Environmental Performance of Modular Fabrication:

Calculating the Carbon Footprint of Energy Used in the

Construction of a Modular Home

by

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ABSTRACT

The construction industry is becoming more aware of its impact on the environment. It has become more sensitive to how it operates and how it can reduce the carbon footprint of the construction process. This research identifies the source of and quantities of the carbon emissions created by an operating modular home fabrication plant in producing, transporting and installing modular structures.

This study demonstrates how to measure the carbon footprint created in the production of a modular home. It quantifies and reports the results on a home, on a single module and on a per square foot basis.

The primary conclusions of this study are: a) electricity was found to be the largest energy source used in this fabrication process; b) the modular fabrication process consumes a significant amount of electrical energy per month; c) production volume has a bearing on the carbon footprint of each home since the carbon footprint for each period is allocated to every home produced in that period; and d) transportation of fabricated modules and set-up add to the carbon footprint.

Further, a carbon calculator was produced and is included with the study. The tool calculates the impact of energy consumption on the carbon footprint of a modular factory or a modular home. It may be expanded to other process driven fabrication entities.

This research is valuable to developers and builders who wish to measure the carbon impact of a modular new home delivery system. The study also

provides a methodology for modular home fabricators to measure the carbon footprint of their factories and factory production.

I thank my mom and family for always loving me.

In memory of my father who was always the real builder in our family.

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Introduction

1.1 Overview of the Study

"Production building in the residential sector is often described as the portion of the construction industry that is most like the manufacturing sector" (Bashford, 2003, p. 330).

In the past 50 years, the construction industry has experimented with industrialization processes to advance construction methods. Industrialization processes, also known as pre-fabrication or modularization processes have been used to improve site-built construction and are often used as alternatives to it. Significant among these processes has been the use of pre-fabricated components such as trusses, roof systems, panelized wall systems, and modules making up entire structures, primarily homes.

This research shows the significant impact that industrialization has had on the environmental performance of home construction with focus upon the modular home segment of industrialized home delivery systems. The research defines modularization and, specifically, modular home construction. It describes the factory home fabricating system, reports on the advantages and disadvantages of residential modularization, and specifically describes the carbon footprint associated with modular home fabrication.

In addition, the research provides a methodology for computing the carbon footprint of modular home fabrication. It goes on to measure the carbon footprint of factory production output as measured by home, module, and square foot of fabrication.

Together with modularization, this carbon footprint calculation methodology could be applicable to the majority of industrialized home delivery systems in whole or in part. The methodology that is presented in this study can be adapted and applied to other industrial processes, such as manufactured housing fabricators (HUD Code Homes, formerly called mobile homes), wall panelizers, and component fabricators. Lessons learned from this study may be transferred to other process fabrication systems.

1.2 The Industrial Process, Descriptions, and Benefits

The following is a definition and description of modularization that merits being directly quoted.

> In the fabrication built environment, many words are used interchangeably to describe closely related systems. The industry defines prework as a collective strategy that includes prefabrication, pre-assembly and modularization in industrialized fabrication of buildings. These strategies are employed because they have the potential to significantly reduce project duration, improve productivity, reduce the need for labor and have a positive impact on supply chain problems. Modularization was found to offer substantial opportunity to improve project performance and overcome internal and external project challenges such as adverse site and local area conditions, lack of skilled labor and demanding schedule. (Construction Industry Institute Modularization Task Force [CII], 1992)

Construction has a unique language of its own with specific nomenclature for particular types of buildings. The following describes the particular types of construction.

Traditionally, homes are constructed on site after blueprints are produced and a builder is contracted to build out the project. This method is commonly known as on-site or “stick-built” construction. This method of home construction has been the accepted method of residential construction since the late nineteenth century and represents a significant portion of the housing market today (Zenga & Javor, 2008).

Modular buildings are fabricated, that is, built in a factory in conformance with the same building codes that regulate on-site construction. A simple way to describe modular buildings, including modular homes, is that these are engineered, pre-fabricated buildings that are manufactured in a remote factory location, delivered in sections to their intended location, installed on their foundation using cranes or trucks (R. Lyon, personal communication, April 19, 2010).While modular homes are being manufactured, on-site construction is taking place concurrently with the foundation and utility hookups. Modular homes are then finished on site after they have been delivered and installed onto foundations (Penn Lyon Homes Corporation, 2008).

The National Association of Home Builders (NAHB) also defines fabrication or modular building in a similar manner.

> A system of building construction where individual sections of the building are manufactured off site in factories then transported to the final building site. Minor finish work is completed and the building sections are connected to the ground and utilities.
> This building system is a highly engineered method of producing buildings or building components in an efficient and cost effective manner.
> The use of modular building systems is common in many different types of residential, multifamily, and commercial construction. A modular home is the culmination of one type of building system. Modular homes are constructed in segments or modules in a climate-controlled factory by skilled craftsmen using precise machinery and methods. When these modules come together on a building site and the final finishing touches are completed by a local builder, those modules become a home. Modular buildings range in size from single sections to hundred unit complexes and can utilize temporary or permanent foundation systems. (National Association of Home Builders, 2010).

> Modular homes are the ultimate industrialized prefabricated building system since constructing nearly 90% of a home is done offsite in a fabrication plant. A highly customizable home can be built in a controlled factory environment while the building site is being prepared to receive it. Modular homes are normally constructed to the same building codes as site built homes. New modular homes are inspected at the factory during each phase of construction and an independent third party inspection agency approves each home before it is delivered to the home site (R. Lyon, personal communication, May 28, 2009).

The following offers a summary of the modular home construction process.

> Today’s modular systems are models of efficiency and quality. The building process begins at the design phase, usually using state of the art Computer Aided Design (CAD) systems to create the floor plan. In-house engineering departments eliminate the need for costly outside engineering firms. Once plans are created and the plans are approved by all parties, plans are processed for a building permit application. Once the building is designed and permit is drawn, the building process begins. Quality assurance is a constant process from every area of the factory that ensures quality construction. Modular home fabricators observe the same building codes and standards of site-built homes, including material and care for detail. Efficiency begins with modern factory assembly line techniques. Work is normally not delayed due to weather, subcontractor no-shows, or missing materials. Once the factory constructs the modules, they are ready to be delivered and set. Trucks deliver modules to the site where they are lifted by a crane and placed onto the permanent foundation. Experienced set crews assemble the modules together on the foundation. A local builder will do final finish work before people occupy the home. (National Association of Home Builders, 2010)

Some differences exist between manufactured homes and modular homes and a differentiation needs to be made.. Manufactured homes, sometimes referred to as Housing and Urban Development (HUD) code homes or mobile homes, are distinctly different from modular homes. Although manufactured homes are also constructed in a factory, they are usually fabricated with an attached permanent steel framework and comply only with the HUD Building Code. Modular homes, on the other hand, comply with the residential building codes used for site-built homes, and they do not usually have a steel framework attached. Modular homes must be set on a permanent foundation, much like a site-built home (R.Lyon, personal communication, May 27, 2009) .

Benefits of the modular process:

There are many benefits derived from the modular fabrication process (Haas & Fagerlund, 2002).

A partial list of modular fabrication benefits includes the following.

- Speed of construction;
- Highly engineered fabrication;
- Construction in a climate-controlled environment;
- Efficient building processes and material usage;
- Energy-efficient construction;
- In-plant inspections;
- Consistent quality;
- Design flexibility;
- Construction to meet or exceed state building codes;
- Reduced need for subcontractors;
- Concurrent construction of modules with foundation and on-site utilities.

1.3 The Benefit of Fast Construction

One of the most popular benefits of modular construction is quick turnaround between groundbreaking and occupancy. On average, a home consisting of four modules can be completed in the factory in about a week (R. Lyon, personal communication, April 19, 2010).

Once the modules are set on the foundation at the home site, final finish work can be completed by the local builder in less than one month, depending on the size and scope of the project (Penn Lyon Homes Corporation, 2008, Bobbit's Manufactured Structures Group, 2008).

Because of the fabrication process, the modular industry has enabled the producer and consumer to gain better cost control, home energy efficiency, and construction schedule while maintaining a higher standard of quality (Zenga & Javor, 2008).

The duration of construction may substantially affect the final cost of a project. In commercial applications, quicker completion of buildings by using a manufacturing process implies a speedier market entry for products from the completed building. Similarly, a shorter construction schedule may reduce the field mobilization time and reduce the construction financing cost, thereby improving owner cash flows. Also, a project completed early will begin to generate new income for the owner (Haas & Fagerlund, 2002). Similar benefits can be found for commercial residential structures.

1.4 Industrialization's Impact on Home Delivery

Modular homes represent about 5%-7% of new home construction in the U.S. today (R. Lyon, personal communication, May 13, 2010).

A separate manufacturing process used in residential construction is called panelization. This consists of fabricating panelized portions of the building and shipping them to the construction site for assembly. In this process, wall, ceiling and floor sections are fabricated into sizes convenient for transportation. The largest sections might be 10to12 feet wide by 40 to 50 feet long. This process is called panelization.

Modular and panelized homes, when viewed together, are engineered fabrication processes that represent a significant majority of home delivery systems. In January 2010, the *Automated Builder Magazine* presented the State of the Industry Report (p. 4). The following three charts, Figures 1through 3, summarize information presented in *Automated Builder Magazine* that show the relative distribution of the residential fabrication industry, including modular homes.

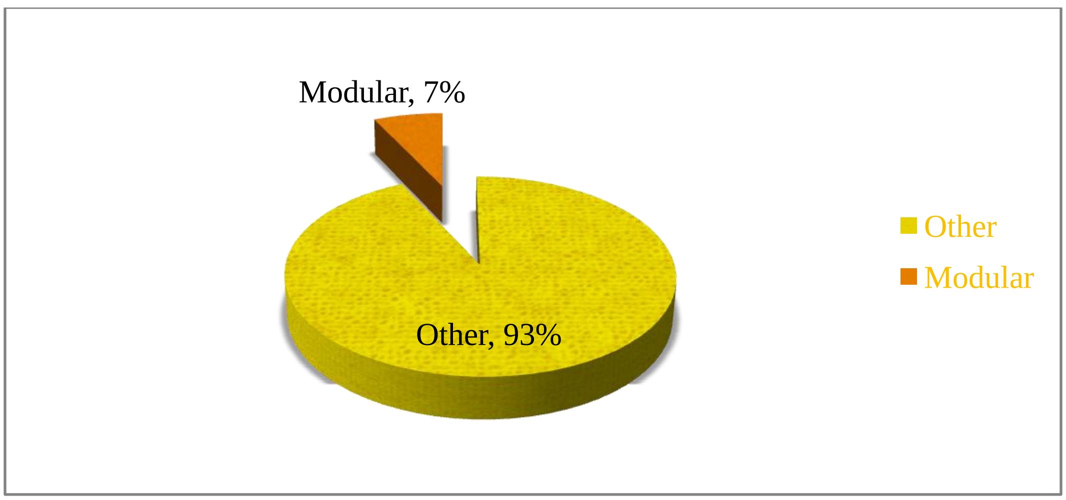

Figure 1. Traditional production builders versus modular.

A majority of production builders have begun to use panelized systems or fabricated wall panels as part of their home delivery system.

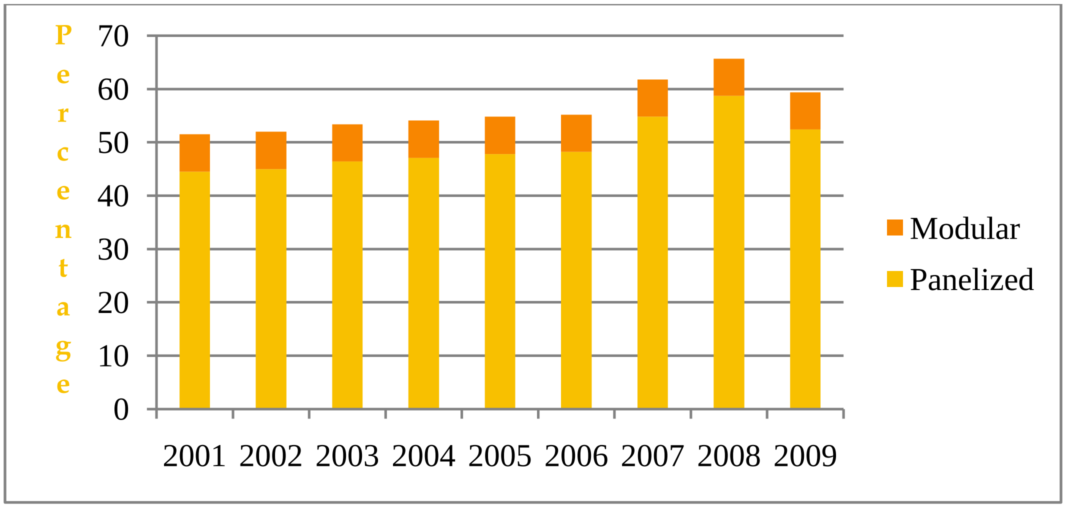

Figure 2. Panelized and modular production share of housing production.

The industrialized delivery methods of panelizing, where the home wall and roof (the shell), is built in a factory, shipped and installed on site (Carlson, 1995), and modularization are now commonly used methods for supplying new homes. Over the last 10 years, these two methods combined have significantly augmented the traditional on-site construction delivery method (Traynor, 2010).

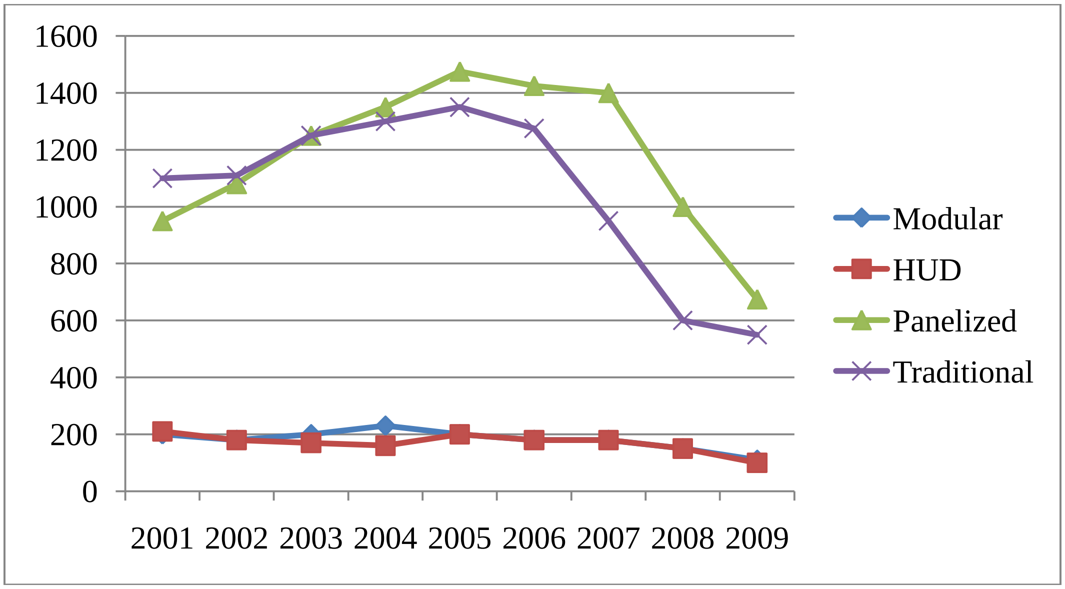

Figure 3. Unit production by housing segment

The modular home industry alone grew by 48% between 1992 and 2002 (Zenga & Javor, 2008). However, the modular industry has been declining since the recession of 2006, though at a lesser rate than the housing industry.

Summary facts about modular homes include the following:

- The building blocks of modular homes-individual modules-are housing components constructed in a controlled factory environment.
- Individual modules are up to 90% complete and shipped from the factory to the home site. All walls, flooring, ceilings, stairs, carpeting, and even wall finishes are completed in the factory before shipment.
- Once all building materials arrive at the factory, some manufacturers can assemble modules in a single day. Typically, a two-story, 2,100–square-foot home can be constructed in a factory in less than a week.
- Aside from any cost savings, modular homebuyers benefit from the short assembly time of their homes—reducing the amount of weather damage or home site vandalism. Over the life of the home, modular homes save money because they are incredibly efficient.
- One of every ten homes built in the northeast is a modular home. That region accounted for 29% of the nation's modular activity in 2001. The south Atlantic region was a close second with 26%, and the Great Lakes region ranked third, accounting for 24%.
- The most popular states for modular construction are North Carolina, Michigan, and New York. (National Association of Home Builders, 2010)

1.5 Sustainable Development in the Construction Industry

As the consumption of natural resources increases, the amount of greenhouse gas (GHG) released into the atmosphere also increases. In turn, this increase in GHG emissions worsens the problem of global warming by trapping sunlight heat radiation in the lower atmosphere. Global GHG emissions such as carbon dioxide, methane and nitrous oxide have grown since preindustrial times, with an increase of 70% between 1970 and 2004 due to human activities. The largest growth in GHG emissions during this period has come from energy production, transport, and industry, including construction (Intergovernmental Panel on Climate Change [IPCC], 2007).

