PRELIMINARY LIFE CYCLE ANALYSIS OF MODULAR AND CONVENTIOINAL HOUSING IN BENTON HARBOR, MICHIGAN

By:

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A practicum submitted in partial fulfillment of requirements
For the degree of Master of Science
(Natural Resource and Environment)

University of Michigan
Ann Arbor
April 16, 2008

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Abstract

A 1,456 ft^2 modular home and conventional site built home in Benton Harbor, Michigan are analyzed to examine how the different construction and design methods of two types of housing influence environmental impact over their 50 year life span. The chosen modular home is fabricated by Redman Homes in Topeka, Indiana and transported to the building site. The conventional home is modeled after the modular home in collaboration with Douglas Construction Company. Many assumptions and simplification were made due to data gaps, so results represent preliminary estimates. The total amount of the materials placed in the conventional home is 9% less than the amount of the modular home because the modular home is framed with larger 2X6 studs and requires additional structural components. The conventional home produces 2.5 times more construction wastes than the modular home. The lesser material consumption of the conventional home is offset by a larger amount of waste generation. The building use phase dominates more than 93% of the life cycle energy consumption and over 95% of the total greenhouse gas emissions for both homes. The total life cycle energy consumption for modular home is 5% less than the conventional site home. The total global warming potential for the modular home is 5% less than the conventional site built home. The use phase energy consumption and greenhouse gas emission differences are attributed to the expected higher air tightness (0.194 ACH) of the modular home over the conventional home. The conventional home was modeled with 80% lower air tightness (0.35 ACH) than the modular home, which results in 7% more of the natural gas consumption over its service life. The modular home requires additional transportation energy compared to the conventional home for delivering the fabricated modular home to the site. However, 4~5 days of the modular home's short fabrication cycle time allows the modular home to significantly reduce the employee's transportation energy compared to that of the conventional home.

1. Introduction

1.1. Overview

Construction, use and demolition of buildings generate substantial social and economic benefits to society, but may also have serious negative impacts to the environment.[1] In the United States, 223,114 buildings were constructed in 2002. The building and construction industry represented more than $531 billion in annual revenue, $62 billion in annual payroll and 1.7 million employees in 2002.[2] However, buildings account for 65 % of electricity and 36% of primary energy use, 12% of potable water and 30% of raw material consumption in the US. Also, buildings discharge 30% of municipal solid wastes and account for 30% of greenhouse gas emissions in the last few years in the US.[3] Residential buildings are the biggest section in the construction industry, which accounts for 116 million buildings. Residential buildings consumed 21.05 quadrillion Btu in 2006, which accounted for approximately 55% of primary energy use from the building sector.[4] In this regard, the environmental impact of residential buildings deserved serious attention.

As a relatively new construction technology, modular homes are gaining in popularity and the modular housing industry segment is gradually increasing. In modular housing, most building parts are built in a factory and delivered to the site as fully assembled volumetric modules. The home modules are placed by crane on a conventional basement or crawl space foundation. According to the Census Bureau, the production of modular homes ranges from 32,000 to 37,000 units per year and they represent 7% of the single family and low-rise multi-family homes built in US.[5,6] The production of modular homes is also growing at a rate of 11%, compared to conventional site built houses, which are experiencing approximately 8% annual growth.[7]

According to the National Modular Housing Council, the modular home is considered superior in quality to the conventional site built home.[8] The research by the US Department of Housing and Urban Development indicated that specialized equipment used in assembly line operations of modular housing raises labor productivity and product quality. Workers are generally not subcontracted, and can be scheduled, managed and deployed by a single authority in the interest of productivity and efficiency.[9] Also, the controlled environment of modular housing minimizes risks and delays due to poor weather. On-site building mostly uses green lumber (higher than MC 19) and in addition, due to the site exposure, high moisture content lumber is often warped or bent after installation.[10]

Modular houses can be built faster than on-site built homes. Redman Homes reported that it usually takes less than 8 weeks from the order of a modular home to installation on site. In comparison, site built homes, take 3~4 months to complete. Therefore, it is expected that modular homes can maximize on efficiency of work, quality of construction and save energy consumption in relation to a shorter construction period.

To date, it would appear that only construction performance of the conventional home has been studied by industry and the academy, whereas environmental and sustainability studies have not yet been carried out on the modular home. The previous life cycle analysis studies have focused on only conventional residential and office buildings. Keoleian et al.[11] studied the life-cycle energy, greenhouse gas emissions and life cycle cost of a residential home to evaluate the opportunity for energy conservation. Asif et al.[12] studied the embodied energy and associated environmental impacts of a semi detached home. The study by Guggemos et al.[13] found that concrete framed buildings use more energy consumption and environmental impact than steel structural-frame buildings.

1.2. Purpose of Study

The modular home can offer advantages in construction quality, time, productivity and efficiency. Referring back to the environmental implications of residential buildings, residential homes significantly influence energy consumption, green house gas emission and solid waste discharge. It is expected that the modular home will offer a reduced environmental impact compared to the conventional site built home.

This study explores some of the perceived design features that distinguish a modular and conventional home. The different features, 2X6 stud framed structure, air tightness and short construction time, are investigated to begin to understand the effect of these differences on the life cycle environmental results. This study uses streamlined life cycle methods to estimate differences in primary energy consumption, greenhouse gas emissions, resource depletion and waste discharge between modular homes and conventional site built homes. Also, the study intends to identify how the differences in design and construction influence environmental impact.

This preliminary life cycle analysis utilizes databases from Sima Pro 6.0 and BEES 3.0 (Building for Environmental and Economic Sustainability). Many assumptions and simplifications are employed in the modeling due to lack of data.

2. Methodology

2.1. Overview of Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a "cradle-to-grave" approach for a system, from initial raw materials acquisition through the manufacturing and production cycle, as well as energy in use, to final disposal. LCA quantifies material and energy flows of all stages of a product's life. LCA evaluates and estimates the cumulative environmental impact resulting from all stages in the product life cycle. LCA provides a comprehensive view of the environmental influences of the products or process and a more accurate view of the true environmental trade-offs in product and process selection.[14]

An LCA study consists of four components: goal definition and scoping, inventory analysis, impact assessment and interpretation. Figure 1 shows the framework of life cycle assessment. Goal definition and scoping states the intended application, the reason for the study, and the intended audience and defines the functional unit and system boundaries. Inventory analysis involves the compilation and quantification of inputs and outputs throughout the life cycle of a system. Impact assessment evaluates the magnitude and significance of the potential environmental impacts of a product system. Interpretation combines the findings of the inventory analysis and impact assessment in order to present conclusions and recommendations.[15]

This life cycle analysis attempts to follow the standard life cycle analysis framework. However, this study is limited because it is not yet able to present a comprehensive life cycle analysis due to difficulty in obtaining sufficient data. Assumptions and simplifications used in this study due to data limitations are listed in Table 1.

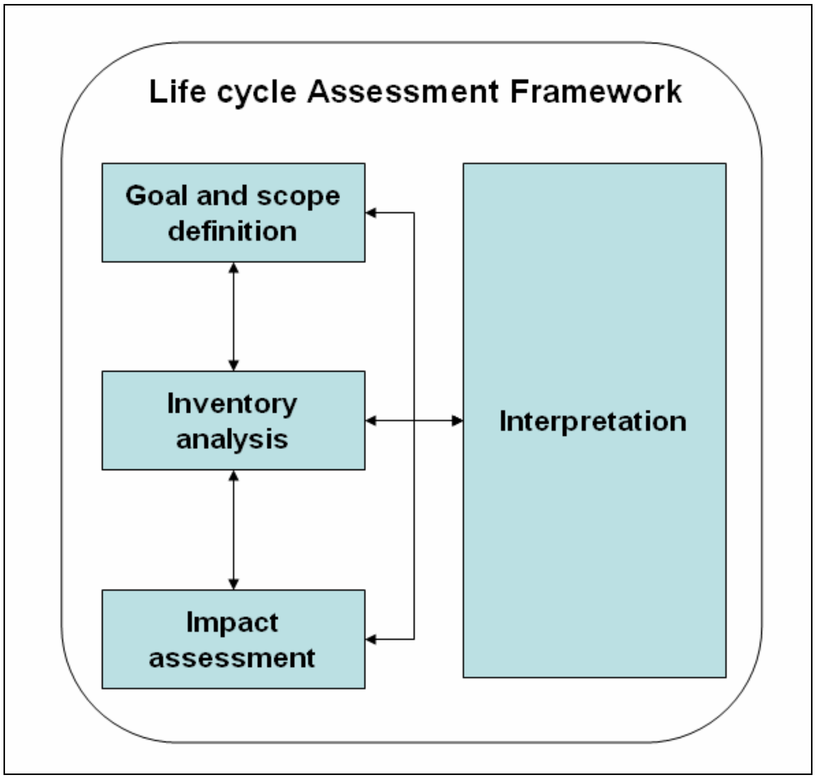

Figure 1 Life Cycle Assessment Framework (from ISO 14040 Standards)

Table 1 Assumptions and Simplifications in this study

Categories	Assumptions
Building materials	It is assumed that the two housing types are built with the same materials. Materials taken into account for the modular and conventional home are based on data for the 150 building materials provided by Redman Homes.
Building component difference	The perceived building component differences between the modular and conventional home are stud size, marriage wall and folding roof truss. Other differences are assumed to be negligible.
Construction energy	Construction energy for the conventional home is assumed to be equal to the modular home fabrication energy.
Air tightness	The air infiltration rate for the conventional home is assumed to be equal to the ASHRAE Standards.
Building energy consumption	Energy consumption of each home only accounts for internal

	house energy consumption. Energy consumption related to the house surroundings (e.g. outside lighting) is excluded.
Waste	It is assumed that all wastes generated from fabrication or construction are disposed in a landfill. The end of life management phase, however, was not modeled.
Material supply transportation	Truck (16 ton load carrying capacity) is assumed as the mode of material transportation. A simplified material supply is modeled with supplier locations provided by Redman Homes and Douglas Construction. The material supply model only pertains to the building site, the modular home factory and supplier locations chosen in this study. The material supply transportation modeled in this study can is not applicable to other building sites.
Employee transportation	One passenger per vehicle occupancy is assumed for employee transportation. Employees use standard passenger cars for commuting.

2.2. System definition

2.2.1. Modular Home

The modular home selected in the study is a *P 164 2660 Ranch* model manufactured by Redman Homes, Inc. The production factory is located at 308 Sheridan Drive, Topeka, Indiana. This model is one of the most representative of modular homes based on Redman Homes's unit production in 2006~2007. The building site is selected based on a recent project completed in Benton Harbor, MI in 2007. Also, the selection of a building site facilitates gathering information regarding material supply and general construction methods, in collaboration with a general contractor working with Redman Homes. The distance from Redman Homes factory to the site is 85 miles. However, according to Redman Home's production record, the modular home delivery distance ranges from 15 miles to 1760 miles and the average distance is approximately 200 miles. The impact of the modular home's delivery distance on the results is analyzed separately in later chapters.

