plumbing Trees</td>
</tr>
<tr>
<td>Best Case</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The final results are as follows:

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Complete Building Duration</th>
<th>Complete Building Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Baseline model with Column Trees and Precast Concrete Exterior Panels, CMU Unit Sep. Walls, Drywall Interior</td>
<td>140 days</td>
<td>$998,350</td>
</tr>
<tr>
<td>Best Case</td>
<td>Best Case model with Column Trees with Pre-cast Concrete, Spray-on Walls for all Interior Partitions, Quickwire and Plumbing Trees</td>
<td>139 days (0%)</td>
<td>$908,982 (-10%)</td>
</tr>
</tbody>
</table>
Chapter 4: Results

An overall labor cost savings of 10%, or $89,368, has been achieved on a single prototype building based on the careful identification of all possible alternatives, including innovations, analysis of impact on a particular subsystem and then its impact on a building system as a whole. Recent research indicates that the platform-based approach can increase construction savings throughout a series of building to up to 20%\(^3\). Thus, the base case scenario seems to be, at least initially, a reliable and verifiable measure of the impact of a composite design approach to the construction of a building platform architecture.

One of the most interesting dynamics in this case is that the best case scenario does not result in complete building construction duration decreases that are as high as the sum of the individual reductions in the overall building construction duration based on each optimal subsystem. For example, duration savings resulting from the use of prefabricated spray-on panels, Quickwire push-in receptacle, EMT and plumbing trees would add up to a 25% reduction in overall building construction duration. However, in the best case scenario, the duration is reduced by only one day (less than 1%). This hints at the specific interdependencies of the particular grouping of subsystems applied to the best case scenario vis-à-vis each system taken by itself.

In addition, the sum of all savings or increases in costs resulting from each aforementioned preferred alternative adds up to 0% (+8%-1%-7%). However, when a simulation is run for the overall building, this same grouping of alternatives leads to a 10% labor cost savings. Again, the results are based on the particular manner in which subsystems interact with one another and cause or reduce bottlenecks in the manufacturing process.

We must note that this 10% labor savings figure is in fact understated due to logistical restrictions relating to already-made decisions which required that the baseline used in this dissertation already include two alternatives: a structural steel system using column trees, and EMT instead of rigid conduit for electrical wiring. Going forward, the

\(^3\) Hoare and Seiler, 2001.
best case scenario will be compared to original baseline scenario which includes in-place welding (instead of Column Trees) and rigid conduit.

In order to further examine the interdependencies between systems, we will now consider two additional groupings of subsystems. First, a simulation will be run incorporating the best of the prototype’s structure and exterior systems, and the worst of the building’s interior divisions and services. Consequently, the worst of the structure and exterior will be married with the best option from the Interior and Services systems. These simulation results will enable us to qualify and quantify the interfaces between several systems and the way they work together, in addition to their impact on the overall building cost when evaluated hand in hand.

4.3.1 Best of Structure and Exterior, Worst from Interior and Services

<table>
<thead>
<tr>
<th>Description</th>
<th>Structural Steel Frame</th>
<th>Unit Sep. Walls</th>
<th>Interior Partition</th>
<th>Exterior Enclosure</th>
<th>Other Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best of Structure and Exterior, Worst from Interior and Services</td>
<td>Column Trees</td>
<td>CMU</td>
<td>Drywall</td>
<td>Pre-cast</td>
<td>-</td>
</tr>
</tbody>
</table>

The most important and costly systems (as a proportion of the overall building construction cost) of our prototype building are the structure and exterior enclosure systems. The purpose of this simulation and interdependability analysis is to assess the impact of these two major systems on the other systems of the building. By reaping benefits of standardization and prefabrication of such systems, a building platform and derivative products can achieve better cost advantages overall than by concentrating on other, less impacting systems.

We now consider the impact of a combination of systems together on the whole building. The results are the following:
Table 28: Best from Structure and Exterior, Worst from Interior and Services

<table>
<thead>
<tr>
<th>Alternative Name</th>
<th>Description</th>
<th>Complete Building Duration</th>
<th>Complete Building Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Baseline model with Column Trees, CMU Unit Sep. Walls, Drywall Interior and Precast Concrete Exterior Panels</td>
<td>140 days</td>
<td>$998,350</td>
</tr>
<tr>
<td>Sensitive Model</td>
<td>Column Trees with CMU Separation Walls, Drywall Partitions, and Pre-cast Exterior Panels</td>
<td>148 days (+6%) (-9%)</td>
<td>$914,843 (-9%)</td>
</tr>
</tbody>
</table>

The optimal grouping of pre-cast exterior panel system as well as the pre-welded column trees system leads to a combined cost savings of 9%, almost identical to our best case scenario.