The following two sentences traditionally define sustainable development.

> Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable development is the development effort that addresses the social needs and minimizes environmental impact. (RSMeans, 2006)

The application of sustainability principles in the construction industry is called sustainable construction. Sustainable construction can also be defined as the creation of a healthy built environment using resource-efficient and ecologically-based principles (Palaniappan, 2009).

Buildings make up 40% of total U.S. energy consumption, including two-thirds of the country's electricity. They are responsible for 40% of all material flows and produce 15% of the waste in landfills. Large scale improvements in resource productivity in buildings would have a significant reduction on the consumption of natural resources and reduce energy cost and pollution byproducts of the resource production (RSMeans, 2006). Other sources report different figures for energy consumption and waste; however each source and each statistic makes the point that these figures are significant.

The vertical construction of a production home consists of several phases and activities, such as: concreting, plumbing and modular, termite treatment, framing, HVAC, electrical, doors/windows, roofing, painting, drywall, siding/stucco, carpeting, countertops, and perimeter walls and fencing (Housing Research Institute [HRI], 2006).

The environmental performance of on-site construction processes is assessed using several parameters: transportation, on-site equipment use, and on-site electricity use (Guggemos & Horvath, 2005; Bilec et al., 2006).

1.6 Importance of Performing Study

Prefabrication and modularization are becoming popular methods employed in constructing buildings. As these methods grow in popularity, it is important to understand how prefabrication and modularization perform environmentally and how they compare to traditional methods. A number of researchers have approached the problem of defining the environmental impact of on-site construction processes using life-cycle assessment modeling (Bilec, et al 2010, Treloar et al, 2000). These modeling efforts have consistently shown that the major impacts associated with the construction process include on-site energy conumption, equipment utilization, transportation, and temporary materials. These studies have been useful in helping to understand the impacts of construction when compared to other impacts associated with the operating phase or end-of-life phase of buildings or other facilities. However, life-cycle assessment is complex, and the studies that have been completed are very general in nature. They rely on information found in national or international databases from sources that cover average or typical conditions across the US. This methodology does not allow comparison of specific data from specific projects or processes (H. Bashford, personal communication, November 5, 2010).

This research is complementary to that performed by Palaniappan (2009), who studied specific projects and processes related to on-site residential construction in Phoenix, Arizona. This research is complementary in that it studies specifics for similar construction processes performed in a factory rather than on-site. The combination of these two studies enables comparison of two different methods of accomplishing the same objective, constructing homes. The knowledge gained in this study will contribute to the acceptance of prefabrication as a viable and environmentally acceptable alternative and a sound construction practice.

1.7 Objective and Scope

The primary goal of this research is to understand the modular home industry and how it produces homes, as well as to study the carbon footprint of the modular residential construction process in a fabrication environment. This study is based upon observations and data collection made in a modular building fabrication plant at Selinsgrove, Pennsylvania. Other factories were also visited to confirm that the construction process of the Selinsgrove plant was representative of the industry.

The following list represents the specific objectives of the study.

- To identify the energy consumption of a modular plant by type of energy consumed and calculate the carbon emissions for a specific period of time;
- To ascertain the unit production volume produced during the study period and determine the per unit carbon emissions for that volume;
- To identify fuel consumption and distances driven for the modular delivery and installation phase of the set-up process to calculate the carbon emissions;
- To develop a methodology for calculating the carbon emissions of a residential production facility;
- To compare the carbon footprint of a modular home to a site-built home.

The scope of the study:

- The study focuses on energy consumption of the fabrication process, module deliveries, and installation phases.
- Employee travel from home to the fabrication facility is excluded.
- The predominance of modules produced by the Penn Lyon factory is 12 ft. wide modules that normally do not require escort vehicles. No caravan escort vehicle information was available or considered in this study.
- Material delivery to the fabrication facility, including indirect material transportation, is excluded.
- The study is limited to measuring carbon dioxide emissions. Other greenhouse gases are excluded.

- Embodied energy is not measured.
- Construction waste is not quantified.
- The study considered all major energy used for fabrication activities and delivery of modules and set up. Finish work on site was also addressed.

1.8 Dissertation Outline

This dissertation is organized into 7 chapters. The chapters that follow this chapter are:

Chapter 2 presents the literature reviewed for the background of this study.

Chapter 3 describes fabrication, the subject company, the processes and methods used, as well as how they were applied.

Chapter 4 presents an analysis of the carbon emissions in fabrication.

Chapter 5 presents an analysis of the carbon emissions in transportation and installation and presents the carbon calculator developed as part of the study.

Chapter 6 reviews the findings, and offers a comparison between site built and modular home construction systems.

Chapter 7 presents a discussion of the findings, formulates a conclusion, and offers suggestions for future studies.

Chapter 2: Literature Review

2.1 Introduction

The objective of this literature review was to understand the modular fabricating process and determine the viability of identifying and measuring the carbon emissions, or carbon footprint of modular home fabrication and construction. The literature review indicated that the appropriate process techniques for this study were modularization, modular homebuilding, prefabrication, and prework.

This chapter presents a review of the literature that relates to this research. This chapter reviews the following research topics.

- Literature that describes modular construction and its benefits;
- Literature that discusses the carbon emissions associated with construction;
- Relevant research papers on sustainability in construction;
- The researcher's opinion of the literature presented;
- Conclusions derived from the literature.

2.2 Benefits and Disadvantages of Modular Construction

Modularization, prefabrication, and preassembly are poorly defined; they are often collectively referred to as prework. In this paper, prework will refer to a collective strategy that includes prefabrication, preassembly, and modularization. These strategies are employed because they may significantly reduce project duration, improve productivity, reduce the need for labor and subcontractors, and have a positive impact on supply chain challenges. Prework, including modularization, was found to offer substantial opportunity to improve project performance and overcome internal and external project problems, such as a demanding schedule, lack of skilled labor, and adverse site and local area conditions (Haas, O'Connor, Tucker, Eickmann, & Fagerlund, 2000).

Prework can take several steps whereby prefabricated components are sent to and assembled in another facility, with other components making a finished assembly, and then transported to a site where they are further assembled and affixed.

Modularization (used in this paper interchangeably with fabrication, prefabrication, and factory construction) is the practice of assembling components of a structure in an assembly facility or factory and then transporting the completed assemblies to a site where they will be affixed. The term is used to distinguish this process from the more conventional practice of transporting basic materials to a construction site where all traditional construction processes are carried out (Carlson, 1995).

Modular buildings, including modular homes, are prefabricated engineered buildings or modules that are manufactured in an off-site fabrication location, delivered in sections to their intended site, assembled, and set on their foundation using trucks or cranes. A modular home is a three-dimensional house that is built off site to 85% or 90% completion. Homes are fabricated to concurrent with on-site construction such as foundations and utility hookups. They are then finished on site after they have been delivered and set. This on-site work represents from 10% to 15% of the entire home construction (R. Lyons, personal communication, April 19, 2009). Modular homes can be customized for individual taste, yet take advantage of the production facilities. Their quality is often equal to or surpasses site-built homes (Haas, O'Connor, et al., 2000; Carlson, 2001).

Modular homes represent about 5% to 7% of new home construction in the U.S. today (Penn Lyon Homes, 2008). There are many forms of factory built homes: modular homes, panelized building systems, post-and-beam construction, and log homes (Haas, O'Connor, et al., 2000).

Employees, rather than subcontractors, perform the traditional functions of construction by trade subcontractors in a factory. Third-party inspectors are present in the factory during the manufacturing process to conduct in-process inspections. They monitor the construction process to make sure the building meets all the building codes for the building's final destination (Zenga & Javor, 2008).

Traditionally homes are built on site after blueprints are produced and a builder is contracted to build out the project. This method is commonly known as on-site or "stick-built" construction.

On-site construction, including panelization, as a method of constructing homes, has been the accepted standard of construction since the late nineteenth century and represents over 85% of the housing market today (Zenga & Javor, 2008).

As specialized labor becomes scarcer, alternative methods for more efficient home construction are being sought. The housing sector of construction has been a key driver of prefabrication. In times of drastic housing needs, such as after wars and during economic booms, prework was used extensively as a quick solution to decrease the construction schedule (Haas, O'Connor, et al., 2000).

Manufactured homes, often confused with modular homes, are sometimes referred to as mobile homes. Manufactured homes are also constructed in a factory, but they are different than modular homes because manufactured homes comply with the Housing and Urban Development (HUD) Building Code, not residential building codes (Zenga & Javor, 2008).

Prefabrication, pre-assembly, and modularization are well established strategies in construction. These strategies have the potential to reduce project duration, improve productivity, reduce labor force, and streamline supply chain (Haas, O'Connor, et al., 2000).

The greatest advantage that prefabrication and modularization have is construction speed. A traditionally built home takes significantly more time to construct than a fabricated modular home. As an example, one experiment showed duration of four months complete construction time for a modular home compared to 14 months for a similar traditionally built home (Zenga & Javor, 2008).

Parallel work, or simultaneous production, can be exploited with the use of prework. Instead of performing work in a linear sequence on site, construction activities can be divided and completed simultaneously at multiple locations and transported to the site (Haas, O'Connor, et al., 2000).

With modularization more engineering is needed up front. Extended planning and design work must be completed before prework can begin. This can lead to faster projects and better scope control. The on-site construction duration can be substantially shortened through the use of prework. More work for a project can be completed off site prior to the scheduled need, thereby decreasing the construction schedule (Haas, O'Connor, et al., 2000).

The home fabrication process more closely resembles an automobile production line than a site-built construction process. Homes are built in an enclosed factory building. They are protected from the weather and constructed over an accelerated schedule (R. Lyon, personal communication, March 15, 2010).

With the factory production method, the modular home industry has enabled the consumer and producer to gain better control of costs, energy efficiency, and the construction schedule while maintaining high standards for quality (Zenga & Javor, 2008).

Subcontractors that traditionally work on site-built homes are usually represented in a modular factory as employees. Third-party inspectors are also present in the factory during the manufacturing process. They monitor the entire construction process while a home is fabricated. Inspectors make sure that the building meets all the building codes of the location where it will finally be delivered (Zenga & Javor, 2008).

In 1992 a Construction Industry Institute modular task force was formed to study modularization. The task force made several observations about the benefits of modularization in their paper. They found that modularization improved the overall quality of the project while reducing cost and time. The following is a list of the modularization advantages that were reported by the task force.

- Safety-There is less danger of fall related injuries in manufacturing plants than on construction sites. For example, pipe support modules can be built prefabricated, reducing the risk of falling. Also, there may be fewer accidents at the plants because of the reduced use of heavy mobile equipment, scaffolding, and other hazards that are present at most construction sites.
- Reduction in construction time-The duration of construction may substantially affect the final cost of a project. An earlier start up of a manufacturing process implies a speedier market entry for products from the completed facility. Similarly, a shorter construction schedule may reduce the field mobilization duration and reduce the construction finance cost, thus improving owner cash flows.
- Reduced labor costs-Net labor costs are generally higher in construction projects than in manufacturing. Project components that are completed offsite at a manufacturing facility can result in potential savings in total project labor cost and therefore total project cost.
- Labor availability-Projects located in remote regions frequently experience problems stemming from the availability of skilled labor. Modularization can be used to reduce the mobilization of skilled labor at the site and the resultant cost from relocation and housing.
- Weather-Adverse weather conditions can deter the construction process. Such limitations can be avoided by constructing modules in manufacturing plants or fabrication yards located in a favorable weather environment and then shipping them to the site.
- Increased quality and efficiency-Manufacturing facilities generally are more efficient in work structuring than construction sites. Many plants use a production line system where the work and tools are brought to the worker. This system is conducive to improved productivity.
- Simultaneous production-Work can be performed at the plant and at the project site at the same time. This can improve the project and reduce the overall schedule.
- Testing and modular-The testing of industrial process equipment can be performed more efficiently at the manufacturing facility than at the project site. This can reduce the cost and time required for tests such as hydrotesting and loop checks. (CII, 1992, p. 3-4)

Another list of advantages of automated building and modular construction is for a contractor, builder dealer, or developer, as reported by Don Carlson of *Automated Builder Magazine* in his book, *How and Why To Buy A Factory-Built Home* (2008):

- Lower interest cost on construction loan
- Faster use, faster income
- Fewer mistakes, less costly corrections
- Optimization of materials
- Guaranteed price
- Better quality materials
- Guaranteed supplies
- Less weather damage
- Less pilferage
- Less danger of fire
- Better security
- Less costly vandalism
- Less costly clean up
- reduced job-site payrolls
- Less costly job-site inspections, fewer red-tag violations
- Less costly appraisals
- Faster loan approvals
- Less costly job site equipment

- Less costly storm damage
- Faster appreciation values
- Reduced costly designing and engineering costs
- Less costly material handling
- Less costly worker's compensation insurance
- Less costly job site liability insurance
- Less costly accounting and recordkeeping
- Less costly punch-list corrections
- Significantly better quality.
- A much better return on investment

In 1992, CII detailed a list of disadvantages of modularization:

- Transportation costs
- Module size limitations
- Transportation accessibility
- Increased engineering effort.

Modular homes, by their design, may require more lumber material. More wood is used in framing the structure especially to strengthen the home for transportation and lifting. There are redundancies in walls, floors, and ceilings (Penn Lyon Homes Corporation, 2008).

2.3 Major Works Dealing with Modularization

Three major works were discovered that set the tone and flavor of this research.

Modex: Automated decision Support System for Modular Construction:

The first work, from the Construction Industry Institute and the Bureau of Engineering Research at the University of Texas at Austin, is *Modex: Automated decision Support System for Modular Construction.* This work discusses the process for deciding when modularization should be considered.

> The document addresses the lack of documented information about modularization decision support and the need to compile knowledge from experts in the field. It also discusses the need of a systematic process to perform modularization feasibility studies. (CII, 1992, p. v)
>
> The research has the potential to see the benefit of modularization. It is expected that construction projects that benefit from prefabrication may be green friendlier than traditional projects. The construction profession also will be able to predict the trend/range of cost savings or increases that modularization is expected to produce in the project being considered. (CII, 1992, p.14)

Examination of the Shipbuilding Industry:

The second guiding document was the Construction Industry Institute's *Examination of the Shipbuilding Industry* (Sawhney, Walsh, & Storch, 2007). The report presents a summary of the research directed toward understanding the modularization design and production methods employed by Asian shipyards in the construction of commercial vessels. The objectives were to examine the methods used in successful shipbuilding and determine how they can be implemented into construction. Interim Product Database, which is akin to a module in construction, was studied since it drove the efficiencies found in the fabrication process in progressive Asian shipyards.

> This study observed the high level of modularization, 3D CAD and supply chain integration being utilized by this industry. The findings found that the Asian shipyards dominate the global shipbuilding market. They are

more advanced than their European or North American counterparts. Over the past 30 years, the Asian shipyards have migrated from a stick-built approach to an integrated design/construct approach driven by an Interim Products Database (IPD). The net result is that Asian yards deliver ships at up to a 30% cost and schedule savings over the U.S.
Summary of findings:

The IPD provides the critical infrastructure allowing the shipbuilder to meaningfully tie together many practices in ways that have so far eluded the construction industry. While many characteristics of the industry are not currently present in construction (perhaps most importantly the single ownership of both the design and production assets in a single entity), nonetheless the IPD seems to be the key enabler of wide adoption of techniques and programs that mirror a wide range of best practices and advanced technologies.

As was previously stated, the Asian shipyards are widely acknowledged as market leaders and dominate global market share. The primary reason for this dominance is their superior cost and schedule performance. U.S. shipbuilding relies much more on a stick-built approach, analogous in many ways to the approach used in the construction sector. At present, the Asian shipyard can produce a similar vessel at approximately 25 percent of the cost and schedule of U.S. yards.

	Traditional	IPD
Cost	$150M	$33M
Schedule	36 months	7-10 months

These outstanding results do not appear to come at the cost of safety or quality. Nonetheless, the results suggest that the IPD concept can produce dramatic improvements.