The modular home consists of 2 modules (Module A and Module B), as shown in

Figure 2, 3 and 4. Module A contains a master bedroom, 1 bathroom, kitchen, dining room and utility spaces. Module B contains 3 bedrooms, 1 bathroom, living room and stairway. The home is constructed with a basement having the same size as the building's footprint area, 1,456 square feet. This modular home is structured with 2X6 lumber and shaped with oriented strand board (OSB) and plywood.

Redman Homes reported that it usually takes 4~5 days to fabricate a modular home. In Addition, approximately 3 weeks are required for site-work including excavation and foundations. Therefore, within maximum 8 weeks, the modular home is manufactured, transported and installed at the site and ready to meet the new home owners. This reduced cycle time means that employees spend less time to build a house, which translates to less employee's transportation energy associated with building a modular home. Considering 3~4 months of typical construction time for building a conventional home, the energy savings in transportation is an advantage to the modular home.

The materials used for a modular home are purchased in large quantity and some of them, such as lumber, are delivered directly from where they are harvested (mostly from Canada). Other materials are also procured directly from suppliers, which mean that the material cost and transportation energy will be less for this type of construction.

Modular home fabrication allows material inventories to be stored in a controlled environment in the factory and they are protected from the weather. The quality of lumber in particular depends on the moisture content (MC). If the lumber has more than 19% of MC, they are categorized as Green lumber and are therefore more likely to experience cracks and easily warp and bend after installation in a building.[9] However, most materials used in a modular home are kept in a dry condition. According to the management at Redman Homes, the probability of material damage is relatively low and therefore the modular home experiences less quality problems than the conventional home.

In general, the modular home requires a more substantial structure to survive transportation damage. During transportation, the modular home experiences dynamic loads on delivery trucks or erection cranes and in order to prevent potential transportation damage, the modular home requires additional structural stiffness and uses larger 2X6 lumber instead of 2X4 lumber. Overall, this results in a much stiffer structure in modular homes which could withstand greater forces such as hurricanes and earthquakes compared to conventional site built homes.

The modular home is fabricated along efficient assembly lines, where more precise cutting and measuring machines are utilized than the conventional site built home. Therefore, building components in the modular home fit more precisely with greater quality controls under the supervisions of trained inspectors. In this respect, Redman Homes reported that modular homes are rarely subject to claims from home owners, compared with site built homes. Repairs can take several months to complete.

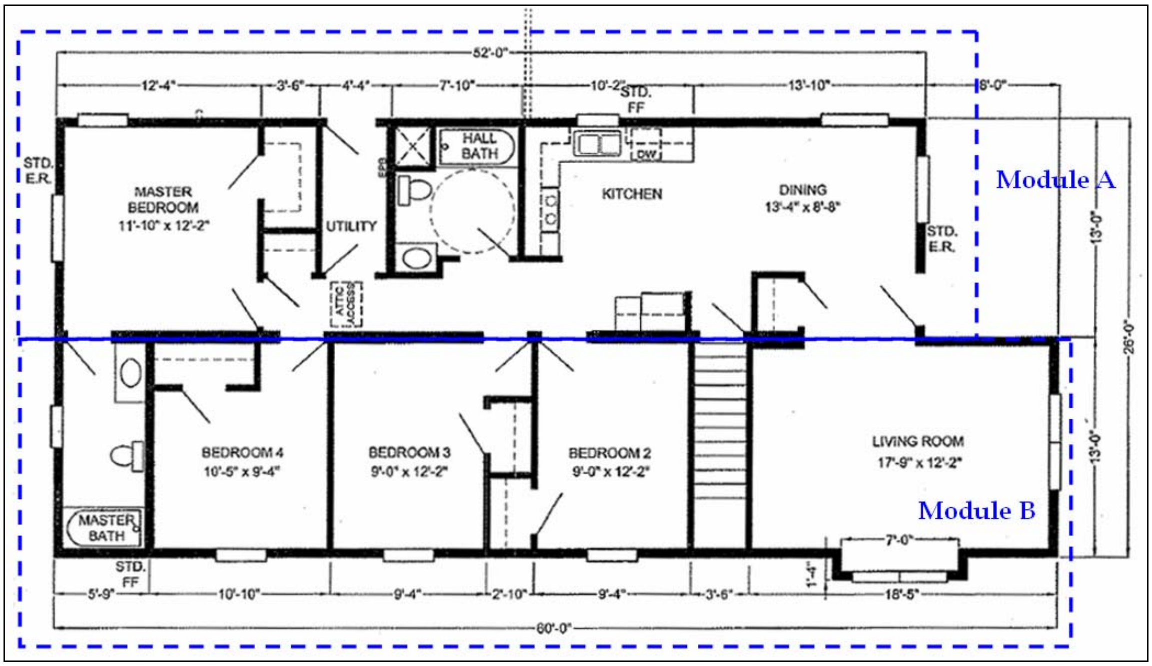

Figure 2 Layout of Modular Home (P 164 2660 Ranch)

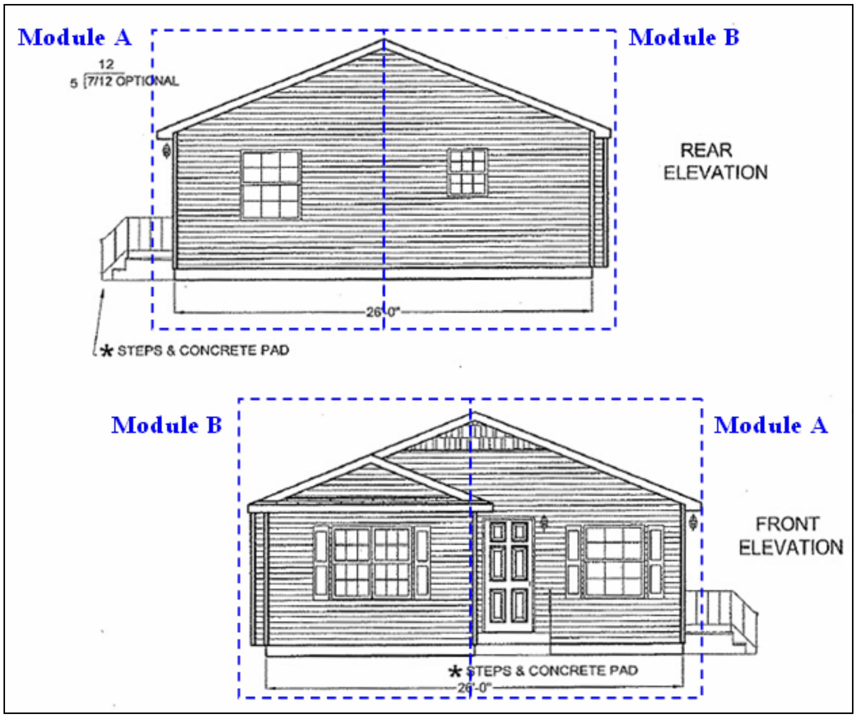

Figure 3 Elevation (rear and front) of Modular Home (P 164 2660 Ranch)

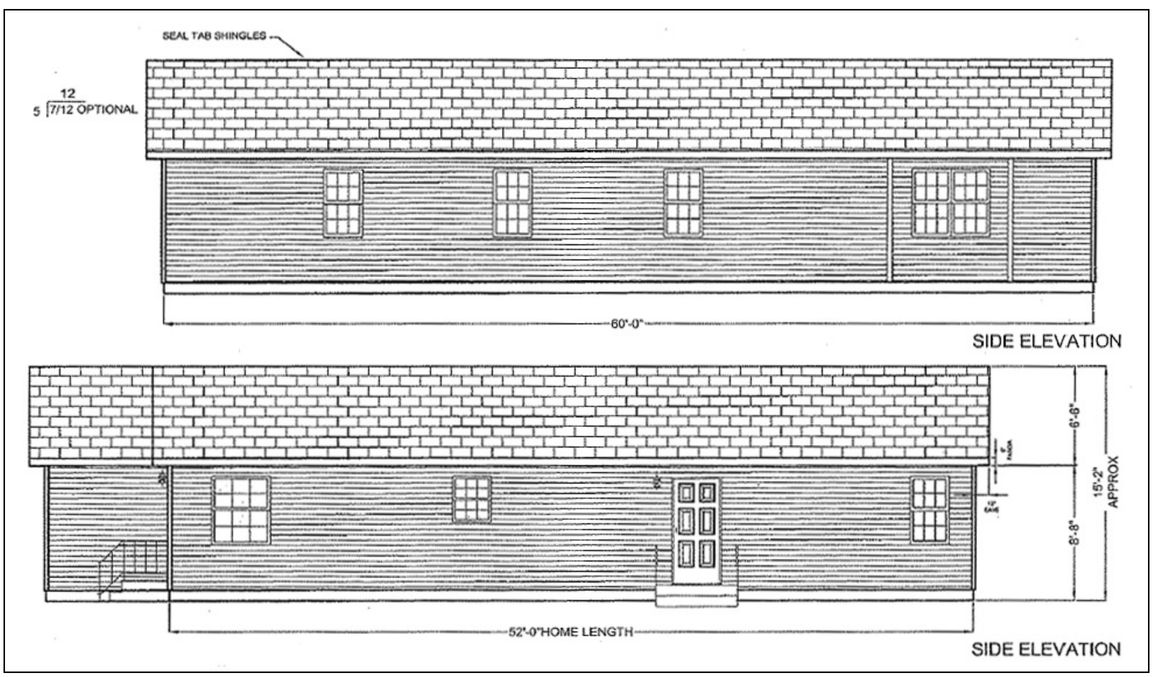

Figure 4 Elevation (side) of Modular Home (P 164 2660 Ranch)

2.2.2. Conventional Home

Due to difficulty in finding a comparable conventional site built home with the same size and quality of a modular home, a conventional home is analyzed with using the industry average data from RS Means[16] combined with information supplied by Douglas Construction Company (1716 Perrysburg-Holland Rd, Holland, OH). The conventional home is modeled after the modular home. As shown in Figure 5, the conventional site built home has a similar floor plan to the modular home. Also, this home has the same floor area and volume as the modular home. However, the conventional home is structured with 2X4 studs and other structural and component differences from modular home are advised by Douglas Construction Company. The perceived modular home's differences from the conventional home include:

- ✓ 2X6 wood framed walls instead of 2x4 wood framed walls
- ✓ marriage walls, which are the structure used for attaching modules to each together
- ✓ roof truss (Redman Homes indicated that folding roof structure of modular home is different from the conventional home's roof structure, but the type and amount of materials used for both roof trusses are almost identical and the differences are neglected in the analysis)