4.3.2 Worst of Structure and Exterior, Best of Interior and Services

At the same time, a sensitivity analysis was executed on the combination of the two most impacting systems that performed the worst in our analysis, combined with the interior systems, where it was harder to force efficiencies. The system assumptions are the following:

<table>
<thead>
<tr>
<th>Description</th>
<th>Structural Steel Frame</th>
<th>Unit Sep. Walls</th>
<th>Interior Partition</th>
<th>Exterior Enclosure</th>
<th>Other Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst of Structure and Exterior, Best from Interior and Services</td>
<td>In-place welding</td>
<td>Spray-on</td>
<td>Spray-on</td>
<td>CMU Wall</td>
<td>Plumbing Trees &amp; Quickwire Pushin</td>
</tr>
</tbody>
</table>

Resulting costs of labor for the prototype building are as follows:
In this case, the number of masons has been significantly increased so that a realistic schedule is assessed. Here we find that the worst case scenarios for structural and exterior enclosure systems are somewhat mitigated by the best case scenarios from interior and service systems. In other words, we do not see the outrageous 171% increase in costs of a CMU exterior enclosure vis-à-vis the baseline model. However, the choice of alternatives for both exterior and structure systems, which represent a larger percentage of overall construction costs, still has an immense impact on the platform design approach to design and construction of buildings.

In this instance, the significant increase in masons needed to finish the exterior enclosure does not affect the duration of building construction because this resource is allowed to finish the exterior of the building without causing bottlenecks in other systems. In addition, the labor costs are higher, representing the increased number of laborers needed to still finish the job at the same time as the baseline model.

We could first quantify the value of knowing the impact of the various alternatives by considering the worst case scenarios and the best case scenarios. For comparing the worst case scenario, we will utilize the “Worst from Structure and Exterior, Best from Interior and Services” simulation results, which is the one nearest to what a worst case scenario would actually be.
Chapter 4: Results

**WORST CASE SCENARIO BUILDING LABOR COST = $1,390,500.00**

<table>
<thead>
<tr>
<th>Description</th>
<th>Structural Steel Frame</th>
<th>Unit Sep. Walls</th>
<th>Interior Partition</th>
<th>Exterior Enclosure</th>
<th>Other Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst Case Scenario</td>
<td>In-place welding</td>
<td>Spray-on</td>
<td>Spray-on</td>
<td>CMU with plaster finish (interior drywall)</td>
<td>Plumbing Trees, Quickwire, EMT</td>
</tr>
<tr>
<td></td>
<td>structural steel frame</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**BEST CASE SCENARIO BUILDING LABOR COST = $908,902.00**

<table>
<thead>
<tr>
<th>Description</th>
<th>Structural Steel Frame</th>
<th>Unit Sep. Walls</th>
<th>Interior Partition</th>
<th>Exterior Enclosure</th>
<th>Other Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Case Scenario</td>
<td>Column Trees</td>
<td>Spray-on</td>
<td>Spray-on</td>
<td>Precast</td>
<td>EMT, Quickwire, Plumbing Trees</td>
</tr>
</tbody>
</table>

**LABOR COST DIFFERENCE BETWEEN BEST AND WORST CASE SCENARIOS: $481,598.00**

The difference in labor costs between our best and worst case scenarios is $481,598, or 35% of the “worst case scenario”. This figure proves that an in-depth analysis of alternatives for a prototype building could lead to significant savings in the design and construction process.

The materials cost increase is minimal in this case, as discussed throughout the results section. The added cost of the column trees and precast panels alternatives have little impact on the magnitude of the cost difference.

Now let us assume that 10 of such buildings will be built one after the other as part of a master-planned community project. The impact increases at least ten-fold in the following manner:

Original (baseline) construction cost of prototype building times 10: $13,905,000
Cost of construction of best case scenario times 10: $9,089,820
Minimum savings (in $): $4,815,180
We refer to the figure as *minimum* savings because it does not account for additional potential savings that are bound to occur from such related platform advantages as: volume procurement, productivity gains, quicker reaction to potential on-site problems, and standardization of design and process optimization.

We must also note that only ten alternatives were identified and analyzed in this research. Per the comprehensive list of all alternatives considered for such a prototype building in Chapter 3: Methodology, many more could have been modeled, resource and time-permitting, each leading to increased savings, especially when considered in a series of buildings.