The research team, especially the industry members, discussed the potential improvements in the construction sector that would result from an IPD-like approach. One issue that surfaced was that cultural changes would block adoption of all aspects of the IPD concepts in the construction industry unless an attempt is made to clearly define benefits. In short, a need to quantify the benefits of the IPD approach was considered crucial. The IPD approach has three major underlying themes: 1) design reuse; 2) supply chain integration; and 3) design for production. (Sawhney, Walsh, & Storch, 2007 p.126)

Preliminary Research on Prefabrication, Pre-Assembly, Modularization and Off-Site Fabrication in Construction:

The third document, from the Construction Industry Institute and the Bureau of Engineering Research at the University of Texas at Austin, is *Preliminary Research on Prefabrication, Pre-Assembly, Modularization and Off-Site Fabrication in Construction* (Haas & Fagerlund, 2002). This document advances the belief that improvement in design and information technologies, combined with industry sensitivity to cost and labor issues, shows prefabrication, preassembly, and modularization to be very viable.

> Successful implementation requires a systematic analysis and decision-making process to evaluate the potential benefits and barriers to using these methods on projects. The research team extended prior CII research effort, identified state-of-the-art practices of prework, and developed a decision framework to assist project teams in the potential use of prework on their projects. The research teams focused on identifying the requirements for effective use of prework on industrial projects, and to further structure the framework and develop it into a computerized tool. (Hass & Fagerlund, 2002 p.i)
>
> Prework isn't for every project, but it can bring major performance improvements for the right ones. (Hass & Fagerlund, 2002 p. i)
>
> Summary of findings:
>
> Prefabrication and preassembly decisions are typically based on unit cost considerations at the tactical level.
>
> Modularization and complex preassembly decisions are typically based on broad project factors at the strategic planning level.
>
> The main impediment to the use of prework is the lack of related expertise that exists in the industry. Advances in 3D presentation and the growth of successful facilities using prework are ways the industry is addressing this concern.
>
> Information technologies are helping to overcome the extra requirements of design, coordination, communication and organization associated with prework. 3D CAD and other modeling software are allowing more efficient design of all types of prework. Information technologies such as electronic file transfer, email and digital imaging are

> helping to overcome the coordination, communication and organizational challenges.
>
> Prework by nature has the potential to address many of the recurring construction industry challenges including workforce issues, tighter budgets and increased needs for schedule compression. (Hass & Fagerlund, 2002 p.76)

2.4 Carbon Footprint of Modularization

There are two popular definitions of sustainable development.

- Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.
- Sustainable development is the development effort that addresses the social needs and minimizes environmental impact. (RSMeans, 2008)

Sustainable utilization of resources refers to the use of natural resources at rates within their capacity to be renewed. The principles of sustainability applied in the construction industry are called sustainable construction. Sustainable construction can be the creation of a healthy, built environment using resource-efficient and ecologically-based principles (Palaniappan, 2009).

Buildings in the U.S. account for 72% of electricity consumption, 39% of energy use, 38% of all carbon dioxide emissions, 40% of raw material use, 30% of waste output, and14% of potable water consumption (U.S. Green Building Council, 2008). They also contribute 46% of the sulfur dioxide emissions, 19% of the nitrogen oxide emission, and 10% of the particulate emission (Holcim, 2010). In addition, buildings account for 33% of energy use and 40% of material use in the world economy (Rees, 1999).

A positive side effect of using prework is potentially decreasing the environmental impact of the project. This is partly due to reduced job site construction duration and a decrease in field labor requirements (CCI, 2000).

Trends in construction practices, including increased automation and off-site fabrication, lead to less waste generation on site. Alternative contracting strategies result in more cost effective construction projects with more flexibility to incorporate sustainable building practices (Augenbroe, Pierce, Guy, & Kibert, 1998).

Limitation in the availability of natural resources and the environmental impact at the local and global levels are causing a paradigm shift in the construction industry. Increased attention is being paid to environmental and social issues in the built environment. In addition, more attention is being paid to traditional project objectives such as time, cost, quality, and safety (Palaniappan, 2009).

Buildings use one-sixth of the world's fresh water withdrawals, one-fourth of the world's wood harvest, and 40% of the world's material and energy flow; and either directly or indirectly, buildings and associated construction activities represent 54% of U.S. energy consumption (Augenbroe, et al., 1998).

Significant use of non-renewable natural resources, materials, and energy in construction, and the associated supply chain processes, cause environmental impact, in terms of pollution to the land, air and water, and social impact, such as occupational and health issues (Palaniappan, 2009).

The Department of Energy (DOE) has set a target of energy savings in the built environment. Buildings for the twenty-first century will reduce the annual U.S. energy consumption by cutting carbon emissions by 32 million metric tons per year. The Environmental Protection Agency (EPA) is interested in advancing pollution prevention programs whereby they or their contractors help manufacturers optimize their production processes to eliminate potential pollution at the source. Some benefits realized from the EPA's pollution prevention program are the reduction of waste, disposal cost and reduction of input materials (Augenbroe, et al., 1998).

The following steps are recommended as strategies to improve the sustainability of the built environment: expand rationalized industrialized building practices, develop plug-and-play building components that are re-configurable, and explore and advocate an international dimension to system modularity in building components and systems (Augenbroe, et al., 1998).

Carbon footprint:

A carbon footprint is the total set of greenhouse gas (GHG) emissions caused by an organization, event or product. For simplicity of reporting, it is often expressed in terms of the amount of carbon dioxide, or its equivalent of other GHGs, emitted (U.S. Green Building Council, 2008).

A number of studies that focus on defining a sustainable built environment. These studies concentrate on the use phase of buildings, which consider a building to have a lifecycle use from 50 to 100 years. Energy consumption during the use phase has one of the largest environmental impacts of a building, approximately 80% (Palaniappan, 2009).

The lifecycle of buildings consist of several phases. Palaniappan (2009) reported the following in his research.

- Production phase: extraction and processing of raw materials, transportation of raw materials, manufacturing of building materials, and transportation of building materials to regional supply centers and contractors.
- Construction phase: transportation to the jobsite and on-site construction processes.
- Use phase: building use or operation, reconfiguration, renovation, repair, or maintenance.
- End-of-life phase: demolition, recycling, reuses, transportation, and land filling.

Numerous studies (Ochoa et al. 2002; Cole & Kernan 1996; Junnila & Horvath 2003; Junnila et al. 2006) have defined a sustainable built environment. These studies primarily focused on selecting building materials with low embodied energy and life cycle environmental impact, attain energy efficiency in the use phase, minimizing construction waste, as well as recycling and reusing building materials. Energy use, during the operational phase, is one of the most significant components (more than 80%) when considering the entire building life cycle with a life span of 50 to 100 years (Palaniappan, 2009).

Previous studies found construction phase-related impact as either underestimated (Hendrickson or Horvath 2000) or negligible (Junnila or Horvath 2003). The impact of the construction phase, or fabrication phase, could be reduced when considering the entire building's life of 50 to 100 years. However, the significance of measuring construction phase impacts is reported by Cole (2000), Guggemos and Horvath (2005), Guggemos and Horvath (2006), Junnila et al. (2006) and Bilec et al. (2006) as follows:

- The impacts of the construction phase can be significant at the aggregate level, for example, in the temporal and spatial dimensions.
- As the energy efficiency of the use phase reaches a threshold, the next focus of improvement is the construction phase and initial embodied energy.
- Measurement of the environmental performance of on-site construction processes is essential to obtain a holistic view of life cycle impacts.
- As the re-construction, repair, and reconfiguration of buildings become more frequent, the impact of other phases such as construction, maintenance, and end-of-life assumes more significance compared to the use phase. (Palaniappan, 2009 p. 44)

The environmental performance of on-site construction processes is assessed using several parameters. These parameters are: (a) transportation, (b) on-site equipment use, and (c) on-site electricity use (Guggemos & Horvath, 2005; Bilec, Ries, Matthews, & Sharrard, 2006). The challenges in collecting accurate data related to on-site construction processes are reported in the literature as being difficult to gather or not available.(Cole, 2000; Guggemos & Horvath, 2006; Bilec et al., 2006; Sharrard, Matthews, & Roth, 2007).

Although construction phase impacts were often quantified using national average data, these impacts were not consistent (Bilec et al., 2006). Due to challenges in data collection previous studies either ignored or approximated construction phase impacts (Guggemos & Horvath, 2006). There is a perceived lower significance of construction phase impacts and limited information is available about what actually happens on the construction site (Cole, 2000).

Accurate process-specific measurement of the environmental performance of on-site construction processes would help fabricators, developers, and contractors understand the performance of their construction processes, identify significant process components and parameters, and identify practices and processes that might be improved. Furthermore, case studies that focus on factory processes would provide a foundation for future research to identify and include parameters specific to factory construction processes for green rating systems.

The vertical construction of a traditionally built home consists of several phases and activities: concreting, plumbing, termite treatment, framing, HVAC, electrical, doors/windows, roofing, painting, drywall, siding/stucco, carpeting, countertops.

The vertical construction of a production home consists of 10 to 12 major phases and a total of 90 to 100 different activities. These activities are completed through the coordination of 25 to 35 specialty trade subcontractors (Bashford, Sawhney, & Walsh, 2003; Bashford, Walsh, & Sawhney, 2005).

Among these phases, the framing phase represents 22% to 29% of the total vertical construction cost of a production home, and the concreting phase represents approximately 14% of the vertical construction cost. Other phases of vertical construction account for less than 7% (each) of the production home cost (HRI, 2006; Palaniappan, 2009).

Similarly, a modular home on its final resting site includes all the above mentioned phases and activities. Most of the activities are performed in a factory. The concreting phase, which normally includes the foundation for the building, is an exception. This phase is performed on site, as is the termite treatment. On-site construction may include some finish work that was not finished in the factory. Also included are setting the building, connecting the modules, setting up utility connections, and doing minor cosmetic and finish work associated with connecting the modules.

On-site construction usually represents 10% to 15% of the total production effort of a manufactured home (Penn Lyon Homes Corporation, 2010).

This research is primarily designed to extend the study of the carbon impact of site-built residential construction. This study will report the carbon impact on the fabrication phase of modular construction, including module delivery and installation. This phase is equivalent to the production phase of on-site construction in the traditional model.

2.5 Researcher's Views

Prefabrication and on-site assembly is used most successfully in construction, shipbuilding, production of aircraft, and assorted other heavy industries. The most current innovation in prework and modularization seems to be coming from the ship building industry.

There are significant advantages to prefabrication, summarized from the above readings.

- Construction time is reduced and structures are completed sooner, allowing earlier placement of the structure into service, quicker return on the capital investment, and thus quicker and more profit.
- Quality can be easier to control in a factory setting, rather than a job site environment.
- Greater precision can be accomplished in a fabrication environment.
- Large, computerized machinery is easier to use in a fixed assembly building.
- Manufacture and subassembly prefabrication can be located in areas where skilled labor is more readily available and there is a lower cost of labor, power, materials, space, and overhead.
- Prefabrication and assembly reduces the need for subcontractor labor on site, reducing family hardships and housing and subsistence allowances for remote locations.
- More work is performed in relative comfort, under a roof, reducing weather problems and hazardous environments.
- Efficiencies, which bring cost savings, are easier to identify and measure in the controlled environment of a fabrication or assembly facility.
- Less waste is generated in factory environments, and the waste that is generated is easier to control and recycle and dispose.

There are also disadvantages to prefabrication:

- Transporting modules or components to the destination site can be challenging and costly.
- Large, prefabricated assemblies may require specialized or heavy-duty cranes to place them in position for affixing.
- Careful handling of prefabricated components is required.
- Joining and affixing prefabricated components must be done with attention to strength and avoidance of failure of joints.

2.6 Researcher's Questions

It seems proper to concentrate on prefabrication and modularization as dominant research priorities because of the significant contribution these industrialized techniques could have on the current residential delivery system. There are several important issues that must be addressed to report the successes of the venture. Several key questions must be answered to highlight the critical areas of the project:

- What is the best way to build homes to assure optimization of cost and quality for the effort and the lowest carbon emissions? Is industrialized fabrication viable?
- How can the carbon footprint of modularization be measured?
- How can a company measure and assure itself that it is making constant reduction to its carbon emissions within a period or a project and from one project to another?

Professors Howard Bashford, PhD, of Arizona State University and Kenneth D. Walsh, PhD, of San Diego State University, both with significant experience and expertise in the fields of prefabrication, production construction, and research, are completing a mathematical economic and cost formula that helps with the analysis of some pressing issues: when it is feasible to prefabricate and how to quantify the economic benefits. Professor Richard Storch, PhD, of the University of Washington joins the above mentioned professors as prefabrication researchers in the ship building and construction industries.

In addition Professor Bashford produced four papers that point out areas of potential improvement in site-built construction. Bashford makes recommendations on how these weaknesses can be overcome. His studies were invaluable in determining the viability of modularization since fabrication addresses some of these issues. The four studies that influenced this research include:

- Bashford, Sawhney, and Walsh (2003) presented the application of even flow production, a workflow leveling strategy, using a simulation model. This study reports that even flow production (as found in modular home) fabrication significantly reduces the variability in the workload assigned to specialty trade subcontractors.
- Bashford, Walsh, and Sawhney (2005a) presented the application of factory production management models (such as Little's law) for modeling the relationship among cycle time, work in 38 process, and throughput (number of units completed per time period) in the Phoenix housing market. This

study suggests that production system loading aspects are important and should be considered to estimate the cycle time.

- Bashford, Sawhney, Walsh, and Thompson (2005b) reported the pass rate of code compliance inspections based on the 2001-2003 data collected in the study from one city in Arizona, the first-time inspection pass rate of critical code compliance inspections such as pre-slab, rough framing/rough plumbing/rough electric, drywall, and final are found to be 74%, 16%, 80%, and 27% respectively.
- Bashford, Sawhney, Felt, and Koh (2007) provided a quantification of idle time in residential construction based on the data collected for three homes. The study found, based on three residential homes, that: (a) the average cycle time was 120 days, (b) total site hours were 1200 hours,(c) average site activity hours per home was 305 man hours, and (d) percentage of site activity was 25.4%. The study concluded that that only 25.4% of the entire cycle time is utilized for actual construction activities.

Several successful industries were studied to determine if there was any potential to draw from their practices, including discussions of well-known methods and practices such as six sigma, lean production, and the like. Researchers ascertained from their month-long industry study and literature that the shipbuilding industry was most advanced in the area of prefabrication technology. The shipbuilding industry successfully borrowed techniques used in aircraft production and modular construction industries and advanced them for their own purposes.

Two practices stand out. The first practice is used by the luxury cruise line builders, as well as cargo and other major shipbuilders. These companies establish a prefabrication plant in, or in close proximity to, the shipyard. In this plant they prefabricate and assemble room modules that are transported to the ship construction site and integrated with the ship (plugged in). By doing this, the industry builds two critical components of the end product simultaneously. The added benefit of the modularization of the rooms is that the rooms are built in a factory under quality controlled conditions of prefabrication and expediency.

The second practice is relatively newer. Shipbuilders have decided to standardize subassemblies that are used multiple times in the same application or that can be used many times in different applications. The term "interim product database" (IPD) is used when referring to this practice. Simply said, the industry designs a subassembly that fits multiple purposes or can be easily replicated many times. The shipbuilders then have a database inventory of these subassemblies and use them when an application is called for. The benefit to this system is one of expediency. Users of IPD strive to design it once, work with it, perfect it, make it easy to build, and use it multiple times without having to invent it each time. The learning curve price is paid once, and there is the potential of constant improvement of the component every time it is used.

In addition, two other studies co-authored by Dr. Bashford were consulted. These studies also contributed to the research presented here:

- Sawhney, Bashford, Palaniappan, Walsh, and Thompson (2005) discussed the influence of inspections failures in residential construction using a discrete-event simulation model. The application of Discrete Event Systems Specification (DEVS) framework in developing simulation models of production home construction.

- Sawhney, Walsh, Bashford, and Palaniappan (2009) presented the influence of inspected buffers on workflow in production home construction. This study discusses the influence of inspection pass rate on work-in-process (WIP), work arrival rate to downstream process, and resource utilization using a discrete-event simulation model.

2.7 Conclusion from the Literature

- Modularization is reported as a viable construction delivery system and should be further studied.
- Modularization has many benefits, especially increasing the speed of construction.
- Simultaneous construction favorably impacts the project duration.
- Prefabrication, or modularization, has been expanding, especially because of component standardization.
- The carbon footprint should be measured and studied in prefabrication and modularization because the delivery system is growing in popularity.
- A methodology should be developed to study the ways and means that carbon emissions can be measured.
- A sophisticated, yet simple tool should be developed to help calculate the carbon footprint in modular construction.

- Modular home fabrication should be studied to see how the carbon emissions compare to traditional construction.