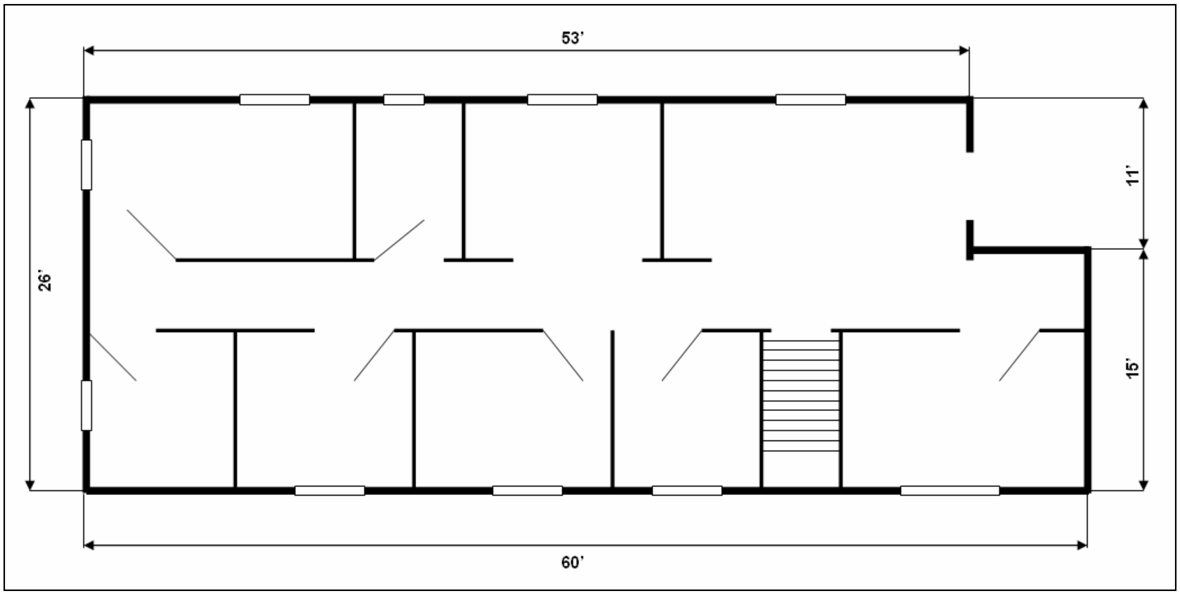

Figure 5 Conventional Home Floor Plan

3. Life Cycle Assessment

3.1. Functional Unit and System Boundary

3.1.1. Functional Unit

Functional unit is defined as a measure of the performance of the functional outputs of the product system. In LCA study, the functional unit provides a reference to which the inputs and outputs are related.[5] In order to set a baseline to compare a modular home and conventional home, the functional unit for this study is defined as a unit of house, of which components and criteria include:

- One story single family house
- 4 bedrooms, 2 bathrooms, kitchen, dining, living room and utility space as usable area
- 50 years of expected service life
- Thermal comfort: occupied cooling set-point (70˚F), heating set-point (70˚F); unoccupied cooling set-point point (80˚F), heating set-point (65˚F); and unoccupied setting from 7am to 5 pm
- Heating and hot water is supplied by a natural gas boiler
- Other energy using devices using grid-supplied 110V or 220V electricity

A basement floor and a garage area are not considered in the functional unit. The foundation and basement for both types of housing are identical, so comparison of both homes' substructure does not provide a comparative result. Also, the modular home does not employ an in-door garage. Therefore, a garage for the conventional home is also excluded from the functional unit.

This study does not include the replacement of each home, which means that any maintenance or renovation is not taken into account. The environmental impacts of each home are projected in the 50 years estimated for each building's service life.

Electrical energy loads include cooling, interior lighting, cooking equipment, refrigeration, laundry and miscellaneous equipment. Natural gas is used for a space heating furnace and a water heating boiler. The domestic energy load is simulated with e-Quest 3.6.

This study includes most major components and systems of each home. Major building materials included in this study are lumber, plywood, oriented strand board (OSB), gypsum board, insulation material, shingle, plastics, carpet, steel, urethane, polyethylene and wood trim. However, several components and processes were not included in this study:

- ✓ basement and foundation of each home
- ✓ replacement materials (e.g. paint, carpet and shingle) over the 50 year service life
- ✓ furniture and appliance used in each home
- ✓ materials and energy used for installing the modular home at the site
- ✓ garage

3.1.2. System Boundary

Figure 6 Life Cycle System of Modular Home

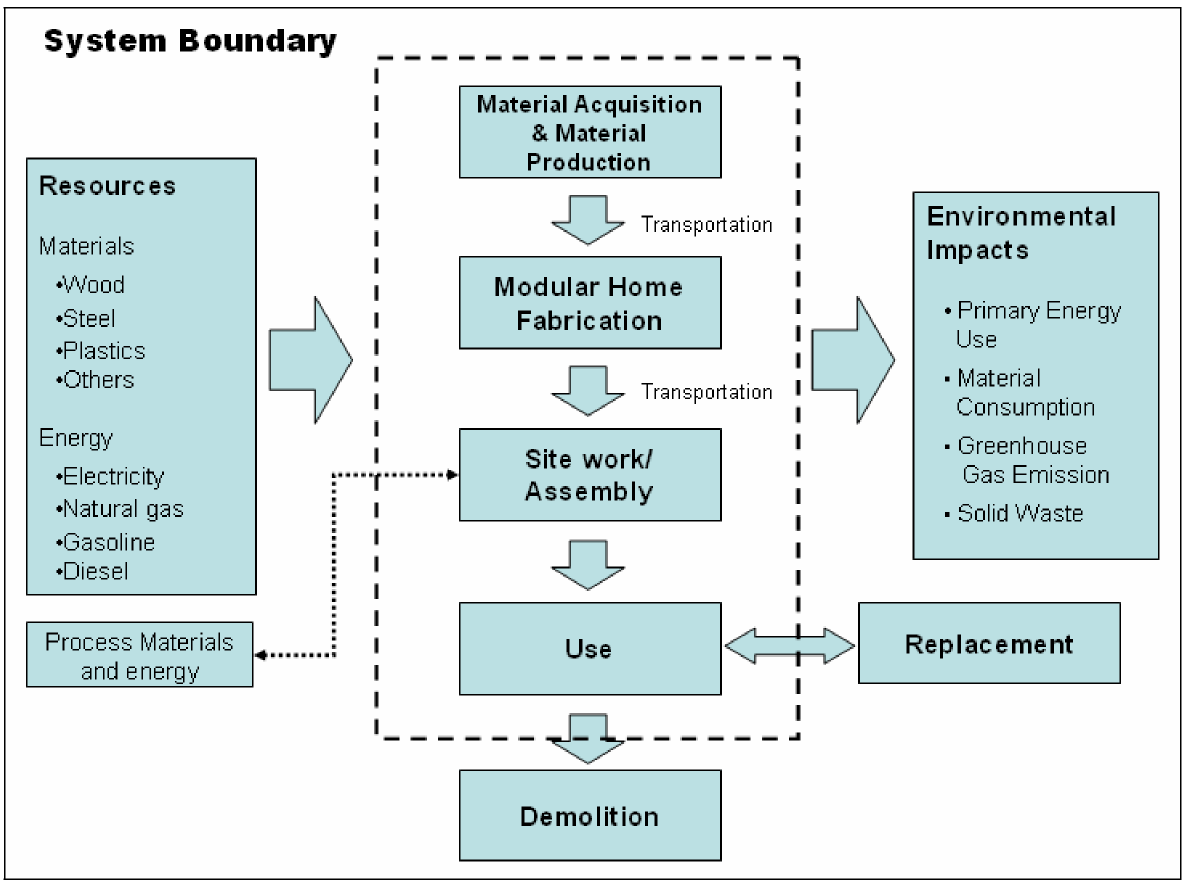

Figure 6 explains the life cycle of the modular home and its system boundary for this study. The life cycle of the modular home includes four phases: material acquisition/material production, modular home fabrication, site work/assembly and use. Replacement, which includes maintenance or renovation of the home, is not taken into account for this study. Also, demolition and waste treatment after the end of building use are excluded from the boundary of this study because there are foreseen challenges in data gathering in respect to demolition and waste treatment. Moreover, current demolition wastes are mostly landfilled and it is unlikely that both housing methods result in any significant differences under the current waste treatment scheme.

First, the material acquisition comprises activities such as harvesting, extracting and mining of raw materials (iron ores, bauxite, wood, petroleum and etc). The material production includes the phase in which the raw materials are converted into engineered products usable for a certain proposed purpose. In this phase, steel bars, aluminum plates and 2X4 lumber are processed from the raw materials (iron ores, bauxite and wood). The assessment of material and energy consumption (including transportation) for this phase utilizes inventory database from Sima Pro 6.0.

The modular home fabrication phase includes assembly of the processed materials including lumber, plywood, asphalt shingles, windows and steel at the modular home fabrication site. In this phase, material and energy used for manufacturing and assembly of a modular home are collected from Redman Homes.

The installation of the modular home and site-work are accounted for site work/assembly phase. This phase accounts for site-work including excavation, footing installation and other earthworks. This phase includes the modular home installation when the each completed module of the modular home is transported to the building site. However, since it was not possible to find data related to the work, materials and energy used for leveling, supporting and anchoring of the modular home are not included in the study.

Transportation is separated into the three categories: material transportation, employee transportation and module transportation. The material transportation is the transportation required for moving materials between each phase, such as transporting raw materials for the material processing. All material's transportation is traced from where the building materials are processed and manufactured to the final materials that are eventually installed in the building. The employee transportation accounts for the transportation energy used for commuting by employees at the modular home fabrication site and at the building site. The module transportation is the delivery process of the completed modular home, from the fabrication site to the building site. This study analyzes the material transportation and module transportation based on the information provided by Redman Homes. The information only pertains to the specific location of the building site and the modular home factory chosen in this study. Depending on their locations, the material and modular home transportation generates significantly different impacts. This study is not yet able to provide a comprehensive transportation impact according to location differences.