### 4.4 Summary

In this Chapter, we have carefully examined the results of various alternatives on the cost and duration of construction of a particular prototype building that will constitute the first of a series of buildings within a platform. After outlining the composite design approach and process in earlier chapters, we applied this approach to the design of the first building in a residential platform series. The concepts of system and process optimization were addressed in order to arrive at the best possible scenario of alternatives, which led to an overall 10% savings in the cost of labor, with the cost of materials taken into consideration.

The next chapter will seek to derive some general conclusions about the topic from the research and analysis conducted herein. In addition, we will place these results in the context of a larger platform with the aim of taking the resulting data and using it as a basis for projecting further cost savings from a derivative series rollout.
5.1 Relevance of Concept and Results

Until recently, the concept of platform design and development had only been applied to the manufacturing of mainstream consumer products, including automobiles, electronics, power tools, and software. Acknowledging that the construction industry is plagued with inefficiencies all throughout the value chain encourages us to seek better and more efficient ways of managing the process. This exposition has sought to propose the platform manufacturing alternative as a means of eliminating some of those inefficiencies that afflict the construction industry.

A “product platform” is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced to target various market segments. In construction, a platform refers to a limited set of common building systems and processes that are shared amongst projects with similar or different uses and whose commonality leads to decreased costs and lead times. The application of this concept to the construction industry is interesting because product design and development using a platform approach can lead to significant benefits for all parties involved:

<table>
<thead>
<tr>
<th>Advantages of a Platform Approach to Design and Development in Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Greater ability to tailor real estate products to the needs of various market segments</td>
</tr>
<tr>
<td>2. Reduction in development costs and time</td>
</tr>
<tr>
<td>3. Reduction in manufacturing costs</td>
</tr>
<tr>
<td>4. Reduction in production investment</td>
</tr>
<tr>
<td>5. Simplification of systemic complexity</td>
</tr>
<tr>
<td>6. Lower risks associated with construction</td>
</tr>
</tbody>
</table>

These benefits have been proven in the case of other products with complex subsystems and numerous parts. All indications in our research led us to conclude that the concept

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Chapter 5: Conclusions

ought to be explored in more depth in terms of its potential application to the construction industry.

Thus, we applied the concept to the design and development of a prototype building that would serve as the first in a series of derivative buildings comprising a platform. Results indicated that the application of such a concept to the construction of a new building could lead to an initial 10% savings in labor and material costs, allowing us to conclude that as an approach, the concept clearly has demonstrable benefits.

Even if the specific innovations identified in this thesis differed, the relevance of the research lies in the viability of the approach as a source of efficiencies in the construction process. In addition, this 10% cost savings originated by our methodology focused only on five primary systems and about 10 alternatives overall. Clearly, expanding the number of alternatives and systems could yield additional potential benefits.

5.2 Progress Review

Throughout this exposition, we have attempted to understand if and how the concept of platform manufacturing in consumer products can be applied to the building construction industry. In order to do so, we first discussed the possible advantages that the use of a platform approach can provide to contractors and builders of real estate. In this analysis, we chose to focus on those advantages that could be quantified, and thus assessed the ability of a platform approach to reduce manufacturing costs and duration. The other perceived advantages would prove interesting topics for further research.

Furthermore, we traced the development of the platform concept as it came into being within the automotive industry and made its way into consumer products. Our review included numerous examples of how a platform approach created cost savings, lower risks, more predictability and better products for various companies and industries.
Finally, we applied the concepts of a composite design, which is the process of designing a platform of products, to identify significant cost and duration advantages in a prototype building. In summary, we proved that employing the core elements of a composite design approach to design and construction of buildings can lead to at least a 10% cost savings from the get go, with increased savings as common costs are spread throughout a series of derivative buildings.

5.3 Other Factors Influencing Cost and Duration Advantages in Platforming

We must note that the cost and duration savings resulting from all simulations do not include increased potential savings that are bound to occur per building in each of a series of derivative products from the following platform related advantages:

1. Volume procurement savings;
2. Productivity gains by labor force through time;
3. Quicker reaction to potential on-site problems;
4. Design standardization and process optimization.