Chapter 3: Methodology

3.1 Objectives and Scope

Scientific measurement is a desirable way to accurately document the true performance of construction products or processes. This research presents a quantification of carbon footprint of fabrication processes for residential fabricated modules and the delivery and installation process of the modular homes.

Typical metrics of environmental performance are emissions to air, land, and water, embodied energy, and solid waste. This study focuses on understanding and measuring carbon emissions (CO_2) of factory modular home construction.

The primary objective of this research is to study the environmental performance of the modular residential construction process in a fabrication environment. This study is based upon observations and data collection made in a modular home fabrication plant in Selinsgrove, Pennsylvania. Penn Lyon Homes, a residential modular home fabrication company, was chosen as the subject company for this case study.

The following are specific objectives of this study.

- To identify the energy consumption sources of a modular fabrication plant by type of energy (e.g. Electricity, diesel fuel, etc.);
- To calculate the carbon footprint for the fabrication plant over a specific period of time;

- To determine the production volume during the study period and calculate the per unit carbon footprint for that volume;
- To identify fuel consumption and distances driven for the modular delivery and installation phase of the set up process;
- To develop a simple tool to calculate the carbon footprint of this production facility.

The scope of the study includes the following items on this list.

- The study focuses on carbon emissions of the fabrication process and module deliveries, and installation phases.
- The study considers all energy used for fabrication activities, delivery and installation of modules.
- The study is limited to measuring carbon dioxide emissions. Other greenhouse gases are excluded, embodied energy is not measured, and construction waste is not quantified.
- Employee travel from home to the fabrication facility is excluded.
- Material delivery to the fabrication facility including indirect material transportation is excluded.

3.2 Methodology

The research components include the following items.

- To gain an understanding of modular construction
- To determine the carbon footprint impact this construction delivery process has on the environment

- To develop a methodology for determination of carbon emissions per unit of production, module, or home
- To measure the carbon footprint of transportation and installation of modules
- To create a tool for measuring carbon footprint in the modular industry
- To determine the carbon footprint of a finished, delivered, and installed modular home.

To better understand the modern fabrication process of a modular factory, the researcher searched the literature as outlined in chapter 2. The researcher also made numerous visits to production facilities located in Pennsylvania and Arizona. A modular plant that is owned and operated by Penn Lyon Homes of Selinsgrove Pennsylvania was chosen for the study. This company has been in the industry for more than thirty years and operating continuously since 1981 as a modular facility.

3.3 Company Overview

Figure 4. Corporate headquarters of Penn Lyon Homes Corporation, located at 195 Airport Road, Selinsgrove, PA, 17870.

History:

Penn Lyon Homes, Inc., (Penn Lyon) is a privately held corporation that is engaged in the design, manufacture, and sale of modular housing. The company is located in central Pennsylvania in the town of Selinsgrove. It was formed in July 1981 by Roger A. Lyons, who remains the Chairman and CEO and is active in the day-to-day operations of the business. The company is owned by four stockholders: Roger Lyons (Chairman and CEO), David Reed (President and COO), Scott Lyons (President of Penn Lyon Solutions), and Debra Lyons (President of Penn Craft Kitchens). All of the stockholders are veterans of the modular and kitchen cabinet industries. Over the years, Penn Lyon Homes has attracted and retained experienced employees in the industry and all of their senior managers, excluding the ownership team, each have more than 10 years of industry experience.

Penn Lyon has two manufacturing facilities, a corporate office building, a modular carrier maintenance building, and a kitchen cabinet manufacturing plant, located on a 50-acre campus in Selinsgrove, PA. . The total manufacturing space is in excess of 120,000 square feet, including storage buildings. The entire campus was built and designed by Penn Lyon. The first modular home plant was built in 1985,

and the subject plant was built in 1987.

In the late 1990s, the company made a strategic move to specialize in higher end customized modular housing and expanded its market share by also focusing on permanent commercial products. Today, Penn Lyon is diversified in the residential, permanent commercial, and temporary commercial markets and is projecting solid growth in all divisions.

Penn Lyon maintains that it focuses its competitive advantage by producing a superior product compared to site-built homes. Penn Lyon claims to excel in: the quality of the home, delivering homes on schedule and by utilizing more efficient and less costly labor, Penn Lyon is able to effectively deliver a home at a more attractive price. Modular construction results in decreased carrying costs and many other decreased soft costs because the company claims that the process is 50% faster than site-built construction. With an in-house engineering group of eight professional designers, Penn Lyon engineers all of their buildings, produces all of the building drawings for permit, and completes their own shop drawings.

The company's total current building capacity for both plants is 2,000-plus modules per year, or 25,000 square feet of housing per week. Penn Lyon has operated at approximately 80% of this capacity over the past decade. That percentage has been severely reduced during the recent recession.

Penn Lyon believes that modular housing market penetration in the Northeast continues to gain ground over time. According to Penn Lyon management, current statistics that are available through represented modular organizations indicate that modular homes account for 15% of all new housing sold in the Northeast and Mid Atlantic states. The company expects strong growth over the next ten years. Penn Lyon has additional acreage at its current campus and is prepared to expand to meet this expected demand for modular housing.

During 2007, Penn Lyon entered into the retail modular market through its sister company Penn Lyon Solutions. The move into the retail market increases speed and ease of completion of the modular product and is designed for a faster production cycle for the project owner/developer. Penn Lyon Solutions gives Penn Lyon control of the project from initiation to completion and more directly competes with the scope of a site-built contractor.

With over 15,000 modular structures built to date, Penn Lyon is a fair representation of production longevity in the modular industry. *USA TODAY*, *New York Times*, *The Philadelphia Inquirer*, *Builder Magazine*, and numerous industry publications have published articles about Penn Lyon's efficiencies and progressive building systems. Penn Lyon has experienced strong growth throughout its time span. In 1987 and again in 1988, Penn Lyon was selected as one of the fastest growing privately held corporations in America and recognized by *INC Magazines* in their Top 500 List. Penn Lyon is a recognized brand in the modular housing industry in the United States.

The company is optimistic about the future success for modular housing throughout the Northeast United States. To assure its success, Penn Lyon has closely aligned itself with the green movement in housing. The company partnered with Architect Michelle Roberts to develop a new sustainable ECOHEALTH homes collection.

Financial history:

The company's production revenue capacity at the present facility is $60 million per year. During the early 2000s, Penn Lyon reached $43 million. This number gradually subsided to an annual production value of $12-14 million in sales. That same dollar volume is being forecast for 2010 to be conservative with the current market conditions.

New product line:

Penn Lyon Homes Corporation has also entered the Pod business. These are modular kitchen and bathroom Pod's that are constructed in the production facilities. They are then transported to either a new hotel or commercial high rise and installed. This new product line is being marketed as a cost-effective way for the developer/builder to achieve higher quality and save money on labor costs. The company is currently negotiating two potential contracts of two hundred Pods each. These contracts represent approximately $2 million in sales that can supplement the company's core modular business.

Five-year forecast:

The five-year forecast for the modular division is for $20 million in sales for 2011, $24 million for 2012, $28 million for 2013, and $32 million for 2014. These numbers do not reflect any sales increase in the pods division. The pods could contribute $2 million in additional earnings for each of those years. With the commercial building business expected to be slow for the next five years, Penn Lyon does not expect much of a growth spurt in that area. After five years, the company expects that part of the business to expand rapidly.

The company projects that the new housing business has turned the corner and will begin a slow continuous growth for at least the next five to seven years. They are not expecting any surge in housing for the northeast United States. Penn Lyon expects to remain an upscale modular housing manufacturer and to maintain its presence in that market.

3.4 Production Process

The following is the production model for the Penn Lyon modular plant. The fabrication description represents the construction of a Penn Lyon home as used for this investigation. It was compiled from personal observation, discussions, and various tours taken with company management. Additionally, materials posted on the company's web site were incorporated in the descriptions.

Penn Lyon manufacturing process:

Penn Lyon's corporate complex has production facilities containing more than 100,000 square feet of production space. Each facility employs skilled craftsmen dedicated to home fabrication. Each of the two facilities builds about 350 homes each year, or more than 700 total houses in normal operating times. Workers construct the entire house indoors, away from the elements and weather. The company stores all the raw materials under roof cover as well; this allows the lumber to be in a premium state with less than 17% moisture content. This low moisture content promotes fewer nail pops and cracks and allows the product to remain consistent throughout the building process. The construction of a Penn Lyon home is divided into fourteen work stations on the residential production line, including the mill area.

Diagram of production facilities:

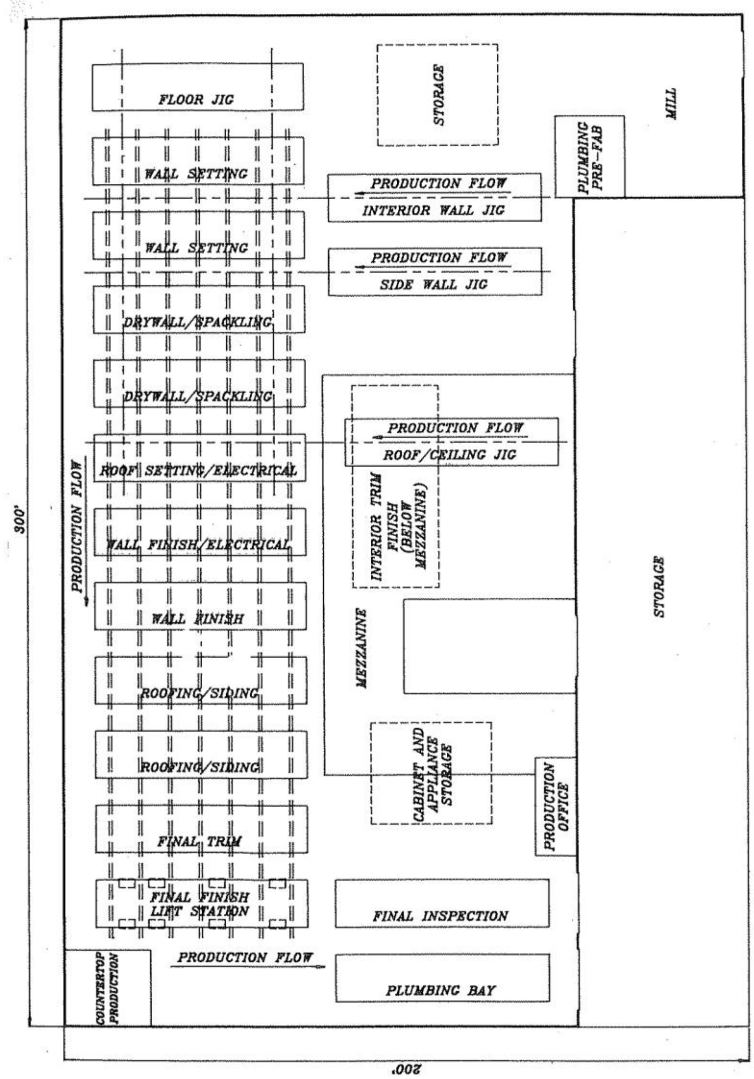

Figure 5. Plan view of Penn Lyon facility showing process work stations.

Areas, observations, activities, and sequence.

The mill area

- In the mill area lumber is cut to the required sizes. Mill workers saw studs, roof rafters, and all wood material that will be used later for construction and assembly.
- The mill area also houses the stair component station. Penn Lyon Homes fabricates all of its stairs in the area.
- All cutting and preparation work is completed in the mill area; actual construction takes place on the construction line.

Flooring:

- Technicians construct all floors on a jig. In addition to speeding up the process, this jig allows the craftsman assurance that the floor they are building will be square.
- Carpenters frame a floor with wood joists at 16 inches on center with three-quarter-inch OSB decking. Trusses may also be used.
- All materials are glued and nailed for added strength.
- To maximize energy efficiency, the company also installs foam insulation on the perimeter joists at this phase of the construction process. All Penn Lyon Homes are constructed to be eligible to receive the Energy Star label that certifies energy efficiency.
- Hot and cold water plumbing lines and drain lines are installed.
- Technicians install insulation in floor cavities.

- After workers assemble a floor and install decking, they move the floor to the next station.

Figure 6. Fabricate I-joist floor trusses.

Figure 7. Web-style floor trusses used in flooring for plumbing access.

Figure 8. Workers building floors on floor jig using dimensional lumber.

Figure 9. Completed floors being moved from jig to rollers.

Interior wall installation:

- The next step in production is to move the interior walls, which have been fabricated off- line, into position and attach them to the previously completed floors. Note, in *Figure 10*, that the drywall is frequently attached to one side of the walls in the off line framing table.

- As the walls are moved into place, technicians fasten and lag them to the floor structure. Workmen nail and lag all places where interior and exterior walls join together.
- Technicians strap the walls to the floor using galvanized strapping which helps assure greater structural integrity.
- For strength and efficiency, Penn Lyon uses the inside-out approach to building the home. They secure interior walls first, and later attach the exterior walls. This gives workmen more access to the structure.
- Technicians seal all penetrations. They seal every pipe that penetrates the floor, ceiling, and walls to eliminate air infiltration.
- The company uses additional lumber in the structural system than would be used in conventional construction, and be required by conventional building standards. This practice is designed to provide more strength to the structure, especially during transportation and erection.

Figure 10. Completed exterior wall with drywall installed on inclined framing table.

Plumbing installation:

- Plumbing technicians install plumbing on the production line. This practice reduces on-site connections.
- Sub-assembly plumbing stations are used, allowing craftsmen to prepare sinks, toilets, and other plumbing assemblies prior to connecting them in the home. Using sub-assembled plumbing is more convenient and more efficient and can improve the quality of the installation of fixtures.
- Plumbers place tubs, showers, and sinks in the units and make all connections on the production floor.
- Technicians again seal all penetrations to eliminate air infiltration.
- Workers clearly identify and label all connections that are to be made on site.

Floor goods:

- Workers roll and secure vinyl into place when vinyl is selected as the flooring choice.
- If the home requires carpet, ceramic tile, or hardwood flooring, technicians install it later in the construction process.
- When vinyl flooring is required, workers prepare the floor for vinyl goods by gluing quarter-inch thick sub-floor material under laminate flooring, and fastening all vinyl locations and install the vinyl floor prior to wall installation. This makes the installation a very quick process. Trimming around walls becomes unnecessary.
- The vinyl is perimeter fastened. This process also allows for easy removal if a home owner decides to upgrade or change the flooring at a later time.

Exterior wall installation:

- While workers install the flooring, carpenters build the exterior walls at the wall off line framing table (*Figure 11*). This wall sub-assembly process is a key to efficiency in the production line. Again, carpenters build the walls on a jig to ensure that the walls are square.
- When the walls are completely framed, workers attach drywall using a special formulated adhesive for quick setting. The drywall adheres to the wood and is then also fastened by screwing the drywall into the lumber. This combination of both glue and screws adds strength.

Figure 11. Exterior wall framed with dimensional lumber on inclined framing table.

Figure 12. Drywall applied to framed exterior wall on inclined framing table.

Ceiling and roofing systems:

- Like the floor and wall systems, carpenters construct the ceiling and roof system on a jig to assure that the roofs will be square.

- Penn Lyon builds two types of roof systems: rafters and trusses. Company engineers design the rafters, and Penn Lyon Homes manufactures them.
- The company usually uses rafters when the roof area will be used for living space.
- An outside company designs and builds trusses that are used for typical roof designs.
- When workers complete the roof and ceiling system, they move it into position on the previously constructed walls. They secure the system on the walls and add metal straps it for added strength.
- Craftsmen install the ceiling insulation once the workers move the roof assembly into place and secure the ceiling and roof system on to the previously installed walls; Penn Lyon uses R-30 and R-38 insulation in ceilings.
- Roofers install all the sheathing at this time. The company uses a 30-year architectural shingle as its standard roofing material. Single, over-ridge venting is also installed in every home.
- The construction crew installs an ice and water dam barrier for the lower three feet of the roof.
- The company installs 15-pound felt paper for the rest of the roof.
- Workers build the roof, including flips, overhangs, and knee walls, and the crew folds down the roof for transportation.
- A certified Penn Lyon set crew raises the roof and puts it in place during the set process.

The roof and ceiling installation is shown in Figure 13 through 17.

Figure 13. Workers installing module ceilings.

Figure 14. Module ceilings ready for insulation and roof installation.

Figure 15. A module ceiling after insulation has been added.