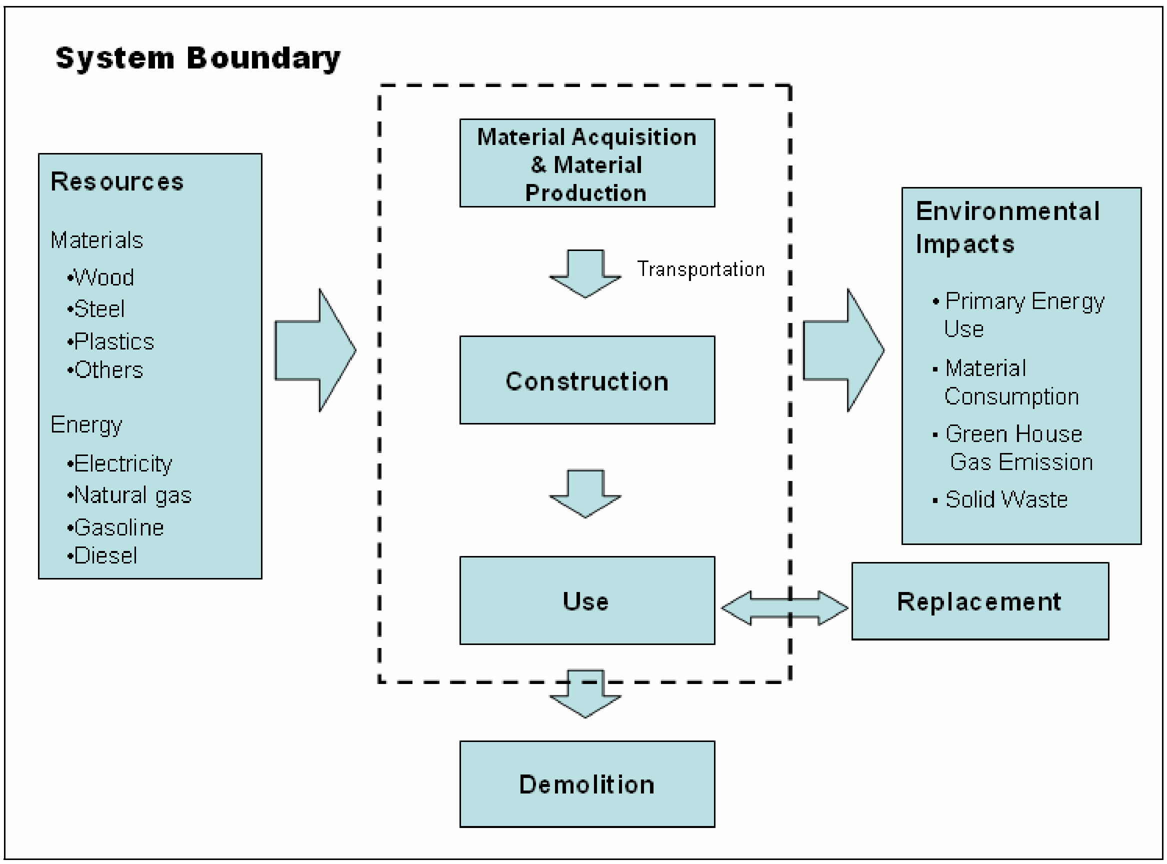

Figure 7 Life Cycle System of Conventional Home

The life cycle of the conventional home is different from that of the modular home due to the construction process differences. As shown in Figure 7, the life cycle of the conventional home includes three phases: material acquisition/material production, construction and use. Material acquisition/material production and use phases are the same as the modular home. The construction phase is comparable to the modular home fabrication and site work/assembly phases. The conventional housing begins at the building site and is completed there. The construction phase includes material and energy inputs required and processed during the conventional home construction. The material and energy data for this phase is based on information from Douglas Construction Company, assumptions about the conventional home, and referenced construction literature.

Transportation consists of material transportation and employee transportation. The material transportation is the transportation required for moving materials where materials are manufactured and processed to the point where the building materials are installed in the building. The employee transportation accounts for the transportation energy used by workers at the building site. The material and employee transportation analysis is based on information provided by Douglas Construction Company. The transportation impact will be significantly different depending on the location of building site and material suppliers. The conventional home transportation analysis is limited to the building site chosen in this study.

3.2. Life Cycle Inventory Analysis for Modular Home

3.2.1. Material Consumption

More than 150 building material components are taken into account for material analysis. Among them, 95 components are sorted out based on the volume and weight of materials. 95 building components are categorized into 13 building materials: lumber (Douglas Fir), plywood, OSB, gypsum board, fiber glass, cellulose, shingle, PVC, carpet, high density urethane, polyethylene, galvanized steel and other wood (western oak).

The total material consumption counts the materials used for building a modular home and the amount of waste generated. The total material consumption is listed in Table 2. Regarding material waste, there is no waste record on modular home fabrication at Redman Home. Based on the waste quantity survey at Redman's production line, the management at Redman Homes reported that the wastes generated from the fabrication processes are approximately 3% of the overall materials used. Due to the efficiently processed assembly line in modular housing, the modular home can reduce the amount of waste generated in its fabrication, compared to a conventional site built house. The 3% waste factor reported by Redman Homes is considered as a rough estimate, so a 5% waste factor is also taken into account to measure the material consumption sensitivity depending on different waste factors, shown in Table 3. When the waste factor is increased from 3% to 5%, the amount of waste is increased 1.67 times and the total material consumption is increased 2%.

However, the materials used for leveling, supporting and anchoring the modular home during its assembly and installation at the site are not taken into account, as noted in the system boundary, due to lack of available data.

Table 2 Material Consumption for Modular Home (3% waste factor)

Materials	Material Placed	Waste Factor	Waste Generated	Material Total
Douglas Fir	19,962 lbs	3%	599 lbs	20,561 lbs
Plywood	2,693 lbs	3%	81 lbs	2,773 lbs
OSB	5,577 lbs	3%	167 lbs	5,744 lbs
Gypsum Board	9,947 lbs	3%	298 lbs	10,245 lbs
Fiber glass	823 lbs	3%	25 lbs	847 lbs
Cellulose	1,661 lbs	3%	50 lbs	1,710 lbs
Shingle	4,214 lbs	3%	126 lbs	4,340 lbs
PVC	848 lbs	3%	25 lbs	873 lbs
Carpet	407 lbs	3%	12 lbs	419 lbs
HD urethane	271 lbs	3%	8 lbs	279 lbs
Polyethylene	39 lbs	3%	1 lbs	40 lbs
Galvanized steel	120 lbs	3%	4 lbs	123 lbs
Western oak	566 lbs	3%	17 lbs	583 lbs
Total	47,125 lbs		1,414 lbs	48,539 lbs

Table 3 Material Consumption for Modular Home (5% waste factor)

Materials	Material Placed	Waste Factor	Waste Generated	Material Total
Douglas Fir	19,962 lbs	5%	998 lbs	20,960 lbs

Plywood	2,693	lbs	5%	135	lbs	2,827	lbs
OSB	5,577	lbs	5%	279	lbs	5,855	lbs
Gypsum Board	9,947	lbs	5%	497	lbs	10,444	lbs
Fiber glass	823	lbs	5%	41	lbs	864	lbs
Cellulose	1,661	lbs	5%	83	lbs	1,744	lbs
Shingle	4,214	lbs	5%	211	lbs	4,425	lbs
PVC	848	lbs	5%	42	lbs	890	lbs
Carpet	407	lbs	5%	20	lbs	427	lbs
HD urethane	271	lbs	5%	14	lbs	284	lbs
Polyethylene	39	lbs	5%	2	lbs	41	lbs
Galvanized steel	120	lbs	5%	6	lbs	126	lbs
Western oak	566	lbs	5%	28	lbs	594	lbs
Total	47,125	lbs		2,356	lbs	49,482	lbs

3.2.2. Energy use for Modular Home Fabrication

Redman Homes indicated that the annual utility bill in 2006~2007 period was \$21,628.09 for natural gas and \$4,219.39 for electricity. The annual average Redman Homes's energy price is \$0.9255 per CCF for natural gas and \$0.088 per KWh for electricity. Redman Homes used 23,369 CCF of natural gas per year and 47,947 KWh of electricity per year, as shown in Table 4. This energy consumption totals the energy used for both modular home production and their general office. Redman Homes does not have a separate energy profile for production.

In order to separate the energy consumption for the modular home production from the total energy consumption, it is assumed that the office energy consumption is 91,000 Btu per ft^2, which is the average energy consumption of office building from Energy Information Administration (EIA).[17] The total office floor area is 2,485 ft^2 and the energy consumption of the office area is estimated to be 226.1 million Btu per year, which is 10% of the total energy consumption. Therefore, the estimated energy consumption for the modular home production is 43,152 KWh of electricity and 21,032 CCF of natural gas per year.

During the same period, Redman Homes produced 365 modular homes and 45

HUD coded homes. Considering the total production per year, it is computed that a single modular home requires 105.25 KWh of electricity and 51.3 CCF of natural gas for its production.

Table 4 Energy Consumption for Modular Home Fabrication

Month	Natural Gas Charge	Used Amount (CCF)	Electricity Charge	Used Amount (KWh)
11/2007	$1,524	1,647	$435	4,944
10/2007	$834	902	$384	4,364
9/2007	$1,049	1,134	$326	3,699
8/2007	$1,067	1,153	$285	3,234
7/2007	$1,064	1,150	$286	3,248
6/2007	$1,047	1,131	$240	2,733
5/2007	$483	522	$255	2,899
5/2007	$273	295	$318	3,618
4/2007	$3,611	3,902	$403	4,577
2/2007	$4,155	4,490	$411	4,668
1/2007	$3,486	3,767	$454	5,156
12/2006	$3,033	3,278	$423	4,808
Total	$21,628	23,369	$4,219	47,948

3.2.3. Transportation

Transportation for modular housing is categorized into three parts: material transportation, employee transportation and module transportation. Material transportation is the transportation required to deliver all building materials from suppliers to the modular home fabrication site at Redman Homes. Employee transportation accounts for the transportation of the employees working for modular home manufacturing at Redman Homes. Module transportation is the transportation from the fabrication site to the final building site.

Material transportation highly depends on the distance of material supply chain. Redman Homes procures most materials from manufacturers or distributors directly. The list of suppliers is shown in Table 5 with location and distance from Redman Homes at

Topeka, Indiana. The locations of major suppliers are also mapped in Figure 8. However, tracing supply chain up to the raw material acquisition is beyond the scope of this study, since the data would be difficult to obtain. Therefore, the boundary of material transportation delimits the first tier suppliers of 13 building materials. This most likely underestimates the material transportation impacts.

Table 5 Modular Home Supplier Information

#*	Suppliers	Materials	Location	Distance	Type
1	Universal Forest Prod	Douglas Fir	White Pigeon, MI	23.7 mile	Manufacturer
2	BlueLinx Dist.	Plywood	Elkhart,IN	30.8 mile	Distributor
2	BlueLinx Dist.	OSB	Elkhart,IN	30.8 mile	Distributor
3	US GYPSUM	Gypsum Board	Shoals, IN	262 mile	Manufacturer
4	Guardian	Fiber glass	Albion, MI	86 mile	Manufacturer
5	Applegate Ins.	Cellulose	Webberville, MI	141.7 mile	Manufacturer
6	Owens Corning	Shingle	Summit, IL	155.4 mile	Manufacturer
7	Crane Plastics	PVC	Columbus, OH	207 mile	Manufacturer
8	Shaw Carpet	Carpet	Dalton, GA	609 mile	Manufacturer
9	Leggett and Platt	HD urethane	Fairmont, IL	402 mile	Manufacturer
2	Shepherd Products	Polyethylene	Elkhart,IN	30.8 mile	Distributor
2	Fastec Industrial	Galvanized steel	Elkhart,IN	30.8 mile	Manufacturer
2	BlueLinx Dist.	Western oak	Elkhart,IN	30.8 mile	Distributor

*The numbers of each location are shown in the map, Figure 8

Employee transportation is determined in relation to the number of employees and commuting distances. Particularly, Redman Homes has 23 Amish employees, who use only bicycle or horses for their transportation instead of fossil fuel driven vehicles. Due to this extraordinary situation, the employee transportation is modeled with two scenarios: 1) all employees drive cars and 2) 23 Amish people do not use cars.

Figure 8 Map of Modular Home Supplier Location

As shown in Table 6, the total number of employees is 101 people and the total round trip mileage per day is estimated 3,147 miles. First, assuming that all employees are driving, the annual travel miles are computed to be 818,220 miles with 260 work-days per year. According to last year's production, Redman Homes produced 410 unit homes, so the travel mile per unit modular home production is calculated as 1,995.6 miles.

With another scenario that 23 Amish people do not drive, the total daily mileage is 3,078 miles and annual travel mile is 800,280 miles. In this scenario, the travel mile per unit home production is 1,951.9 miles.