Because fixed costs per unit tend to decrease with larger volumes, savings in both cost and time can be magnified by spreading these costs out over a series of buildings. These factors mean that the gap in costs between a typical system and a more efficient alternative that could also be slightly more expensive (in material and labor costs) can be closed further through standardization of the latter in a platform.
Chapter 5: Conclusions

5.4 Summary of Results

We can now identify three main questions that ought to be asked and answered regarding the goals of this research:

**Can a platform-based approach be applied to large construction projects?**
Yes. We have proved that the process of composite design can be applied to construction of occupied buildings and result in significant cost and duration advantages.

**If it possible to identify cost and time benefits for systems as well as for a whole building using the methodology employed in this thesis?**
Yes. We have identified at least a 10% cost savings in labor costs for our prototype building using a methodology which focused on five primary systems and 10 alternatives overall. Clearly, expanding the number of alternatives and systems could yield additional potential benefits.

**Can interdependency between systems be measured utilizing this methodology?**
Yes. We have proven that the impact that an alternative can have on the cost and duration of a particular system installation can be different from the impact it may have on the overall building cost and duration. This leads us to conclude that the software tool employed in this research, accompanied by the methodology, is effective in measuring the degree of interdependency between systems or the impact one choice may have on the overall system.

We can then conclude, then, that, even if material costs may be higher, savings in building construction time and duration may result in a faster, better and cheaper derivative product, at least for a residential building of this type with the particular innovations assessed in this dissertation.
Chapter 5: Conclusions

5.5 Further Application of Concept to Other Uses

The concept of platform manufacturing of buildings can be applied to a considerable array of markets in construction and real estate. In this study, we have addressed one of the most immediate applications of platforming: the housing sector. The concept can be applied to the development of new single-family homes and multi-family mid- and high- rises, for all income levels.

Now that residential building efficiencies have been identified using this approach, it must be further considered for application to commercial, industrial and retail usage types. All indications are that the approach can work, but the results of this thesis have not proven that it can for those usage types.

In the commercial arena, the platform concept could be replicated in both office spaces as well as other uses such as hotels and hospitals, where repetitive layouts and space distributions are prevalent. For example, from a developer’s or constructor’s perspective, a standard office building could be designed by a renowned architect, and offered to private companies for sale. The product could have certain options and finishes that could make it unique, including the outside shell. However, since most of the interiors would be standardized, the building would not be custom-built and designed, thus leading to significant time and cost savings, assuming the office building in question is one of a series of building products. The same can be applied to hotels such as small Marriott Courtyards, Best Westerns and the like, which are small two to three floor structures with medium-end finishes. In all of these cases, clients can select from a “kit of parts” available to construct such buildings. Users might have to tradeoff slight uniqueness and differentiation factors for each offering. However, there are many organizations out there that are willing to sacrifice some uniqueness for a large gain in cost savings. These firms realize they could occupy or own a larger building, designed by a top-notch architect, at a 20% savings vis-à-vis a custom-built one. Herein lies the value of a platform approach to users of real estate space.
Chapter 5: Conclusions

The government sector could also be a great benefactor of this manufacturing concept. Schools, government buildings and public infrastructure projects could gain efficiencies through some degree of standardization in building design and systems, in addition to product design and development using a platform-based approach.

Finally, many large companies have started to utilize a platform approach in the development of large capital projects – power stations, chemical plants, oil rigs, or amusement parks. The companies involved treat a series of projects as a portfolio, not as a series of individual schemes. The resulting shortened lead times, reduced inventories, and lower engineering, operating, and maintenance expenses are cutting the cost of the projects by as much as 30 percent\(^2\), representing, in some instances, hundreds of millions of dollars. Furthermore, the uniform interfaces presented to operators promote safety by minimizing the risk of confusion.

As one can see, there is large scope of potential sectors in which a platform approach can deliver sizeable advantages. It will be interesting to follow the development of this manufacturing practice in the coming decade.

5.6 Platform-based Approach as Competitive Advantage

The results of this research represents a key tool to compete successfully in an increasingly competitive and fragmented industry, with players that end up with diminutive margins that hover in the 1 to 3 basis points, if these players break even at all. Perhaps today more than ever before, delivering a better product faster and cheaper is a key competency for competitors in the real estate and construction industries. Application of a platform approach could represent a sound competitive strategy for constructors and developers that seek to focus on a segment and exploit opportunities within it.

Because the industry has proved that innovation is more challenged using a bottoms-up approach, then the real gains ought to be tried by implementing strategic management at the top. Players that focus on segments and seek more efficient ways to execute, through implementation of concepts such as the platform-based approach discussed in this thesis, could create the most value for themselves, end users and the whole value chain, creating a long-term sustainable organization for years to come.
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