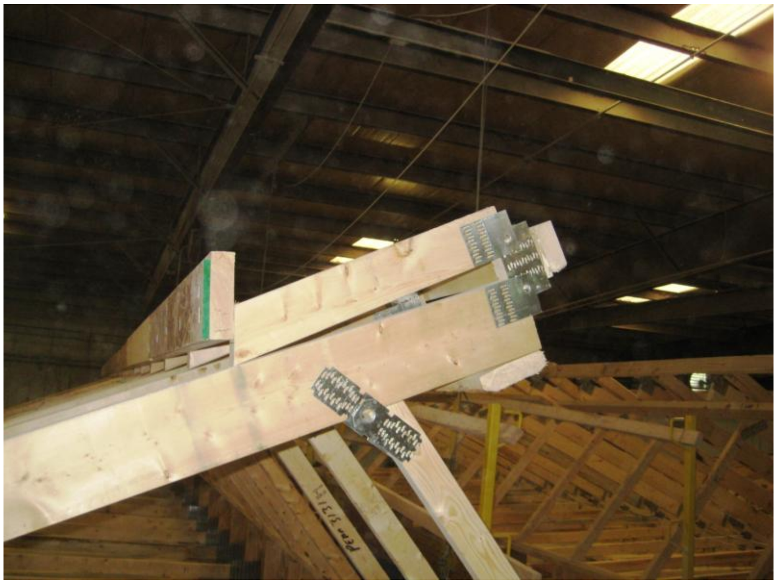

Figure 16. Module roof showing close-up of hinged component.

Figure 17. Module roof showing wall bracing.

Electrical and rough wiring:

- The company wires their modular homes to comply with the national electric code for wiring residential construction.
- Penn Lyon uses a prefabricated wiring harness that it installs in the ceiling; wire drops are then added down the walls that then feed into the panel box.
- Technicians seal all wall penetrations for energy efficiency.
- On-site electricians complete limited connections at the panel box.
- Employees label all breakers for ease of connection.
- Company electricians test each unit prior to leaving the factory to ensure that all electrical connections are functioning properly.

Drywall finishing:

- The next process on the production line is drywall finishing.

- Drywall techs hand spackle and hand sand all drywall. This complies with the factory standard of a three-coat manual application.
- The second shift technicians do all the final sanding and painting to maximize production efficiency.

Figure 18. Interior of module showing drywall finishing.

Sheathing and windows, doors, siding, and shutters:

- Workers apply glue to walls and sheathing and wrap the home with house wrap if requested by the customer.
- Carpenters install the house windows in the factory when appropriate; they level and flash all windows. As a standard, the company uses a double-hung vinyl window with tilt features.
- Carpenters also install doors in the factory. The company uses a fiberglass door that is dent resistant. For fire doors, they use steel six-panel doors.
- Penn Lyon employees install siding and shutters in the factory.

Kitchens:

- Penn Craft Kitchens is Penn Lyon Homes' custom kitchen design company. It is located in the Penn Lyon complex.
- Penn Craft offers many design options for clients' selections.
- Penn Craft builds cabinetry and kitchens in its production facility. They install them in homes on the production line.
- Cabinets, counter tops, kitchen sinks, and appliances, as chosen by buyers, are also installed in the homes on the production line.

Figures 19 and 20 illustrate kitchen installation.

Figure 19. Fabricated cabinets awaiting installation.

Figure 20. Cabinets being installed in the modular home.

Final trim and finish:

- Carpenters complete the house trim as the home nears the end of the production line. Workers install all trim and base molding at this time.
- Workers install carpet, ceramic tile, or hardwood floors as the home requires.
- Technicians complete all electrical tests and plumbing air tests at this station.
- When a home is completed, it is prepared to ship.
- Workers shrink wrap a home in plastic for transportation to the job site.

Figure 21. Final touch-up painting and quality control.

Quality control:

- Employees build the home to the company and industry standards.
- Third-party inspectors certify that every home is built to exacting standards.

State and local codes:

- Penn Lyon builds every home to comply with state codes, and every home leaves the factory with labels that certify the home's compliance with these codes.
- The labels are affixed and typically located under the home's kitchen sink.

Preparing for delivery:

- Once the home is labeled and construction is completed, the home is shipped to the job site.

- A certified Penn Lyon set crew installs the new home on its foundation.

Figure 22. Module shown with house wrap protection being readied.

Figure 23. Completed module ready to be delivered.

Typical Penn Lyon modular home:

Modular homes look like any other home. The design flexibility of modular construction allows manufacturers to build from the simplest to the most complex designs in residential, multifamily, and commercial construction. Included here is a small sampling of typical Penn Lyon modular homes, including interiors.

Figure 24. Example of a modular home exterior.

Figure 25. Example of a modular home interior.

Figure 26. Example of a modular home interior with cathedral ceilings.

Benefits of modular homes:

- Speed of construction
- Highly engineered
- Constructed in climate controlled environment
- Efficient building process and material usage
- Energy efficient
- In-plant inspections
- Consistent quality
- Constructed to meet or exceed state building codes
- Ease of financing and insuring
- Reduced need for subcontractors (Penn Lyon Homes Corporation, 2010)

3.5 Research Steps

Major steps followed in this study:

- Carbon footprint due to modular fabrication:
    - Ascertain what energy sources and quantities were used in the fabrication process.

    - Determine source of fuel for the energy used.
    - Ascertain the carbon footprint per unit of fuel used.
    - Calculate the carbon footprint of the plant for a chosen period of time.
    - Calculate the carbon footprint per fabricated module.
- Carbon footprint due to transportation of modules:
    - Determine the fuel used in transporting the modules.
    - Determine the total distance travelled for the study period.
    - Ascertain the miles per gallon of fuel used by the vehicles.
    - Calculate the gallons of fuel used.
    - Determine the carbon footprint per gallon of fuel.
    - Calculate the carbon footprint for the study period.
    - Calculate the carbon footprint per fabricated floor and per square foot of construction.
- Carbon footprint due to installation of modules:
    - Determine what energy sources or fuels are used in the installation phase.
    - Determine the carbon footprint for this phase.
- Calculate the carbon footprint per fabricated module and per square foot of construction.
- Calculate the carbon footprint per typical home using two-, three-, and four-module sized homes.

- Design a carbon calculator tool that can expedite carbon calculation in the modular home fabricated environment.

Data collection:

The literature and field research was conducted over a period of two years to gain an understanding of the modular home industry. This process was instrumental in learning the history of factory production and the methods used in fabrication. This research culminated with a number of plant visits of production facilities and two multiple-day visits to Penn Lyon Homes in Selinsgrove, Pennsylvania, over a period of one year. The plant visits served as a way of observing production methods and identifying energy sources used in the manufacturing process. The energy used in production was measured to calculate the carbon footprint.

Data was collected during the plant visits as well as through communication as the research progressed.

Key observations:

- Electricity was the main source of energy consumed in the facility. Lighting, saws, cranes, small tools, and production motors were all powered by electricity.
- The factory was serviced by a pneumatic network that powered air tools. This system was also powered by electricity.
- Kerosene heaters are used to dry the drywall.
- Floors, on rollers, were moved manually.
- The vacuum air purification system was electric.

- Two small forklifts used to move material operate on propane.
- A number of large, diesel-powered trucks used to deliver modules were parked on the campus grounds.
- After touring the facility, key managers were interviewed to confirm observations.

Research period:

Under the advice of Roger Lyons, the month of August 2009, was chosen as a study period. During this period of time, 45 modules were fabricated in one operating manufacturing facility. The full production capacity of the plant is 80 modules per month.

During the research period of August 2009, 42,640 kilowatt hours of electricity were consumed to fabricate the 45 modules and to light and service the office facilities. These 45 fabricated modules represented sales to five customers in five different locations. These modules were delivered to their respective permanent locations using company vehicles for an accumulated distance driven of 21,820 miles.

Conclusion:

The inquiry validated that Penn Lyon Homes uses a process-driven modular home fabricating facility and would provide a reasonable example for the research. This inquiry also validated that data is available to calculate the carbon footprint of the overall production. The production output can then be used to determine the per-unit or per-module carbon footprint in total and by square footage. In addition, calculations can be made to calculate the carbon footprint at different levels of production.

Once a baseline carbon footprint is calculated, the process can be repeated using different periods to determine a correlation with the carbon footprint and seasonality, as well as the production level. In periods when additional types of energy are in use, they can be incorporated into the calculation.

The ability to monitor improvement from period to period is another feature of the methodology. Users of the methodology can use it as a tool to track results and make improvements. “What if” scenarios can be executed to help identify opportunities to reduce the impact of carbon.

Consistency in the application of the methodology is important. A method may have minor errors in value, but if the value is applied on a consistent basis, it can give visibility to changes in the result.

Chapter 4: Fabrication Emissions

4.1 Introduction

Chapter 4 deals with general observations and data collected during this research study, with the computation of carbon emissions from energy used in fabricating residential modules. Chapter 5 presents the carbon emissions of delivery and installation of these modules. Chapter 5 presents the carbon calculator developed by this researcher for this study. Chapter 6 presents a comparison between the carbon impact of a typical modular home versus a traditional site built home. Step by step data is included to in both table and narrative form for clarification, and as an aid to future replication of this study.

4.2 Key Observations

- Electricity was the main source of energy consumed in the Penn Lyon fabricating facility. It powered lighting, saws, cranes, small tools, production motors, and air compressors.
- The factory was serviced by a pneumatic network that powered air tools. The air compressor for this system was powered by a 50 horsepower electric motor.
- No heating or air conditioning was provided in the factory for the period of study, the month of August 2009. The factory included a heating system, but no air conditioning system. No other heating or cooling energy was considered in this study.
- Fabricated floors, on rollers, were moved manually.
- A vacuum air purification system was powered by electricity.

- Two small forklifts used to move material operated on propane.
- Kerosene fired heaters are used to dry plaster wallboard.
- Numerous large trucks used to deliver modules were parked on the campus grounds. These trucks were diesel powered.

In conjunction with the facility tours, meetings were conducted with company management and internal company documents were reviewed to confirm and supplement plant observations.

4.3 Research Period

With the concurrence of Penn Lyon management, August 2009 was chosen as the month for the in-depth study. Table 1 shows that during this month 45 modules were fabricated in one operating manufacturing facility. The maximum production for this facility is 80 modules per month.

Table 1

August 2009 Production and Sales by Client

Serial Number	Customer Name	City and State	Number of Modules	Types of Modules
55408	Bella Loretta	Brentwood, NY	17	Townhouse
11437	Avalon	Ware, NY	4	Single Family
11468	Hometown	Kingsbury, NY	4	Single Family
11469	Malone	Corning, NY	2	Single Family
55409	Habitat	Baltimore, MD	18	Townhouse
TOTAL			45	

These 45 fabricated modules represented sales to 5 customers in 5 different locations, including 3 single family homes and 2 town house projects.

These modules were delivered to their permanent locations using company vehicles for an accumulated distance of 21,820 miles driven as shown in Table 2.

Table 2

Miles Driven for August 2009 Production

Customer Name	City, State	Number of Modules	Type of Modules	Mileage One Way	Total Miles Driven
Bella Loretta	Brentwood, NY	17	Townhouse	310	10,540
Avalon	Ware, NY	4	Single Family	330	2,640
Hometown	Kingsbury, NY	4	Single Family	250	2,000
Malone	Corning, NY	2	Single Family	130	520
Habitat	Baltimore, MD	18	Townhouse	170	6,120
TOTAL		45			21,820

Steps 1 (concreting) and 3 (termite treatment), as seen in Table 3, are normally left to the general contractor to complete on-site. Concreting, or step 1, can be exactly the same for modular and site-built houses built with basements or crawl spaces. In the site-built application, the basement or crawl space would include a framed truss or joist floor.

Table 3

Construction Steps for Site-Built and Modular Homes

Construction steps	Site built	Modular
Concreting	Yes	No
Plumbing	Yes	Yes
Termite treatment	Yes	No
Framing	Yes	Yes
HVAC	Yes	Yes
Electrical	Yes	Yes
Doors/Windows	Yes	Yes
Roofing	Yes	Yes
Painting	Yes	Yes
Drywall	Yes	Yes
Siding/Stucco	Yes	Yes
Carpeting	Yes	Yes
Countertops	Yes	Yes

The modular factory completes 85% to 90% of the total construction of the home in the plant. In addition, several steps are performed in the modular application that normally would not be considered as part of the site-built process. These steps are the delivery and installation of modules. The installation responsibility varies with each project; either Penn Lyon or a client contractor can install the modules.

4.4 Energy Used

After choosing an appropriate time period for the study, the next step was to determine what energy was used in the factory for the production of homes. In two factory visits, this researcher made several observations of energy uses, confirmed with management. Management prepared a list of energy consumption for August 2009 by usage and energy source as listed in Table 4.

Table 4

Factory Energy Consumption for August 2009 Production

Energy Used	Amount
Electricity	42640 kWh
Propane	150 lb
Kerosene	60 gal

Electricity is the predominant energy source used in the manufacturing process, operating all construction equipment either directly or indirectly by running compressors and pumps for pneumatic tools. Electricity is also used to operate the Penn Lyon office and administrative building. During August 2009, 42,640 kilowatt hours of electricity were consumed to fabricate the 45 modules.

A second source of energy is propane. Propane is used as fuel to operate the forklift trucks that move material in the factory and perform other delivery and movement functions. During August 2009, 150 pounds of propane were used in the fabrication of the 45 modules.

Kerosene is the third source of energy that is used in the manufacturing process. Kerosene is consumed as fuel in heaters to dry the drywall joint compound. During August 2009, 60 gallons of kerosene were used to produce the 45 modules.

For the month of August, the plant operated at approximately 56% capacity, producing 45 modules. Full capacity was 80 modules.

Table 5

Production for August 2009 as Percent of Full Production

August Production	45 modules
Full Capacity Production	80 modules
Percent of Full Production	56%

The average size for each module used in this study was 50 feet long by 14 feet wide, for a total of 700 square feet. The total square footage of the 45 modules was 31,500 square feet.

Table 6

The Average Size of Each Module

Total Square Feet Produced	31,500 sq ft
Number of Modules Produced	45 modules
Square Feet Per Module	700 sq ft

All the modules produced in August were delivered to 5 customers. The average per module consisted of 45 modules averaging 700 sq ft each. The modules delivered were not uniform in size and generally 12 foot wide. Table 7 shows various size modules that approximate 700sq ft when combined. A base size, 700 square foot module was used to determine carbon footprint per module.

Table 7

The Average Dimension of Each Module

Average Length of Module	60ft	58ft	56ft	50ft
Average Width of Module	12ft	12ft	12ft	14ft
Average Size of Module	720 sq ft	696 sq ft	672 sq ft	700 sq ft

4.5 Electricity

The entire Penn Lyon campus has one electric power meter. Electricity usage as reported by Penn Lyon management was used in calculating energy used in manufacturing. Total electricity used during August 2009 was 42,640 kilowatt hours at a cost of $5,700.

According to company management, no significant additional electricity would be used to produce the full capacity volume of 80 modules. Electricity usage cost behaves like a fixed cost with little variation depending on volume. Table 8 shows the Penn Lyon production volume and electricity cost for 2009 to demonstrate the small cost variation with production volume.

Table 8

Production Volume and Electricity Cost for 2009

Month	Modules Produced	Electricity Cost
January	29	$5,800
February	26	$5,800
March	38	$5,900
April	28	$5,700
May	21	$5,400
June	18	$5,000
July	20	$5,000
August	45	$5,700
September	15	$4,900
October	14	$4,900
November	13	$5,000
December	2	$4,500

The total electricity consumed in August 2009 to produce the 45 modules was 42,640 kilowatt hours. This results in an energy usage of 948 kilowatt hours per module as shown on Table 9.

Table 9

Electricity Used per Module in August 2009

Total Electricity Consumed in Production	42,640 kWh
Modules Produced in August 2009	45 modules
Electricity Used per Module	948 kWh

Table 10

Electricity Used per Module in Full Capacity Production

Total Electricity Used in Production	42,640 kWh
Modules Produced Assuming Full Capacity	80 modules
Electricity Used per Module	533 kWh

However, electricity usage is considered a fixed volume up to a maximum production of 80 modules per month. Therefore, total electricity per module decreases as production volume increases to meet the optimum threshold of 80 units. As Table 10 shows, the electricity usage per module decreases to 533 kilowatt hours for 80 modules.

4.6 Propane

One hundred and fifty pounds of propane were used in August to produce 45 modules. Table 11 shows that propane used per module was 3.33 pounds. To produce the maximum production level of 80 modules, 116.5 more pounds of propane would be used, for a total of 266.5 pounds as shown on Table 12.