Table 6 Employee Travel for Modular Home Fabrication

No. of Emp	Location	1 way	Totals	No. of Emp	Location	1 way	Totals
5	Albion, IN.	22	220	13	LaGrange, IN.	15	390

1	Auburn, IN.	39	78	9	Ligonier, IN.	8	144
1	Avilla, IN.	29	58	1	Middlebury, IN.	18	36
1	Camden, MI.	58	116	2	Millersburg, IN.	9	36
1	Coldwater, MI.	53	106	4	Rome City, IN.	14	112
2	Colon, MI.	38	152	1	Sherwood, MI.	49	98
3	Cromwell, IN.	15	90	3	Shipshewana, IN.	12	72
1	Fort Wayne, IN.	56	112	4	Sturgis, MI.	24	192
1	Garrett, IN.	36	72	23	Topeka, IN.	3	69
3	Goshen, IN.	25	150	1	Waterloo, IN.	37	74
1	Howe, IN.	21	42	4	Wawaka, IN.	12	96
1	Hudson, IN.	33	66	1	White Pigeon, MI.	24	48
6	Kendallville, IN.	24	288	7	Wolcottville, IN.	14	196
1	Kimmell, IN.	17	34				

The distance for a modular home transportation is already determined by the distance from Topeka, Indiana to Benton Harbor, Michigan, where the modular home is to be placed. The distance is 85 miles. However, based on last year's record, the average delivery distance of a modular home is 200 miles, and the distance ranges from 15 miles to 1,760 miles. The delivery distance of a modular home plays an important role in the total transportation energy. The transportation energy is calculated as a function of delivery distance and weight of shipment. The weight of a modular home delivered includes the sum of all material installed, so the shipment of a completed modular home becomes the most important factor in total transportation energy.

3.2.4. Energy use in Building Use

Energy consumption during the life time of the modular home is simulated with eQuest 3.6, which is DOE-2 based energy analysis software to assess a building's energy performance with today's state-of-the-art building design technologies. The energy modeling reflects the modular home's design, structure and material use including insulation details. The HVAC system for the modular home employs a DX coil system for cooling and a natural gas furnace for heating. Therefore, electricity is used for cooling and other home appliances, and natural gas is used for space heating and water heating.

According to previous research by Hales, et al.[18] and the modular home infiltration study by Lubliner[19], air infiltration rate of modular homes is lower than conventional site built homes. The study by Hale, et al reported that the air change rate for an average double wide modular home is 0.194 ACH (air change per hour). However, from Lawrence Berkeley National Laboratory (LBNL), US residential house's average air infiltration is 1.485 ACH.[20] This air change rate difference indicates that a modular home is 7.6 times more air tight than a conventional home. However, these data sets have significant time gaps. The modular home air leakage tests were conducted in 2004. The air leakage tests for conventional homes were performed with houses built between 1850 and 1993. Instead of 1.485 ACH for the conventional home, ASHRAE standard air change rate, 0.35 ACH, is considered as the representative ACH for recently built conventional homes.

The results of energy simulation are shown in Figure 9, Table 7 and Table 8. Estimated annual energy consumption is 7,432 KWh of electricity and 56.97 X 10^6 Btu of natural gas. During the expected modular home's service life (50 years), the modular home will consume 371,600 KWh of electricity and 2,848.5 X 10^6 Btu of natural gas.

Figure 9 Modular Home Energy Consumption Graph

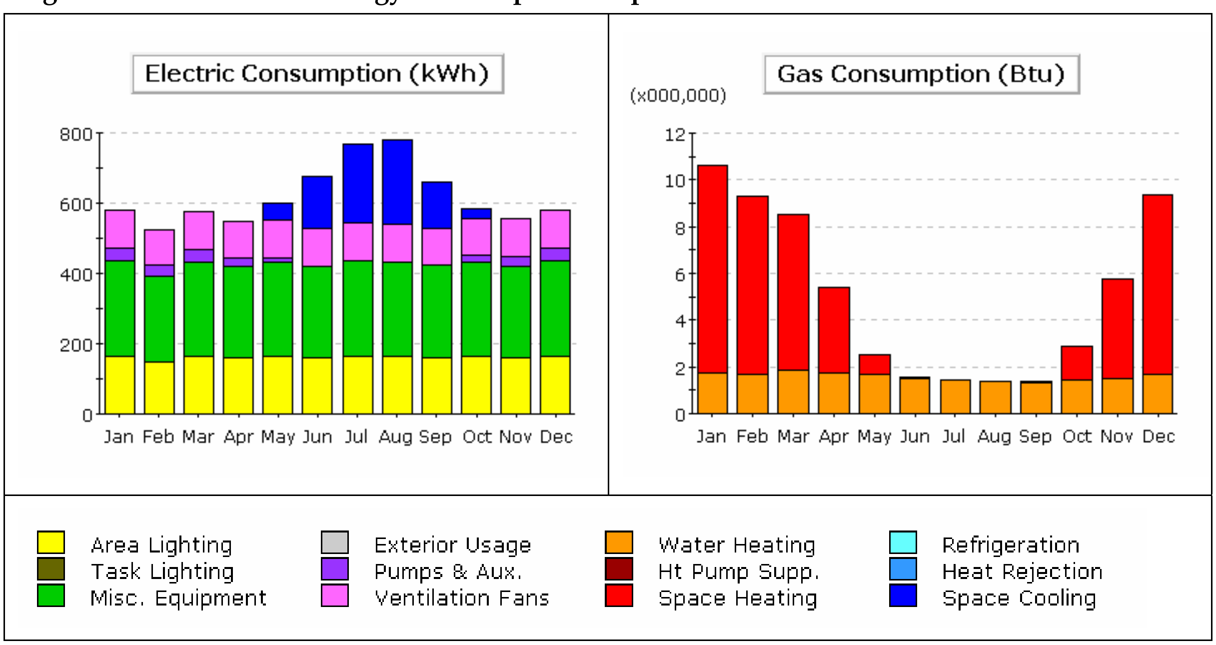

Table 7 Modular Home Electricity Consumption (KWh)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total

Space Cool	0	0	0	0.4	49.9	150.1	224.7	236.9	131.9	30.5	0.9	0	825.3
Vent. Fans	108.2	97.7	108.2	103.5	107.5	104.9	107.5	107.5	104.9	107.5	105.6	108.2	1,271.2
Pump&Aux.	37.1	33.3	33.9	24.4	9.3	1.9	0	0.7	2.1	16.7	28.6	34.5	222.7
Misc. Equip.	270.1	244.0	270.1	261.1	270.0	261.4	270.0	270.0	261.4	270.0	261.6	270.1	3,179.8
Area Lights	164.5	148.5	164.5	157.4	163.6	159.4	163.5	163.6	159.4	163.6	160.5	164.5	1,933.0
Total	580.0	523.6	576.8	546.9	600.2	677.8	765.6	778.6	659.8	588.2	557.3	577.4	7,432.0

Table 8 Modular Home Natural Gas Consumption (Btu X 1,000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	8.31	7.15	6.22	3.28	0.71	0.02	0	0	0.03	1.21	3.95	7.15	38.03
Hot Water	1.76	1.65	1.84	1.77	1.68	1.50	1.45	1.40	1.32	1.44	1.48	1.65	18.95
Total	10.07	8.80	8.06	5.05	2.39	1.52	1.45	1.40	1.35	2.65	5.43	8.80	56.97

3.3. Life Cycle Inventory Analysis for Conventional Site Built Home

3.3.1. Material Consumption

The material consumption of the conventional site built home is calculated by modeling the conventional home after the modular home. Douglas Construction Company identified the different components and structures used in the conventional home. The material quantity includes wasted materials during the construction processes. The waste factors used here are US national average residential construction wastes, with reference to the research carried out by the National Association of Home Builders (NAHB).[21] However, the materials used for site work including excavation, footings, and floor slab are not taken into account because Douglas Construction Company indicated that there is no difference in the foundation for both modular and conventional homes. Also, the site work for the modular home, such as installing the foundation and basement, is not included in the system boundary of this study, as noted in the system boundary section. Therefore, the site work for the conventional home is excluded in this study.

According to the material estimation in Table 9, the total amount of the materials placed in the conventional home is 42,893.3 lbs, which is 9% less than the amount of the modular home. The modular home's unique structure, marriage walls, requires additional lumber and gypsum board inputs. Also, the 2X6 stud framed modular home entails a larger amount of lumber consumption than the conventional home structured with 2X4 studs. However, the conventional home discharges 2.5 times more construction wastes than the modular home. Therefore, the smaller material consumption of the conventional home is offset by a larger amount of waste generation. There is not a significant mass difference between the two types of housing with respect to material consumption.

Table 9Material Consumption for Conventional Home

Material	Material Placed	Waste factor	Waste Generated	Material Total
Douglas Fir	17,146 lbs	0.8 lb/ ft^2	1,164 lbs	18,310 lbs
Plywood	2,693 lbs	0.7 lb/ ft^2	332 lbs	3,025 lbs
OSB	5,577 lbs		713 lbs	6,290 lbs
Gypsum Board	8,531 lbs	1 lb/ ft^2	510 lbs	9,040 lbs
PVC	848 lbs	0.075 lb/ ft^2	109 lbs	957 lbs
Fiber glass	823 lbs	0.525 lb/ ft^2	78 lbs	900 lbs
Cellulose	1,661 lbs		157 lbs	1,817 lbs
Shingle	4,214 lbs		398 lbs	4,612 lbs
Carpet	407 lbs		38 lbs	445 lbs
HD urethane	271 lbs		26 lbs	296 lbs
Polyethylene	39 lbs		4 lbs	43 lbs
Galvanized steel	120 lbs		11 lbs	131 lbs
Western oak	566 lbs		53 lbs	619 lbs
Total	42,893 lbs		3,593 lbs	46,486 lbs

3.3.2. Energy use for Conventional Home Construction

Energy use during the conventional home construction may include operation of construction equipment including crawler crane, skid loader, motorized saw, other machines and overhead equipments. However, the information regarding construction energy is not available from the construction industry. There are limited reference data regarding residential construction equipment operation cost and operation hours, in order to indirectly measure the energy use in construction processes. However, wood-framed residential construction is mostly done by laborers or carpenters. Also, most of the equipment related jobs are performed in earthworks or foundation installation. Those site works are not included in the system boundary. In this regard, the construction energy calculation using equipment hours from the reference data is not applicable to this study.

It is expected that the conventional home construction consumes more energy than the modular home fabrication because the conventional home building takes longer time and more labor input than the modular home building. However, due to lack of data, it is assumed that conventional housing uses the same amount of energy as the modular housing. Correspondingly, the estimated construction energy consumption for a conventional home is 105.25 KWh of electricity and 51.3 CCF of natural gas.

3.3.3. Transportation

Transportation for the conventional stick built home includes building material transportation and employee transportation. For the material transportation calculation, the material supply chain information for the conventional home is obtained from Douglas Construction Company. As shown in Table 10, most of the materials are supplied from wholesalers or retailers. The locations of suppliers are also mapped in Figure 10. By comparison with the modular home's supply chain, the conventional home has more intermediate suppliers in its supply chain. The additional suppliers therefore increase the material supply chain for the conventional home. This material transportation is only relevant to the specific location of the building site and suppliers chosen in this study. It can not be applied to different site locations.