Table 11

Propane Used per Module in August 2009

Propane Used in August 2009	150 lb
Number of Modules Produced	45 modules
Propane Used Per Module	3.33 lb

Table 12

Propane Used per Module in Full Capacity Production

Propane Used per Module	3.33 lb
Additional Modules Produced	35 modules
Additional Propane for 35 Modules	116.5 lb
Propane Used for 45 Modules	150 lb
Total Propane Used for 80 Modules	266.5 lb

4.7 Kerosene

Three gallons of kerosene are used each day for the drywall drying operation. Operation period of the drying process is over 20 days. A total of 60 gallons of kerosene were used in the drywall drying operation to produce the 45 modules. This results in a 1.33 gallon-per-module usage as shown in Table 13. If the number of modules is increased to full capacity, the additional 35 modules would require 46.6 more gallons of kerosene. Therefore, a total 106.5 gallons of kerosene would be used to produce 80 modules as shown in Table 14.

Table 13

Kerosene Used per Module in August 2009

Kerosene Used in Production	60 gal
Number of Modules	45 modules
Gallons per Module	1.33 gal/module

Table 14

Kerosene Used per Module in Full Capacity Production

Kerosene Used per Module	1.33 gal
Additional Modules Produced	35 modules
Additional Kerosene for 35 Modules	46.6 gal
Kerosene Used for 45 Modules	59.9 gal
Total Kerosene Used for 80 Modules	106.5 gal

4.8 Findings

Electricity:

Electricity is the largest source of energy consumed in modular home production in the Penn Lyon fabrication plant. As stated earlier, approximately 42,640 kilowatt hours of electricity were consumed to build 45 modules in August 2009. This electricity was generated in the nearby Pennsylvania Power and Light grid in the RFC East sub region classification by the U.S. EPA. The EPA shows an annual carbon dioxide emission rate of 1.15 pounds for each kilowatt hour of electricity produced as shown in Table 15 below (Diem, 2009).

Table 15

eGrid Sub Region Carbon Dioxide Annual Output Emission Rates

eGrid sub region acronym	eGrid sub region name	Carbon Dioxide equivalent pounds per kWh
AKGD	ASCC Alaska Grid	1.235
AKMS	ASCC Miscellaneous	0.50
ERCT	ARCOT All	1.33
FRCC	FRCC All	1.33
HIMS	HICC Miscellaneous	1.54
HIOA	HICC Oahu	1.82
MORE	MRO East	1.85
MROW	MRO West	1.83
NYLI	NPCC Long Island	1.55
NEWE	NPCC New England	0.94
NYCW	NPCC NYC/Westchester	0.82
NYUP	NPCC Upstate NY	0.72
RFCE	RFC East	1.15
RFCM	RFC Michigan	1.57
RFCW	RFC West	1.55
SRMW	SERC Midwest	1.84
SRMV	SERC Mississippi Valley	1.02
SRSO	SERC South	1.50
SRTV	SERC Tennessee Valley	1.52
SRVC	SERC Virginia/Carolina	1.14
SPNO	SPP North	1.97
SPSO	SPP South	1.67
CAMX	WECC California	0.73
NWPP	WECC Northwest	0.91
RMPA	WECC Rockies	1.89
AZNM	WECC Southwest	1.32
U.S.	Average	1.34

The electricity consumed to build 45 modules produced 49,036 pounds of carbon dioxide. The fabrication of each module was responsible for producing 1,090 pounds of carbon dioxide as seen on Table 16.

Table 16

Carbon Dioxide Produced per Module from Electricity for August 2009

Total Electricity Consumed in Production	42,640 kWh
Carbon Dioxide Produced per kWh	1.15 lb
Total Carbon Dioxide Produced	49,036 lb
Total Modules Produced	45 modules
Carbon Pounds Dioxide Produced per Module	1,090 lb

Since the average module size was 700 square feet, Table 17 shows that each square foot of module production resulted in 1.56 pounds of carbon dioxide emissions.

Table 17

Carbon Dioxide Produced from Electricity Per Square Foot

Carbon Dioxide Produced per Module	1,090 lb
Average Square Feet per Module	700 sq ft
Carbon Dioxide Produced per Square Foot	1.56 lb

Table 18 shows that at full capacity production of 80 modules, the carbon footprint per module would be reduced to 613 pounds of carbon dioxide per module.

Table 18

Carbon Dioxide Produced from Electricity per Module in Full Capacity Production

Total Carbon Dioxide Produced	49,036 lb
Total Modules Produced	80 modules
Carbon Dioxide Produced per Module	613 lb

This higher production would reduce the impact of carbon produced to 0.88 pounds of carbon dioxide per square foot of production per Table 19.

Table 19

Carbon Dioxide Produced from Electricity per Square Foot in Full Capacity Production

Carbon Dioxide Produced per Module	613 lb
Average Square Feet per Module	700 sq ft
Carbon Dioxide Produced per Square Foot	0.88 lb

Table 20 shows that a typical two-module, 1,400-square-foot home built in August 2009 would contribute 2,180 pounds of carbon dioxide from the electricity consumed.

Table 20

Carbon Dioxide Emissions for a Two-Module Home Produced in August 2009

Carbon Dioxide Produced per Module	1,090 lb
Number of Modules in 1400-Square-Foot Home	2 modules
Carbon Dioxide Produced per Home	2,180 lb

This same home, built under the full production scenario of 80 modules per month, would contribute 1,226 pounds of carbon dioxide from the electricity consumed as illustrated in Table 21.

Table 21

Carbon Dioxide Emissions for a Two-Module Home Produced in Full Capacity Production

Carbon Dioxide Produced per Module	613 lb
Number of Modules in 1400-Square-Foot Home	2 modules
Carbon Dioxide Produced per Home	1,226 lb

Table 22 illustrates that larger three- and four-module homes built in August 2009 would contribute 3,270 pounds and 4,360 pounds, respectively, of carbon dioxide per home.

Table 22

Carbon Dioxide Emissions for Three- and Four-Module Homes Produced in August 2009

Carbon Dioxide Produced per Module	1,090 lb
Number of Modules in 2100-Square-Foot Home	3 modules
Carbon Dioxide Produced per 2100-Square-Foot Home	3,270 lb
Number of Modules in 2800-Square-Foot Home	4 modules
Carbon Dioxide Produced per 2800-Square-Foot Home	4,360 lb

These two larger homes built under full production of 80 modules per month would produce 1,839 pounds and 2,452 pounds, respectively, of carbon dioxide per home as shown in Table 23.

Table 23

Carbon Dioxide Emissions for Three- and Four-Module Homes Produced in Full Capacity Production

Carbon Dioxide Produced per Module	613 lb
Number of Modules in 2100-Square-Foot Home	3 modules
Carbon Dioxide Produced per 2100-Square-Foot Home	1,839 lb
Number of Modules in 2800-Square-Foot Home	4 modules
Carbon Dioxide Produced per 2800-Square-Foot Home	2,452 lb

Propane:

Propane consumption in the fabrication process was relatively minor. Only 150 pounds of propane were used in August to produce 45 modules. This equals 3.33 pounds of propane per module. Propane usage is variable with production, so at full production of 80 modules per month, 116.5 more pounds of propane are used than when just 45 modules are produced.

Each pound of propane consumed contributes approximately 12.67 pounds of carbon dioxide emissions (EIA, 2010). Table 24 shows the carbon dioxide emissions for propane under the scenarios discussed above.

Table 24

Carbon Dioxide Emissions from Propane Usage for 45 and 80 Modules

Propane Used per Module	3.33 lb
Carbon Dioxide Produced per Pound of Propane	12.67 lb
Carbon Dioxide Produced per Module	42.19 lb
Carbon Dioxide Produced from 45-Module Production	1,899 lb
Carbon Dioxide Produced from 80-Module Production	3,375 lb

Kerosene:

Kerosene consumption in the fabrication process was also relatively minor. Only 60 gallons of kerosene was used in August to produce 45 modules. This consumption equals 1.33 gallons of kerosene per module. Since kerosene usage is variable with production, at full production of 80 modules per month, 46.6 more gallons of kerosene would be consumed.

Each gallon of kerosene consumed contributes approximately 21.54 pounds of carbon dioxide emissions (EIA 2010). Table 25 shows the carbon dioxide emissions for kerosene under the scenarios discussed above.

Table 25

Carbon Emissions from Kerosene Usage for 45 and 80 Modules

Kerosene Used per Module	1.33 gal
Carbon Dioxide Produced per Gallon of Kerosene	21.54 lb
Carbon Dioxide Produced per Module	28.65 lb
Carbon Dioxide Produced from 45-Module Production	1,289 lb
Carbon Dioxide Produced from 80-Module Production	1,723 lb

The following Tables 26 and 27 summarize the energy used in fabrication and its carbon emission equivalent for the August 2009 production volume of 45 modules and for full capacity production volume of 80 modules. Additional information is provided for carbon emissions per square foot for three different homes: a two-module 1,400-square-foot home, a three-module, 2,100-square-foot home, and a four-module 2,800-square-foot home.

Table 26

Energy Consumed and Carbon Emissions Produced per Module,August 2009

Energy Type	Energy Consumed	CO_2 per Unit	Total CO_2 per Month	Number of Modules	CO_2 per Module
Electricity	42640 kWh	1.15 lb	49,036 lb	45	1,090 lb
Propane	150 lb	12.67 lb	1,900 lb	45	42.2 lb
Kerosene	60 gal	21.54 lb	1,292 lb	45	28.7 lb
TOTAL			52,228 lb	45	1,161 lb

Table 27

Energy Consumed and Carbon Emissions Produced per Module in Full Capacity Production

Energy Type	Energy Consumed	CO_2 per Unit	Total CO_2 per Month	Number of Modules	CO_2 per Module
Electricity	42,640 kWh	1.15 lb	49,036 lb	80	613 lb
Propane	266.4 lb	12.67 lb	3,375 lb	80	42.2 lb
Kerosene	106.4 gal	21.54 lb	2,292 lb	80	28.7 lb
TOTAL			54,703 lb	80	684 lb

A calculation of energy consumption and carbon emissions is offered on a per-square-foot basis using the actual August production of 45 modules, with each module averaging 700 square feet. Table 28 shows 1.66 lb of carbon dioxide emissions per -square -foot.

Table 28

Energy Consumed and Carbon Emissions Produced per Square Foot in August 2009

Carbon Dioxide Produced per Module	1,161 lb
Number of Square Feet per Module	700 sq ft
Carbon Dioxide Produced per Square Foot	1.66 lb

Table 29 shows the calculation of energy consumption presented on a per-square-foot basis using the 80-module full capacity production.

Table 29

Energy Consumed and Carbon Emissions Produced per Square Foot in Full Capacity Production

Carbon Dioxide Produced per Module	684 lb
Number of Square Feet per Module	700 sq ft
Carbon Dioxide Produced per Square Feet	0.98 lb

4.9 Emissions per Home

Several additional calculations were made to determine the energy used to manufacture three hypothetical house sizes as illustrated in Table 30. The first home assumed a home size of two modules, or 1,400 square feet. The second home assumed a three-module or a 2,100-square-foot home. The third house was a four-module home, or 2,800 square feet. These initial calculations were made using the August consumption of energy for the production of 45 modules.

Table 30

Energy Consumed and Carbon Emissions for Homes Produced in August 2009

Home Size	1,400 sq ft	2,100 sq ft	2,800 sq ft
Number of Modules	2	3	4
Carbon Dioxide Produced per Module	1,161 lb	1,161 lb	1,161 lb
Carbon Dioxide Produced per Home	2,322 lb	3,483 lb	4,644 lb

Additional calculations were made, as shown in Table 31, using the same three home sizes but with energy consumption calculated at the full capacity production of 80 modules per month.

Table 31

Energy Consumed and Carbon Emissions for Homes Produced in Full Capacity Production

Home Size	1,400 sq ft	2,100 sq ft	2,800 sq ft
Number of Modules	2	3	4
Carbon Dioxide Produced per Module	684 lb	684 lb	684 lb
Carbon Dioxide Produced per Home	1,368 lb	2,052 lb	2,736 lb

4.10 Conclusion for Fabrication

The majority of carbon emissions in the fabrication segment of this study comes from electricity usage. Electricity is the predominant energy source that drives the factory. It is used for lighting, operation of production tools and equipment, ventilation, crane operation, and operation of the compressed air system. Records show that the energy consumption of electricity behaves predominantly as a fixed cost with little variation for volume. High production output takes advantage of fixed electricity costs and carbon emissions by allocating the cost and emissions over a larger amount of production. High production output in a given period of time results in a lower cost and decreased carbon footprint for each production unit.

Propane and kerosene are also used in small quantities in modular fabrication. Their usage varies with volume, so when production increases, the carbon emissions from these sources of energy also increase.

Chapter 5: Transportation and Installation

5.1 Transportation and Delivery

For site-built home construction, vendors and subcontractors transport and deliver components of the building to the job site as they are required. Numerous trips are made by most trade subcontractors and their suppliers as they bring material and equipment to be installed. In modularization, whole modules are delivered to the job site ready for installation. This section of the study addresses the carbon emissions attributed to the transportation and delivery of the 45 modules to their final destinations during the August 2009 study period.

The 45 modules were delivered to five delivery sites, for a total driving distance of 21,820 miles, including the return trips for the trucks driving back to the factory. The shortest driving distance (one way) was 130 miles, and the longest distance was 330 miles.

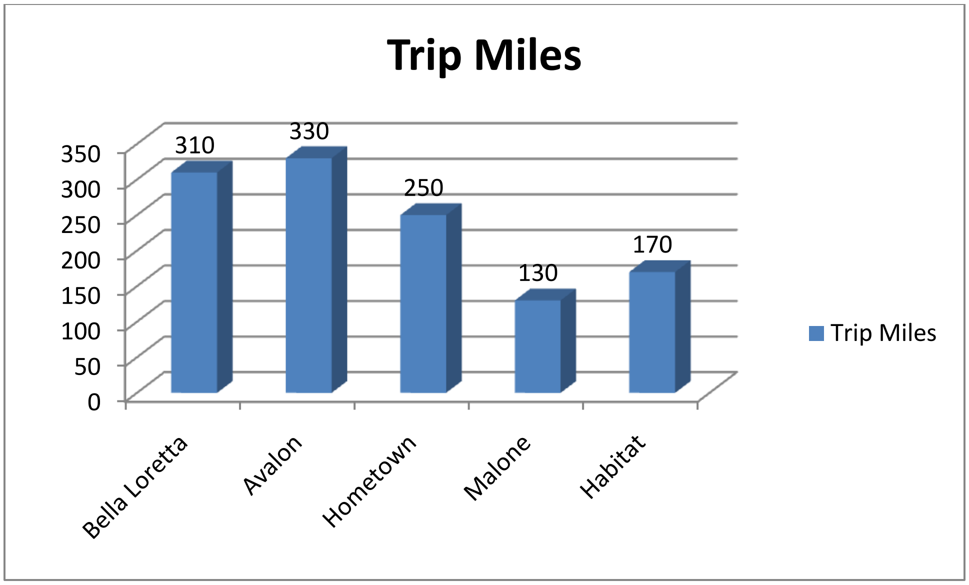

Figure 27. One-way trip miles by client for module delivery.

Penn Lyon delivery trucks use diesel fuel to operate. According to Penn Lyon management, these trucks average 5 miles per gallon of diesel fuel. To confirm that 5 miles per gallon was a reasonable number to use in this study, The US government census databank, Vehicle Use Survey, was consulted. The data found validated that the per- mile claim was reasonable. The trucks consumed a total of 4,364 gallons of diesel fuel to deliver 45 modules during August.

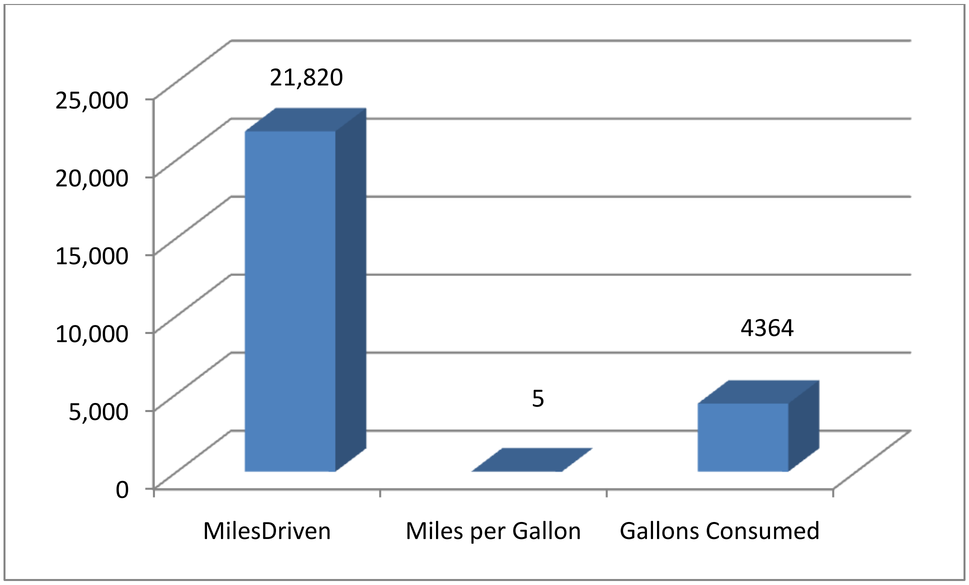

Figure 28. Gallons of diesel fuel consumed for August 2009 deliveries.