In this study, it is assumed that the hierarchy of material supply chain follows the sequence: the manufacturer, distributor or wholesaler and retailer. The conventional home's supply chain is traced up to the manufacturer or wholesaler, so that the supply chains for the modular and conventional homes are aligned at the same level of the hierarchy. For example, the modular home's lumber is supplied from a manufacturer, but the conventional home's lumber is provided from a wholesaler. The conventional home's supply chain for lumber is traced further to the manufacturer level, so that the supply chains for both homes start at the same level of supply chain hierarchy so that the two supply chains are compatible.

Table 11 and 12 are the estimated mileage and ton-miles of building material transportation. The total material transportation ton-miles for the modular home is 2,265.61 ton-miles, as calculated in Table 11. The material supply ton-miles for the conventional home is 6,393.86 ton-miles, as calculated in Table 12. The different distance implies that the conventional home requires more than double the material travel miles of a modular home. The conventional home takes 2.8 times more ton-miles than the modular home. This explains the higher material transportation energy associated with the conventional home.

Table 10 Conventional Home Supplier Information

#*	Suppliers	Materials	Location	Distance	Type
1	Emerson Precision Panel	Douglas Fir	Jeromesville, OH	283 miles	Wholesale
1	Emerson Precision Panel	Plywood	Jeromesville, OH	283 miles	Wholesale
1	Emerson Precision Panel	OSB	Jeromesville, OH	283 miles	Wholesale
2	Homemakers	Gypsum Board	South Bend, IN	40 miles	Wholesale
3	Fryman Construction	Fiber glass	Dowagiac, MI	25 miles	Retail
3	Fryman Construction	Cellulose	Dowagiac, MI	25 miles	Retail
4	Carter Lumber	Shingle	Bridgman, MI	14 miles	Distributor
5	Vinyl Tech	PVC	Detroit, MI	186 miles	Wholesale
5	Shaw Carpets	Carpet	Detroit, MI	186 miles	Wholesale
5	Shaw Carpets	HD urethane	Detroit, MI	186 miles	Wholesale
6	L.E Smith	Polyethylene	Bryan, OH	140 miles	Wholesale
7	J&L door and hardware	Galvanized steel	Toledo, OH	190 miles	Distributor
7	J&L door and hardware	Western oak	Toledo, OH	190 miles	Distributor

*The numbers of each location are shown in the map, Figure 10

Figure 10 Map of Modular Home Supplier Location

Table 11 Modular home supply chain

Material	Manufacturer	Wholesale(dist.)	Retail	Total (miles)	Ton-miles
Douglas Fir	23.7 miles	X	X	24	221
Plywood	X	30.8 miles	X	31	39
OSB	X	30.8 miles	X	31	80
Gypsum Board	262 miles	X	X	262	1,218
Fiber glass	86	X	X	86	33
Cellulose	141.7 miles	X	X	142	110
Shingle	155.4 miles	X	X	155	306
PVC	207 miles	X	X	207	82
Carpet	609 miles	X	X	609	116
HD urethane	402 miles	X	X	402	51
Polyethylene	X	30.8 miles	X	31	1
Galvanized steel	30.8 miles	X	X	31	2

Western oak	X	30.8 miles	X	31	8
Total					2,266

Table 12 Conventional home supply chain

Material	Manufacturer	Wholesale(dist.)	Retail	Total (mile)	Ton-miles
Douglas Fir	21 miles	283 miles	X	304	2,525
Plywood	X	283 miles	X	283	388
OSB	X	283 miles	X	283	807
Gypsum Board	242 miles	40 miles	X	282	1,156
Fiber glass	86 miles	180 miles	25 miles	291	126
Cellulose	141.2 miles	180 miles	25 miles	346	141
Shingle	88.7 miles	14 miles	X	103	85
PVC	202 miles	186 miles	X	388	812
Carpet	638 miles	186 miles	X	824	166
HD urethane	638 miles	186 miles	X	824	111
Polyethylene	X	140 miles	X	140	3
Galvanized steel	140 miles	190 miles	X	330	20
Western oak	X	190 miles	X	190	53
Total					6,394

The employee transportation for the conventional site built home is determined by the number of employee, the construction period and the commuting miles of employees. According to Douglas Construction Company, it takes 3 to 4 months to build a 1,500 square foot single family house. Approximately 40 workers are engaged during the construction period, as shown in Table 13. The average number of workers at the site is 8~10 people per day. Based on Douglas Construction's survey, the average commuting distance for the job site workers is approximately 25 miles. Therefore, the average round trip mile per day is 50 miles per person.

Table 13 Required Workers for Conventional Home Building

Specialties of Workers	Number of People
Surveyors	2

Excavator	2
Concrete crew	4
Framers	5
Electricians	3
Plumbers	2
HVAC crews	2
Drywall crews	4
Painters	2
Finish carpenters	2
Siders	3
Roofers	4
Pavers	4
Door crew	1
Total	40

In order to calculate the total employee's travel mile for the conventional home building, various months and the number of workers are taken into account in Table 14. The travel mile ranges from 24,000 miles to 40,000 miles. The average is estimated to be 31,500 miles. Compared to the employee travel mile (1,995.6 miles) for the modular home, the conventional home requires approximately 16 times more employee's travel miles than the modular home construction. This is one of the most significant benefits for the modular home and a disadvantage for the conventional home.

Table 14 Estimated Employee Transportation Miles for Conventional Home Building

Month	Workers	Distance (mile)	Work day/Month	Total Miles
3	8	50	20	24,000
3	9	50	20	27,000
3	10	50	20	30,000
4	8	50	20	32,000
4	9	50	20	36,000
4	10	50	20	40,000

3.3.4. Energy use in Building Use

Energy consumption during the life time of the conventional home is also simulated with eQuest 3.6, under the same conditions as the modular home. The life span of a conventional home is assumed to be 50 years. The air infiltration rate for the conventional home adopts the ASHRAE standard (0.35 ACH) as the national average of residential building. The results of energy simulation are shown in Figure 11, Table 15 and 16. Annual estimated energy consumption is 7,426.4 KWh of electricity and 61.20 X 10^6 Btu of natural gas. During the expected conventional home's service life, the conventional home will consume 371,320 KWh of electricity and 3,060 X 10^6 Btu of natural gas.

In comparison with the modular home's air change rate, the conventional home has 80.4% increased air leakage rate, which results in 7.4% more natural gas consumption than the modular home.

Figure 11 Conventional Home Energy Consumption Graph

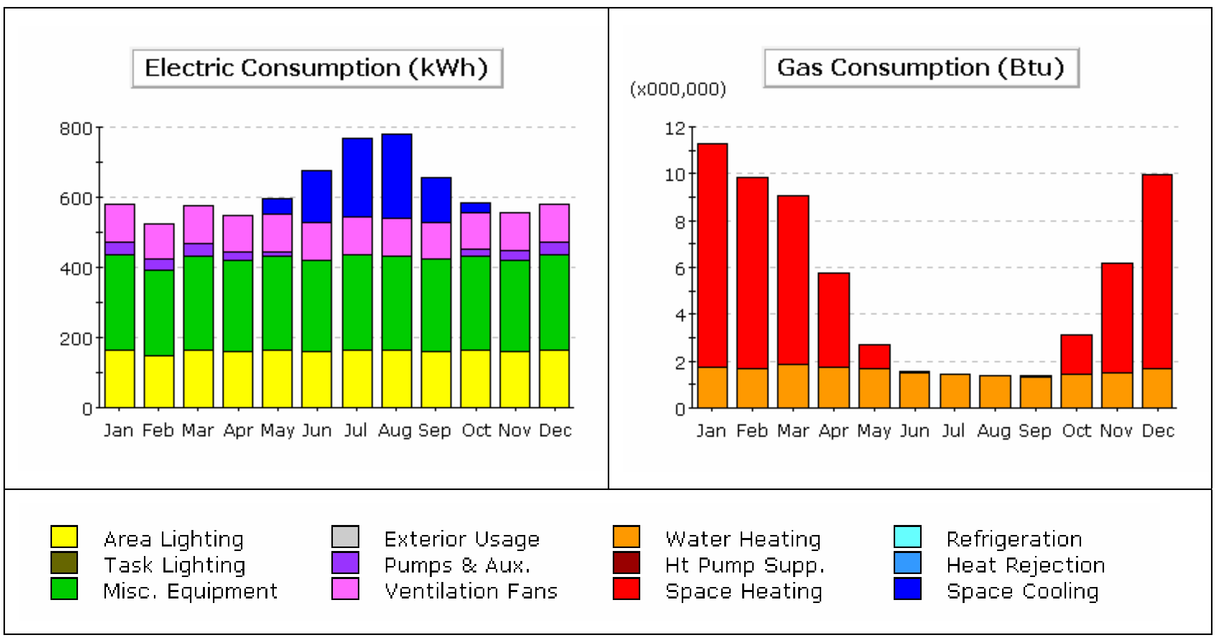

Table 15 Conventional Home Electricity Consumption (KWh)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0	0	0	0.4	47.5	150.1	222.7	242.0	127.8	28.3	0.9	0	819.7
Vent. Fans	108.2	97.7	108.2	103.5	107.5	104.9	107.5	107.5	104.9	107.5	105.6	108.2	1,271.2

Pump& Aux	37.1	33.3	33.9	24.4	9.3	1.9	0	0.7	2.1	16.7	28.6	34.5	222.7
Misc. Equip	270.1	244.0	270.1	261.1	270.0	261.4	270.0	270.0	261.4	270.0	261.6	270.1	3,179.8
Area Lights	164.5	148.5	164.5	157.4	163.6	159.4	163.5	163.6	159.4	163.6	160.5	164.5	1,933.0
Total	580.0	523.6	576.8	546.9	597.8	677.8	763.6	783.7	655.7	586.0	557.3	577.4	7,426.4

Table 16 Conventional Home Natural Gas Consumption (Btu x 1,000, 000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	9.08	7.81	6.86	3.73	0.88	0.04	0	0	0.06	1.49	4.45	7.83	42.25
Hot Water	1.76	1.65	1.84	1.77	1.68	1.51	1.45	1.40	1.32	1.44	1.48	1.65	18.95
Total	10.83	9.47	8.70	5.50	2.56	1.55	1.45	1.40	1.38	2.94	5.93	9.49	61.20

3.4. Life Cycle Impact Results

A life cycle assessment was carried out to explore differences in key design and construction features of the modular and conventional home. This preliminary life cycle assessment estimates the primary energy consumption, greenhouse gas emissions and material consumption for both the modular home and conventional home. Results are relevant for the site in Benton Harbor, Michigan. Many assumptions and simplifications were made due to data limitations as indicated in the methodology section.

3.4.1. Life Cycle Energy Consumption

For the 50 years of service life of each home, the modular home is estimated to consume 8,822 GJ of the life cycle energy, as shown in Figure 12 and 13. The raw material extraction, material production, and modular home fabrication account for 441 GJ (5% of the total). Transportation energy for material supply and modular home delivery is 20.9 GJ (0.2%), and the building use phase energy is 8,359.8 GJ (94.8%).

The total life cycle energy consumption for the conventional home is estimated to be 9,268 GJ. The raw material extraction, material production, and construction accounts for 596 GJ (6.4% of the total). Transportation energy for material supply is 29.7 GJ (0.3%), and the building use phase energy is 8,642.5 GJ (93.2%).