Twenty two and two tenths (22.2) pounds of carbon emission is produced for each gallon of diesel fuel consumed by delivery vehicles, (EPA, 2005). The 4,364 gallons of diesel fuel used to deliver the modules produced 96,881 pounds of carbon dioxide emissions as shown in Table 32, or nearly 48.5 tons of carbon dioxide for the month of August. Table 33 shows that the delivery process produced on average, 2,153 pounds of carbon dioxide emissions per module per average trip or a little more than a ton.

Table 32

Carbon Emissions for Deliveries of 45 Modules in August 2009

Diesel Consumed in August 2009	4,364 gal
Pounds of Carbon Dioxide Emissions per Gallon	22.2 lb/gal
Carbon Dioxide Produced in August 2009	96,881 lb

Table 33

Average Carbon Emissions per Module

Carbon Dioxide Produced in August 2009	96,881 lb
Modules Delivered in August 2009	45 modules
Average Carbon Dioxide Emissions per Module	2,153 lb

If the factory was producing at full capacity the total driving distance would be 38,791 miles, assuming the same average distance for delivery. This means the trucks would consume 7,758 gallons of diesel to deliver the full capacity production of 80 units. Table 34 shows that the carbon emissions would be 172,228 pounds, or a little more than 86 tons. This equates to an average of 2,153 pounds of carbon emissions per module as seen on Table 35.

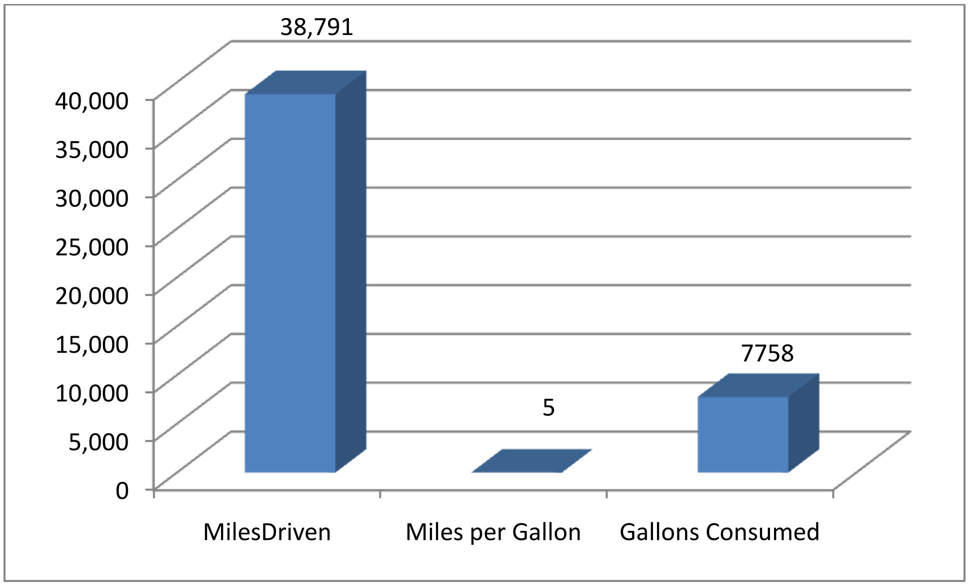

Figure 29. Gallons of diesel fuel required for delivery of 80 modules.

Table 34

Carbon Emissions for Delivery of 80 Modules

Gallons of Diesel Consumed	7,758 gal
Pounds of Carbon Dioxide Emission per Gallon	22.2 lb/gal
Carbon Dioxide Produced for Delivery of 80 Modules	172,228 lb

Table 35

Average Carbon Emissions per Module

Carbon Dioxide Produced for Delivery of 80 Modules	172,228 lb
Modules Delivered at Full Capacity Production	80 modules
Average Carbon Dioxide Emissions per Module	2,153 lb

5.2 Crane Delivery

The largest carbon component of the installation process is the delivery of the crane to the job site and operation of the crane during installation. Cranes can be sent from different distances, but they are usually close to the installation site. They normally require only one round trip. Actual installation time invested in a crane is small; the majority of the time is downtime spent waiting for a module to be set by an installation crew. For the purposes of this study, installation time was found to be a negligible part of the whole process.

According to Penn Lyon management, driving distances from the crane home base to the job site range, on average, from 30 to 40 miles one way. This study assumes that the driving distance for a crane was 35 miles one way and 70 miles round trip for the August 2009 installation projects. This results in a total driving distance of 350 miles to deliver the cranes to the five locations as seen on

Table 36. Table 37 illustrates that 70 gallons of fuel were consumed for the five deliveries.

Table 36

Crane Delivery Mileage for Five Deliveries

Average Round Trip Miles Driven	70 mi
Number of Crane Trips	5 trips
Total Miles Driven for Cranes	350 mi

Table 37

Gallons of Diesel Used for Five Deliveries

Total Miles Driven for Cranes	350 mi
Miles per Gallon of Diesel	5 mi/gal
Gallons of Diesel Consumed	70 gal

Since a crane was delivered to five job sites, the carbon emissions were found to be approximately 1,554 pounds of carbon dioxide for the 45 modules produced in August 2009, or 35 pounds per module as seen on Table 38.

Table 38

Carbon Emissions for Crane Deliveries in August 2009

Gallons of Diesel Consumed	70 gal
Pounds of Carbon Dioxide Emissions per Gallon	22.2 lb/gal
Total Carbon Dioxide Emissions for Crane Delivery	1,554 lb
Modules Produced in August 2009	45 modules
Average Carbon Dioxide Emissions per Module	35 lb

Assuming the same average delivery trips and distances for full production of 80 modules, the carbon emissions would total 2,800 pounds as shown on Table 39.

Table 39

Carbon Emissions for Crane Delivery in Full Capacity Production

Average Carbon Dioxide Emission per Module	35 lb
Modules Produced in Full Capacity Production	80 modules
Total Carbon Dioxide Emission for 80 Module Crane Delivery	2,800 lb

Assuming the same average distance of 35 miles for crane delivery and nine modules lifted per crane per trip, 2,800 pounds the carbon emission would be produced for 80 modules, as shown in Table s 40 and 41.

Table 40

Number of Trips for Crane Delivery in August 2009

Number of Modules Delivered in August 2009	45 modules
Number of Crane Trips	5 trips
Average Modules per Crane Trip	9 modules

Table 41

Number of Crane Trips in Full Capacity Production

Number of Modules for Full Capacity Production	80 modules
Average Modules per Trip in August 2009	9 modules
Number of Crane Trips for Full Capacity Production	8.9 trips
Number of Crane Trips Used for Study	9 trips

Tables 42, 43 and 44 show a recapitulation of crane delivery mileage driven, diesel used, and pounds of carbon dioxide emission for the installation of 80 modules.

Table 42

Total Miles driven for Nine Crane Deliveries

Average Round Trip Miles Driven for Crane Delivery	70 mi
Number of Crane Trips Driven for 80 Modules	9 trips
Total Miles Driven for Nine Trips	630 mi

Table 43

Gallons of Diesel Consumed for Nine Crane Delivery Trips

Total Miles Driven for Nine Trips	630 mi
Miles per Gallon of Diesel	5 mpg
Gallons of Diesel Consumed for Nine Trips	126 gal

Table 44

Average Carbon Dioxide Emissions per Module for Crane Delivery

Gallons of Diesel Consumed for Nine Trips	126 gal
Pounds of Carbon Dioxide Emission per Gallon	22.2 lb/gal
Total Carbon Dioxide Emissions for Crane Delivery	2,797 lb
Modules for Full Capacity Production	80 modules
Average Carbon Dioxide Emissions per Module for Crane Delivery	35 lb

5.3 Installation

The lifting of the modules and the installation process are relatively quick. Most time is spent in preparing for the lift by attaching the two-point lifting strapping and then removing them. Lifting and positioning take relatively little fuel to accomplish. For the purposes of this study, Penn Lyon management estimated that 0.7 gallons of diesel fuel were consumed per lift for the 45 modules that were lifted into position for August 2009 production. To lift all 45 modules, a total of 31.5 gallons of diesel fuel were consumed for the August 2009 installations.

As Tables 45, 46 and 47 show, the carbon emissions attributed to the installation of these 45 modules totaled 699 pounds of carbon dioxide, or 15.5 pounds per module. At a full-capacity 80 modules, the total carbon emissions would be 1,240 pounds of carbon dioxide.

Table 45

Gallons of Diesel Used in Installation of 45 Modules

Number of Modules Lifted	45 modules
Gallons of Diesel Consumed per Lift	0.7 gal
Total Gallons Consumed for Lifting 45 Modules	31.5 gal

Table 46

Pounds of Carbon Dioxide Produced in Installation in August 2009

Total Diesel Consumed	31.5 gal
Pounds of Carbon Dioxide per Gallon of Diesel	22.2 lb/gal
Carbon Dioxide Emissions for Installation of 45 Modules	699 lb
Number of Modules Installed	45 modules
Average Carbon Dioxide per Module	15.5 lb

Table 47

Pounds of Carbon Dioxide in Installation , Full Capacity Production

Carbon Dioxide Emissions per Module	15.5 lb
Number of Modules Installed	80 modules
Carbon Dioxide Emissions for 80 Modules	1,240 lb

5.4 Conclusion for Transportation and Installation

The operation that produced the highest carbon emissions per module in the entire manufacturing, delivery, and installation processes was the transportation of modules to their ultimate destination. On average, the modules traveled nearly 250 miles in one direction. The actual average round trip was calculated to be 484 miles.

In this study, the average delivery per module produced 2,153 pounds of carbon dioxide emissions. An average home consisting of 2,100 square feet, or three modules, would contribute a carbon footprint of 6,459 pounds of carbon dioxide, or more than three tons. Crane delivery and module installation contributed a relatively small amount of carbon dioxide emissions. Crane delivery accounted for 35 pounds of carbon emissions, and the module installation process accounted for 15.5 pounds, for a combined effect of 50.5 pounds per module. The total carbon impact of these processes on a three-module home is 152 pounds. The distance that a module is delivered is the single largest contributor to the carbon footprint of a fabricated, delivered, and installed modular home.

5.5 *Carbon Calculator Model*

A simple carbon calculator was developed in an effort to create awareness of carbon emissions in the modular fabrication, delivery, and installation processes. In order to make the carbon emissions calculating process easier, an interactive calculator is presented to help companies understand their energy consumption and carbon emissions. This tool is designed to help users measure the scale and impact of their carbon production. The calculator serves as a tool to not only determine emissions, but to also help the user manage them. Companies can use the carbon calculator to develop their own production profiles and quickly produce figures for carbon offset.

Carbon calculator developed from this case study:

As a consequence of this study, this researcher designed a carbon calculator to expedite the calculation of carbon emissions for the fabrication facility examined. This researcher compiled the steps into one easy-to-use Excel spreadsheet. The calculator is divided into three sections. The first section is the highlighted area that accepts inputs from the user. The second major area gives intermediate line-item calculations. The third boxed area shows the major outputs that were calculated. The tool offers visibility through key manufacturing indicators: individual standard module, square foot of production, and standard three-module home.

The calculator is a flexible tool that can quickly show monthly carbon footprint results, as well as quarterly and annual results. It is period sensitive.

Several calculators may be strung together to measure interim steps in a process. It can be used as a decision making tool to help reduce carbon output.

The carbon calculator can also be modified and used by other modular home fabricating facilities by simply adding any new energy sources used in the process. Individual pounds per unit of emissions can be used for the region that is appropriate to the factory being studied.

In addition, the calculator can serve other related construction industries with some internal customization. It can be used by HUD code manufacturing facilities, as well as other modular component fabricators, such as truss plants and wall panelizers. Process-driven fabrication facilities in other industries may also adopt this calculator with success. They may choose to incorporate an individual calculator in each natural production break or margin gate where energy can be measured in the same manner that cost or valued added points in the process are measured. The string of calculators can be summed to show carbon output by total or by period desired.

Carbon Calculator:									
	Consumption	**Units per Consumption**	**Units Used**	**Pounds CO2 per Unit**	**Pounds CO2 per Month**	**Modules**	**Pounds CO2 per Module**	**Square Feet per Module**	**Pounds CO2 per Square Foot**
Fabrication:									
Electricity-Kwh			42,640	1.15	**49,036.00**	45	**1,089.69**	700	**1.557**
Propane-pounds			150	12.67	**1,900.50**	45	**42.23**	700	**0.060**
Kerosene-gallons			60	21.54	**1,292.40**	45	**28.72**	700	**0.041**
Heating Oil-gallons									
Natural Gas-pounds									
Delivery:									
Disrance Driven-miles	21,820	5	4364	22.2	**96,880.80**	45	**2,152.91**	700	**3.076**
Pilot Vehicles-miles									
Installation:									
Crane delivery-miles	350	5	70	22.2	**1,554.00**	45	**34.53**	700	**0.049**
Lift-modules	45	0.7	31.5	22.2	**699.30**	45	**15.54**	700	**0.022**
Total:					**151,363**	45	**3,364**	700	**4.805**
Modules per home:							3	3	
Pounds CO2 per Home:							**10,091**	2100	
Pounds per Ton:					2,000.00		2,000.00		
Tons CO2 per Month:					**75.68**				
Tons CO2 per Module:							**1.68**		
Tons CO2 per Home:								**5.05**	
Imput numbers									
Key Output numbers									

Figure 30. Carbon Calculator

Chapter 6: Comparison of Housing Systems

6.1 Introduction

The results of the study show the carbon emissions of fabrication, delivery and installation of a typical modular home. This chapter compares the carbon footprint of a typical modular home to a site built home. It goes on then to isolate delivery of modules as a distinguishing factor that differentiated the two building methods. The study presents a methodology to calculate the breakeven point distance from plant to construction site where the two building methods are equal in carbon emissions.

6.2 Results Recap

The average level of emissions per unit quantity of energy or fuel was researched. Penn Lyon plant consumed electricity from the electric eastern grid called RFC East. Approximately 1.15 pounds of carbon dioxide emissions are produced for every kilowatt hour of electricity consumed. Propane produces 12.67 pounds of carbon dioxide emissions per pound of propane. Kerosene produces 21.54 pounds of carbon dioxide emissions per gallon of kerosene. Diesel fuel, used in transportation and craning activities, emits 22.2 pounds of carbon dioxide emissions per gallon of diesel.

Finally the total emissions for the test month were calculated. Table 48 shows the details of carbon dioxide produced by the plant during fabrication, delivery and installation of the 45 modules produced in August 2009.

Table 48

Carbon Emissions for 45-Module Production

Fabrication, Delivery, and Installation	Total Emissions	Number of Modules	Per Module
Electricity	49,036 lb	45	1,090 lb
Propane	1,901 lb	45	42 lb
Kerosene	1,292 lb	45	29 lb
Total Fabrication	52,229 lb	45	1,161 lb
Module Delivery	96,881 lb	45	2,153 lb
Crane Delivery	1,554 lb	45	35 lb
Module Lift	699 lb	45	16 lb
Total Installation	2,253 lb	45	49 lb
TOTAL	151,363 lb	45	3,364 lb

During the test month the factory was operating at less than full capacity, and electricity, the major contributor to carbon emissions, is considered fixed in usage up to a maximum capacity of 80 modules per month. The following table is provided to show the emissions if the factory was operating at the full capacity 80-module output. Table 49 shows the carbon dioxide that would be produced by the plant during fabrication, delivery, and installation of 80 modules.

Table 49

Carbon Emissions for 80-Module Production

Fabrication, Delivery, and Installation	Total Emission	Number of Modules	Per Module
Electricity	49,036 lb	80	613 lb
Propane	3,375 lb	80	42 lb
Kerosene	2,292 lb	80	29 lb
Total Fabrication	54,703 lb	80	684 lb
Module Delivery	172,228 lb	80	2,153 lb
Crane Delivery	2,800 lb	80	35 lb
Module Lift	1,240 lb	80	15.5 lb
Total Installation	4,040 lb	80	50.5 lb
TOTAL	230,971 lb	80	2,887.5 lb

The carbon footprint for a two-module home of 1,400 square feet, a three-module home of 2,100 square feet and a four-module home of 2,800 square feet was also calculated. Table 50 shows the results of the carbon dioxide emissions that would be produced for the three homes using the data results from August 2009.

Table 50

Carbon Emissions for Three Modular Homes Produced in August 2009

	Carbon Emissions per Module	1,400-Square-Foot Home, 2 Modules	2,100-Square Foot Home, 3 Modules	2,800-Square-Foot Home, 4 Modules
Modules	1,161 lb	2,322 lb	3,483 lb	4,644 lb
Delivery	2,153 lb	4,306 lb	6,459 lb	8,612 lb
Installation	50.5 lb	101 lb	152 lb	202 lb
Total	3,364 lb	6,726 lb	10,090 lb	13,452 lb

The same calculations were made using full production data of 80 modules per month. Table 51 shows the results of the carbon dioxide emissions that would be produced for the same three homes under full production.

Table 51

Carbon Emissions for Three Modular Homes in Full Capacity Production

	Carbon Emissions per Module	1,400-Square-Foot Home, 2 Modules	2,100-Square-Foot Home, 3 Modules	2,800-Square-Foot Home, 4 Modules
Fabrication	684 lb	1,368 lb	2,052 lb	2,736 lb
Delivery	2,153 lb	4,306 lb	6,459 lb	8,612 lb
Installation	50.5 lb	101 lb	152 lb	202 lb
Total	2,887.5 lb	5,775 lb	8,663 lb	11,550 lb

6.3 Observations

Carbon emissions can be quantified in a modular fabrication plant when energy usage can be measured. Within the factory walls, electricity, propane, and kerosene are used in modular production. In the delivery and installation process, diesel fuel is the energy source with the highest consumption and made the largest impact on the carbon emissions for the study period.

The average one-way trip distance for this study was 242 miles, with a total round trip of 484 miles. This distance caused average carbon emissions of 2,124 pounds per module. Carbon emissions are variable with miles driven and gallons of diesel consumed. The conclusion is that reducing the distance that a module travels to its final destination reduces the carbon footprint of the trip and the impact on the environment.

Perhaps a good future strategy that might be considered, when new modular factories are anticipated, is their proximity to the developing market they serve. The closer the factory is located to the building sites, the smaller is the carbon impact from transportation of modules.

6.4 Comparison of Modular Home to a Site-Built Home

An attempt was made to compare two different forms of home production for environmental performance. The results of this case study were used as a starting point for comparison with data found in the Palaniappan 2009 study. Several adjustments were necessary to make the studies comparable. As an example, modular homes are produced with a finished floor and must be set on a foundation. The foundation is normally site-built. Results reported by Palaniappan included home foundations as well as floors. The energy sources used by the Penn Lyon Factory in this study are specifically identified by type and their carbon dioxide emission value is reported for that type. In the Palaniappan study of site-built homes, some energy value averages were used.

A three-module, three-bedroom, single-family home was compared with a similar site-built home. The average one-way module delivery distance of 250 miles was used in the calculation.

The concreting phase of a site-built home included a post-tensioned slab floor and foundation combination that resulted in 3,900 pounds of emissions per home, as reported in the Palaniappan study. Only a foundation is needed for a modular home. The floor is prefabricated and included with the modules. For the sake of this presentation, 600 pounds of carbon dioxide were added to the modular home for foundation emissions. This amount represents 15% of the 3,900 pounds of carbon emissions that were reported by Palaniappan and which were calculated for a foundation and floor together. The emissions experienced to produce a stem wall foundation used in modular construction were assumed to be approximately the same as in a stem wall foundation with no floor used in site built construction. An additional 400 pounds or 12.5% was added for miscellaneous finish work or contractor incurred emissions.

Table 52

Carbon Emissions Comparison between Modular and Site-Built Homes

	Carbon Emissions in August 2009	Carbon Emissions in Full Capacity Production
Fabrication of Modules	3,500 lb	2,200 lb
Delivery of Modules	6,750 lb	6,750 lb
Foundation Added	600 lb	600 lb
Other Finish Work	400 lb	400 lb
Total Modular Home	12,000 pounds	9,950 pounds
Site-Built Home	16,000 pounds	16,000 pounds
Difference	**4,750 pounds**	**6,050 pounds**

Table 52 shows the comparison under the assumptions of both studies. The results show that the modular home produces 4,750 pounds or 30% less carbon than the site-built home for the subject month of August 2009 and 6,050 pounds or 38% less carbon at optimum production, subject to the underlying conditions of each study.

From the results presented, it is very evident that the biggest variable component of carbon emissions for modular home production is the delivery impact. Under the conditions of this study, modules traveled about 250 miles from the factory. Trucks completed the round trip back to the factory once the modules were delivered. The average round trips totaled approximately 500 miles, and that was the distance used to calculate the carbon impact for the subject month.

The study concluded that the greater the delivery distance those modules must travel, the closer the carbon performance of the two methods, modular versus site built, become. Conversely, the closer to the factory the installation sites are, the lower the carbon emissions from transportation are experienced, meaning the modular homes excel in environmental performance.

Tables 53 and 54 show that the delivery distance of 435 miles from the factory produces 11,588 pounds of carbon emissions for the home in the above example, rounded to 11,500 pounds. This distance and the carbon emissions associated with it represent the break-even point where modular homes are comparable to site-built homes based on their carbon footprint. In other words, at 435 miles, the two methods of construction result in equal carbon emissions. To be carbon emissions competitive, modular homes must stay under the 435 mile radius of the fabrication plant to compete with the carbon footprint of a site built home using August, 2009 production output numbers. The upper limit for transportation at optimum production is a 481 mile radius.

Table 53

Equalize Modular and Site-Built Homes with Delivery Emissions

	Carbon Emissions in August 2009	Carbon Emissions in Full Capacity Production
Fabrication of Modules	3,500 pounds	2,200 pounds
Delivery of Modules	**11,500 pounds**	**12,800 pounds**
Foundation Added	600 pounds	600 pounds
Other Finish Work	400 pounds	400 pounds
Total Modular Home	16,000 pounds	16,000 pounds
Site-Built Home	16,000 pounds	16,000 pounds

Table 54

Carbon Emissions for Delivery to Equalize Homes

	Carbon Emissions in August 2009	Carbon Emissions in Full Capacity Production
Miles Drive One Way	**435 mi**	**481 mi**
Total Round Trip	870 mi	962 mi
Number of Modules	3 modules/home	3 modules/home
Total Miles Driven	2,610 mi	2,885 mi
Gallons per Mile	5 gal	5 gal
Total Gallons Consumed	522 gal	577 gal
Carbon Emissions per Gallon	22.2 lb/gal	22.2 lb/gal
Delivery of Modules (rounded)	**11,500 lb**	**12,800 lb**

Chapter 7: Discussion and Findings

7.1 Recapitulation of Work

The major thrust of the study was to determine if a carbon footprint could be calculated for a modular manufacturing facility, and if so, how. The criteria used for measuring the carbon footprint of modular fabrication were the energy usage of the factory in the fabrication process and the energy used in delivery and installation of modules at their destination.

This researcher developed a methodology to calculate the initial carbon dioxide emission of the factory based on the quantities of energy used in a test month. For the test month of August 2009, 42,640 kilowatt hours of electricity were used in the factory to produce 45 modules. In addition, 150 pounds of propane and 60 gallons of kerosene were used to produce those modules. This researcher found that the electricity usage was fixed for the monthly production and would remain at roughly the same consumption up to the maximum output of 80 units. Propane and kerosene usage behaved variably with module unit production.

The carbon footprint of the 45-module production output for the test month of August 2009 was also followed to its delivery destination. This was done to quantify the carbon dioxide emissions of the delivery process for the 45 modules produced. Diesel fuel was used in trucks to deliver the modules. It was consumed at a rate of one gallon for every five miles driven. All distances for module deliveries were calculated, and the number of deliveries per location was collected. Similar computations were made for installation of the 45 modules. Crane delivery and installation energy consumption was also captured.

7.2 Limitations

This study was conducted to find a methodology and a tool to study carbon emissions and to calculate the carbon footprint of fabricated production of a modular factory. One test month in one factory was used to perform the study. This was sufficient to derive a methodology for measuring carbon. Quantifiable conclusions were made from this test month case study, but the methodology can be expanded and recreated to improve both the techniques developed in this study and the accuracy of the resultant data. It should be noted that each production facility in different parts of the country may use different energy sources and quantities, which may give different results. Also, different variables or different seasons in the same facility may alter the results.

Verified average values per unit of energy were used for carbon emissions values to perform the calculations. More specific values, constantly updated from an energy provider and specific to the subject manufacturing facility, could be used to give more specific results.

Energy usage was captured and reported by management for the entire factory for one month. The electric energy used in production was captured from the monthly electric bills of the company compound. The company compound houses a few minor administrative functions. No attempt was made to reduce the electric usage for these nominal consumers of electricity. A better, more accurate method of capturing electric usage for fabrication would be to meter the factory separately for those entities that house significant non-manufacturing functions. The energy used for delivery to the job site and installation were also used in the computation of carbon emissions. However, the energy usage for bringing materials or employees to the fabrication plant was not included. Embodied energy used to produce raw material for construction was also excluded from this study.

In future studies, if pilot vehicles are employed in aiding the transportation and delivery of oversized modules from the factory to the installation site, they should be specifically identified by fuel type, consumption of fuel per mile travelled, and considered in the carbon footprint calculation.

An additional improvement could be made to the accuracy and usefulness of the information by metering key milestone or heavy consumer production departments or processes. Metering would attribute usage of energy to a specific fabrication point. This would give management greater visibility in determining energy consumption and carbon emissions at key points and help management monitor and reduce cost of energy and the carbon footprint.

7.3 Lessons Learned from Results

The methodology developed in this study serves several purposes. First, it establishes that carbon emissions were measurable for the fabrication process in a modular factory. The study identifies the biggest causes of carbon emissions in the production of fabricated residential modular units. It then quantifies carbon dioxide emissions by unit, type, and two levels of production—actual production for the test month and full capacity for one month.

The study led to several conclusions related to carbon emissions from modular fabrication. The Penn Lyon factory, when it operates at full capacity, produces fewer emissions per module than when it operates at less than full capacity.

The methodology is also useful to factory management as a way of monitoring month-to-month emissions based on energy used in production. The first step is choosing reasonably accurate emissions per unit value and then holding those values constant over several periods to make accurate comparisons for different monthly production volumes. This consistency of value is critical to producing meaningful results. Standards can be developed from historical data, and calculations can be made for volume variations and energy usage variations from a standard production.

7.4 Summary of Significant Findings

The following list is a summary recapitulation of the contributions that were made with this case study to the existing knowledge of modularization:

- A methodology was developed to measure the carbon footprint of modular home production, delivery, and installation. It was confirmed that the carbon footprint of a modular home factory can be measured and computed, as can its output in modules, square footage, and homes.
- Electricity was found to be the largest source of energy used and the largest emitter of carbon dioxide in modular fabrication. Reducing electricity consumption of a factory, per module, reduces the carbon footprint significantly.

- Electricity usage in a modular factory behaves as a fixed volume within normal ranges of production. Because of this fixed behavior, the closer the factory operates to optimum production, the less carbon per unit of production will be produced.
- Diesel fuel consumed during transportation of modules was the largest emitter of carbon dioxide in the study. For the approximate 250-mile, one-way delivery distance used in this study for the study month, diesel fuel accounted for 60% of the carbon emissions of a delivered and completed modular home. Using the same delivery distance and optimum production volume for fabrication of modules, diesel fuel represents 68% of the carbon emissions of the same delivered and completed modular home.
- Modular homes were found in this study to have a smaller carbon footprint than site-built homes. For the test month, the study found modular homes, delivered and installed, produce 70% of the carbon footprint of a comparable site-built home. There was a savings of 30% in carbon emissions. At normal production volumes modular homes produce 62% of the carbon footprint of a site built home, with a savings of 38% in carbon emissions.
- Since modular homes are set on foundations, they traditionally use less concrete than site-built homes and have smaller carbon footprints in terms of foundations and floors. Concrete delivery is a significant emitter of carbon as is the embodied energy found in the cement content of concrete.

- Delivery distance is the largest single factor that contributes to carbon emissions in the Modular Home Industry. Fabricated modular homes built in factories located close to home installation site, contribute significantly to a smaller carbon footprint than site-built homes.

- A carbon calculator was developed to expedite the computation of the carbon footprint and aid in decision making by facilitating “what if” scenarios.

- A methodology was developed to calculate the carbon emission breakeven point where the delivery distance makes modular and site built homes equal in carbon emissions.
- Monitoring and metering energy at key production points can create visibility in energy consumption, reduce costs, and help reduce carbon emissions from manufacturing.
- The methodologies and carbon calculator developed in this study can be applied to other housing industry segments. The technology transfers directly to HUD code manufactured homes, as well as residential housing component fabrication sectors such as panelizers and truss manufacturers.
- The technology developed and used in this study has a broader application. Any process-driven manufacturing or fabrication facility in industries unrelated to construction would benefit from the carbon computation methodology learned here.

- There is an economic benefit of reducing carbon emissions. Reducing energy usage, reduces cost. In turn, this reduction in cost has the beneficial effect of improving profits. The profit motive is a built- in incentive in the modular industry to reduce carbon emissions and become more sustainable.
- Smaller, energy efficient factories may ultimately be a viable strategy for reducing the delivery impact on the environment. This may be the model for sizing future manufacturing plants. Smaller factories may also be more cost effective when considering investments in buildings and equipment. Additionally, smaller factories could be designed to have better plant utilization in high production times by creating multiple production shifts that use the same assets.
- Locating permanent factories closer to active markets would reduce transportation distances and therefore carbon emissions and delivery costs.
- Another strategy to reduce delivery distances may be to make the factories themselves mobile. Factories could be designed to be located close to a particular market for an extended period and then moved to another location when that market is exhausted. In essence, the production facility moves with the need. Transportable factories would also be able to serve remote regions.

7.5 Other Benefits

As was reported previously, the same methodology that is presented in this study could be used by manufacturers of housing construction components, such as trusses and panelized walls, to measure their carbon emissions or footprint in their production facility. These fabricators can also use the carbon calculator as a way to measure, control, and diminish the fabrication carbon footprint within the fabrication process at interim steps both in the production process and in specific use applications. The same environmental manufacturing insights that this study discovered for home modularization can be gained by these related construction component industries.

7.6 Expanded Use

Modular factories that measure costs by individual processes could easily use this methodology to measure carbon emissions by process or workstation. By doing so they would monitor the production carbon footprint in smaller segments of production. This closer monitoring would allow better visibility and control of the production steps. Smaller segments of measurement would provide greater opportunity to reduce the impact of carbon emissions because of the increased visibility.

This factory-generated, carbon footprint measurement methodology might be used by process driven factories in other industries. Since modular home production is a process-driven method of manufacturing, any other process-driven manufacturing might benefit from using the methodology reported in this study. Future studies can be conducted to validate that this method can migrate to other fabrication disciplines that are process driven, even though they may be totally unrelated to construction or housing.

7.7 Future Studies

Additional months can be studied at the modular home fabrication facility to determine the effects that seasonality has on carbon emissions. By studying a winter month, additional energy sources may come into play, such as heating. It may be possible to make a correlation between seasons and carbon emissions in fabrication.

Modular factories buy in bulk quantities; a study might be conducted to compute the carbon emissions impact from delivery of the materials to the modular factory. This study can analyze how this delivery method's carbon impact compares to the deliveries of materials and equipment vendors who in turn supply builders of site-built homes. Perhaps it can be discovered that if more efficient delivery of material to the fabricating facility can offset the carbon emission of module delivery to the installation site.

More modular home manufacturing facilities can be studied using the carbon footprint measurement methodology. The studies of additional manufacturing facilities could be used to develop a best practices model for modular fabrication which could benefit all modular manufacturing facilities and help each one reduce its carbon emissions.

A study can be conducted using the method developed in this study and applied to a non-housing fabrication facility. This new study could then be used to determine the applicability of the methodology to other process-driven factories that are not residential modularization factories. These other facilities may benefit from the same carbon footprint insight gained in this original study.

The results of this study, presented here, can be used to compare carbon emissions of modular homes to each other and to site-built homes continually. Even though the modular and site-built technologies differ in execution, many similarities exist between the two home systems that make a comparison reasonable. Comparisons can be made using specific circumstances for each home or each real estate development project. The study and tools presented here can help contractors and real estate developers choose a method of delivering homes to potential homeowners based on value, time, and now environmental considerations.

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