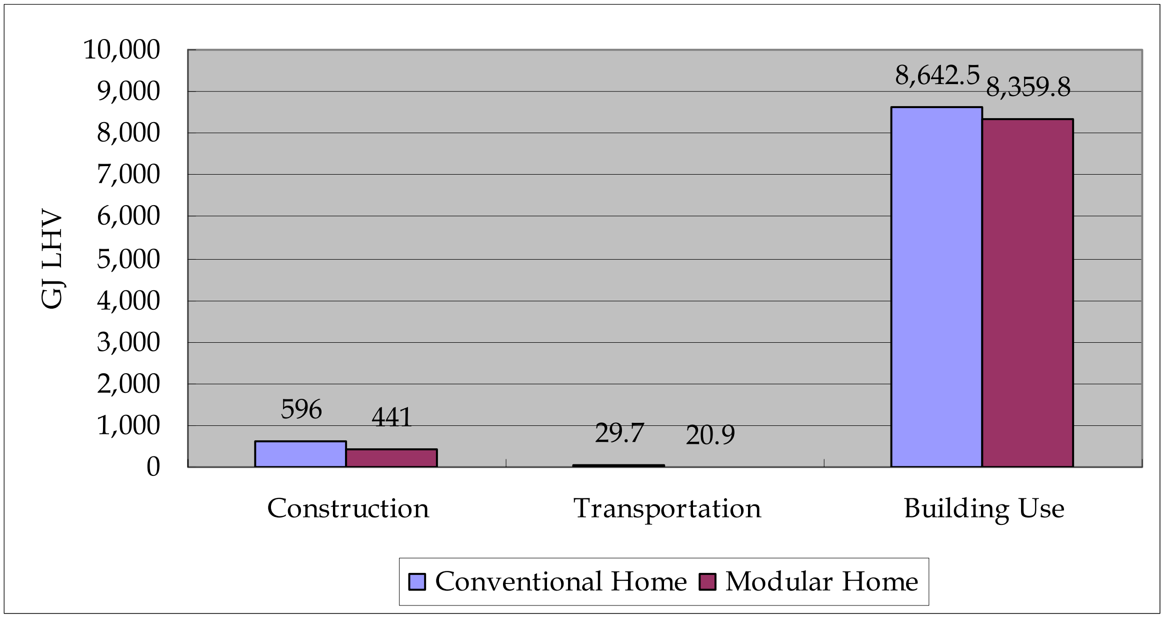

Figure 12 Life Cycle Energy Consumption

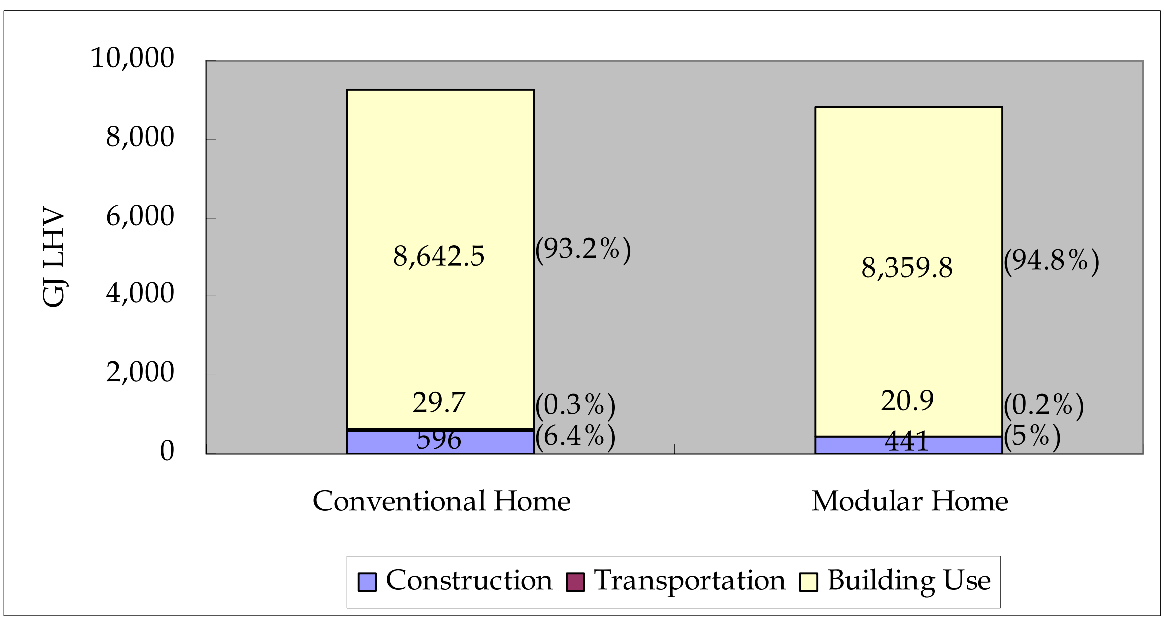

Figure 13 Conventional and Modular Home Total Life Cycle Energy

The building use phase dominates the energy consumption for both homes, which is responsible for over 93% of the total life cycle energy consumption. The heating, cooling, and other electrical energy consumption over 50 years contribute to the building use phase energy consumption. Based on the energy consumption simulation using eQuest 3.6, the conventional home consumes 282.7 GJ more energy than the modular home in the use phase. This difference mainly comes from the air leakage difference between the modular home and conventional home. The higher air tightness (0.194 ACH) of the modular home can save on natural gas consumption by reducing heating load. The conventional home has 80% lower air tightness (0.35 ACH, assuming ASHRAE Standards) than the modular home, which results in 7% more natural gas consumption over its service life.

The modular home requires 21 GJ of energy in its material transportation and modular home delivery, which is 30% less than the conventional home, as shown in Figure 14. For the modular home fabrication, 22.02 metric tons of total materials are delivered by various suppliers through a total of 2,266 ton-miles. Also, additional transportation energy is consumed by delivering the fabricated modular home, 85 miles to the building site, Benton Harbor, MI. However, the conventional home uses 30 GJ of transportation energy for its material supply because the material is supplied through a total of 6,394 ton-miles. The conventional home is supplied with building materials from wholesalers or retailers, but the modular home procures building materials mostly from manufacturers. Therefore, the modular home has as reduced supply chain leading to decrease in material transportation energy.

The modular home selected in this study is located in Benton Harbor 85 miles from the modular home factory. However, according to last year's production records at Redman Homes, the modular home's delivery distance ranged from 15 miles to 1,760 miles.. This transportation energy calculation only pertains to the specific locations of the building site, the modular home factory and suppliers chosen in this study. This transportation analysis is not yet able to be applied to estimating generalized modular home transportation energy. Depending on variable locations of building site, supplier and modular home factory, the transportation energy will generate significantly different results.

Employees of modular home fabrication use 11 MJ of transportation energy, but the conventional home construction requires 172 MJ of transportation energy, as shown in Figure 15. The modular home fabrication usually takes 4~5 days to complete and 8 weeks for delivery and installation at the building site. Considering that a typical construction period for a conventional home is 3~4 months, the reduced cycle time of the modular home fabrication contributes to reducing employee transportation energy to only 6.4% of the energy used in the conventional home construction.

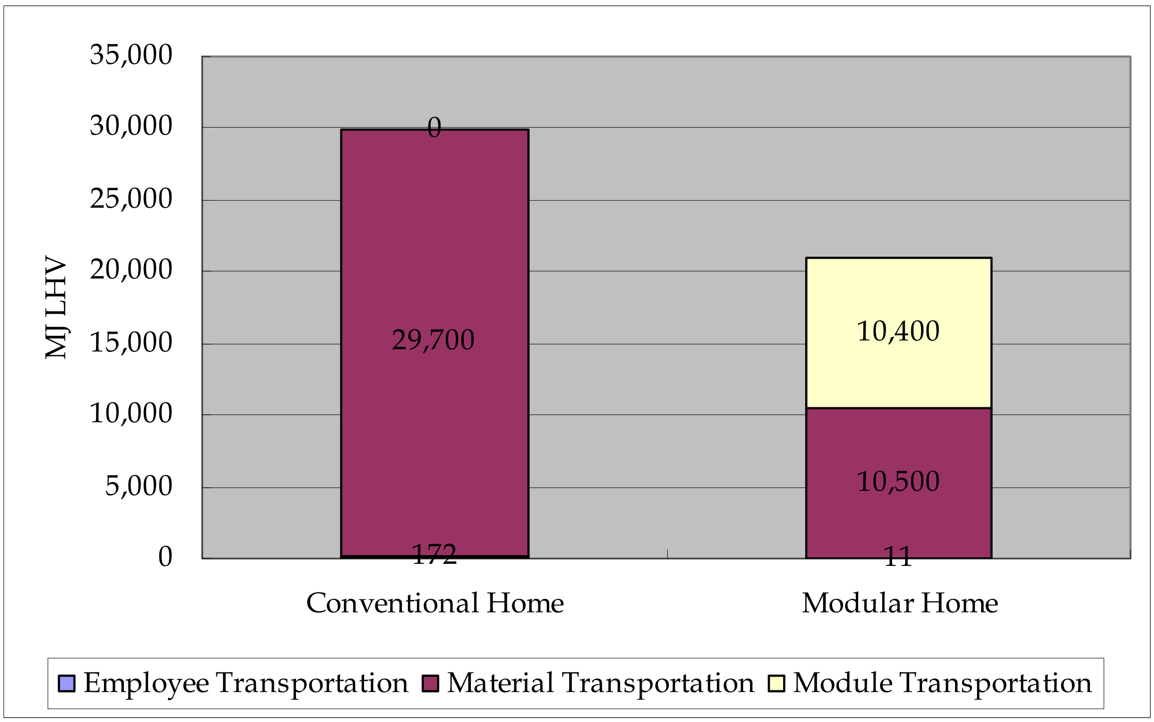

Figure 14 Total Transportation Energy Consumption

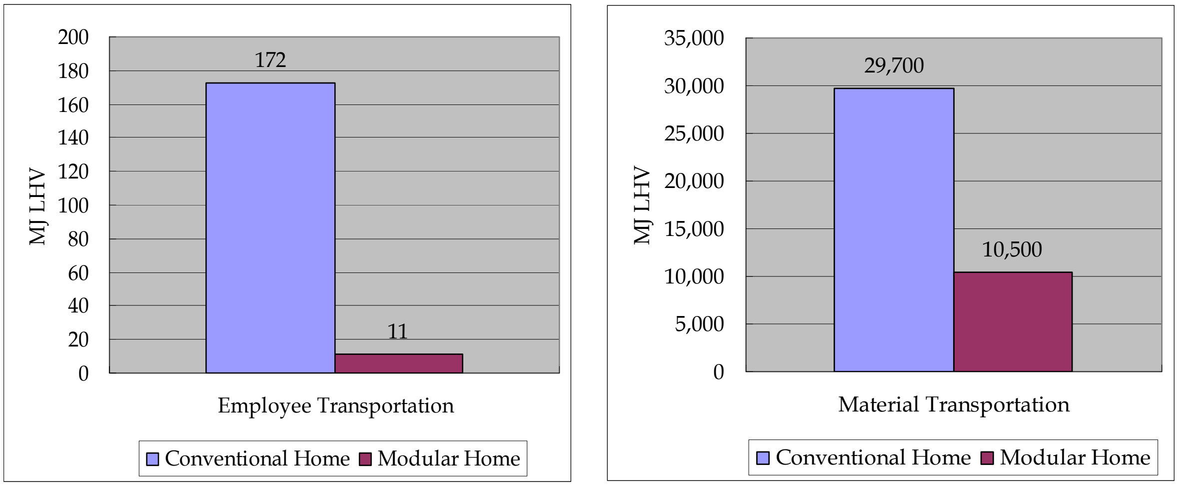

Figure 15 Employee and Material Transportation Energy Consumption

3.4.2. Life Cycle Global Warming Potential

Greenhouse gas emission over the life cycle of each home is calculated from Sima Pro 6.0 database. The total emission is presented as the global warming potential, or CO2 equivalent. The total global warming potential for the modular home is estimated to be 480,287 Kg CO2 equivalent, as shown in Figure 16 and 17. The building use phase accounts for 467,890 Kg CO2 (97.4% of the total). The raw material extraction, material production, and modular home fabrication discharge 11,000 Kg CO2 (2.3%). 1,397 Kg CO2 (0.3%) is emitted from material transportation and modular home delivery alone.

The total global warming potential for the conventional home is estimated to be 505,535 Kg CO2 equivalent. The building use phase is responsible for 482,485 Kg of CO2 emission (95.4% of the total). The raw material extraction, material production, and construction account for 20,900 Kg CO2 (4.1%). The material transportation's global warming potential is 2,150 Kg CO2 (0.4%).

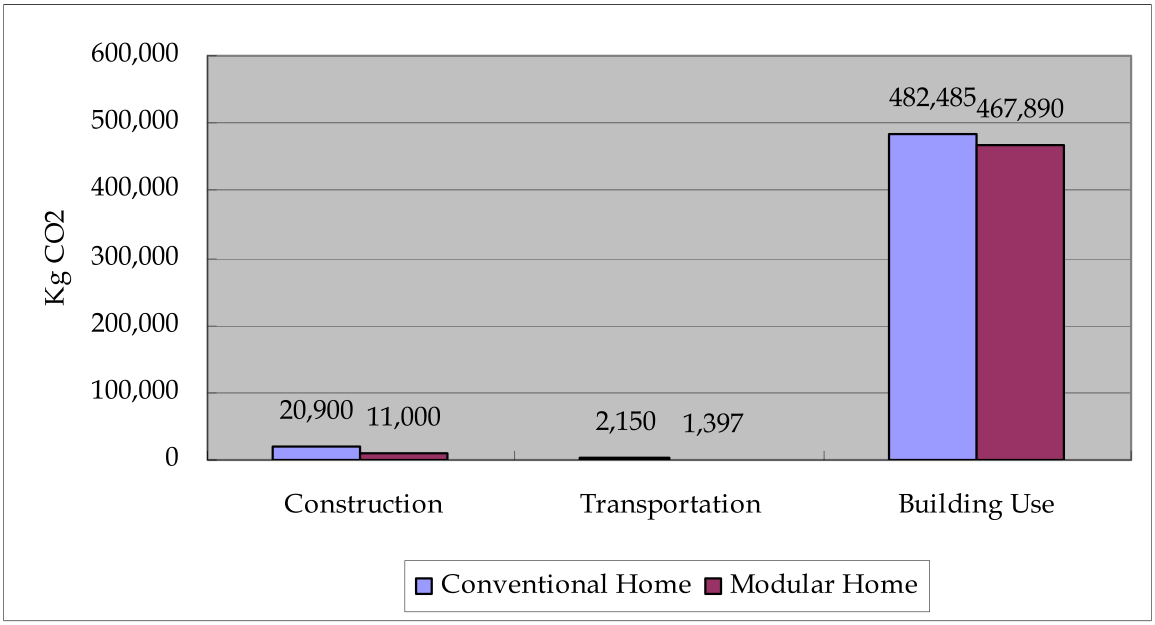

Figure 16 Life Cycle Greenhouse Gas Emissions

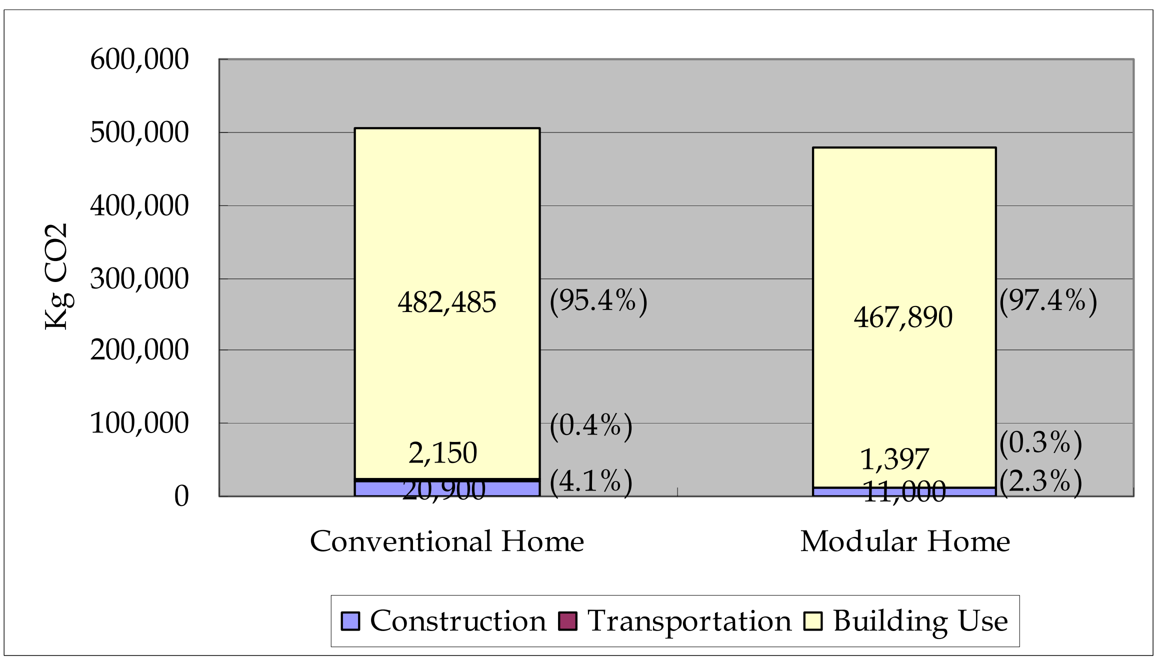

Figure 17 Conventional and Modular Home Total Greenhouse Gas Emissions

The building use phase contributes to more than 95% of each house type greenhouse gas emission because the largest amount of energy is consumed in this phase. The conventional home emits 3% more greenhouse gas than the modular home in the use phase. Again, this gap is attributed to the smaller air leakage in the modular home compared to the conventional home. The modular home's higher air tightness reduces the energy consumption and this leads to less greenhouse gas emissions of the modular home in its use phase.

The modular home fabrication contributes towards 47% less greenhouse gas than the conventional home construction. The modular home emits 11,000 Kg CO2 for fabrication, but the conventional home construction emits 20,900 Kg CO2. The major reason for this difference is a result of employee transportation energy during fabrication/construction. As shown in Figure 18, employee transportation is responsible for 61.6% of conventional home construction. However, employee transportation accounts for 7.4% of modular home fabrication. Therefore, transportation energy has the greatest impact on greenhouse gas emissions during fabrication/construction.

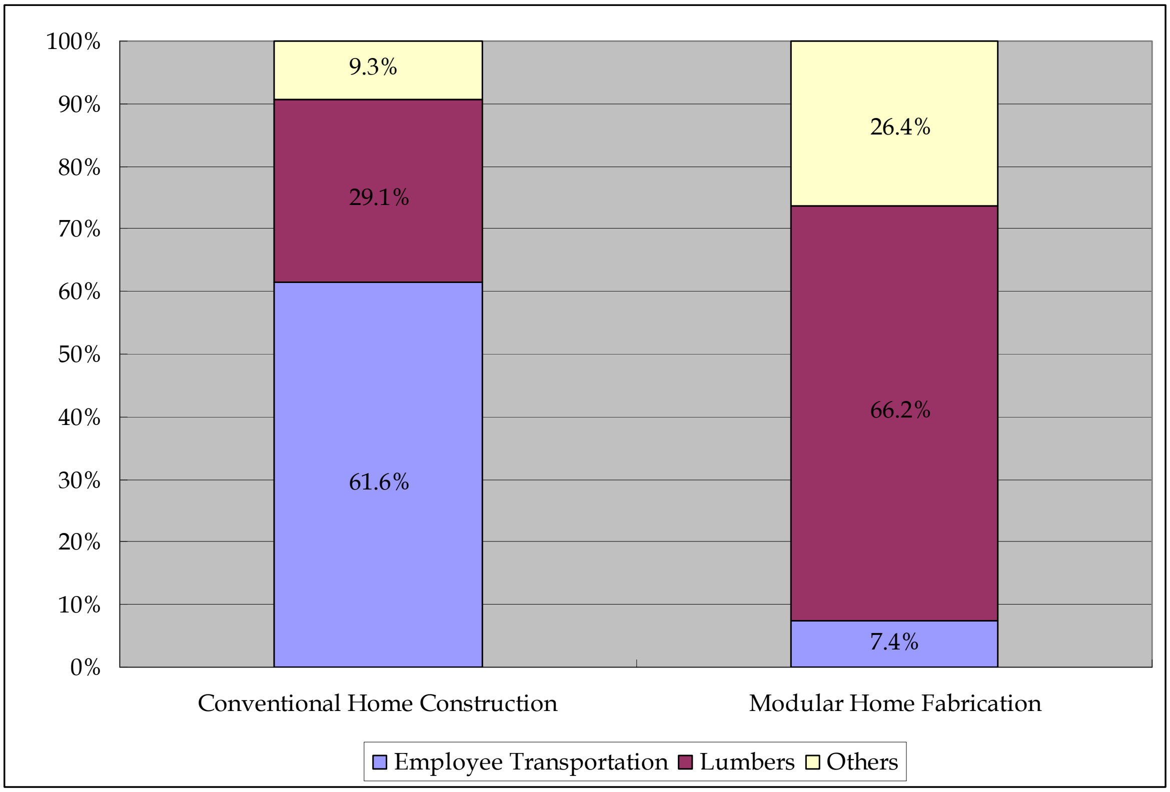

Figure 18 Greenhouse Gas Emission in Construction/Fabrication

3.4.3. Life Cycle Solid Waste Generation and Material Consumption

The modular home generates 51,625 Kg of solid waste over the building life cycle. Material acquisition and material production account for 1,220 Kg of solid wastes, and 641 Kg of wastes discharged (excluding recycling) in the course of modular home fabrication. The building use phase generates 49,759 Kg of solid waste.

The total life cycle solid waste for the conventional home is 52,833 Kg. Material acquisition and material production account for 1,130 Kg of solid waste generation. The construction waste is 1,630 Kg (excluding recycling), and 50,062 Kg of solid waste is generated during the building use phase.

As shown in Figure 19 and Figure 20, the conventional home construction generates 2.5 times more wastes than the modular home fabrication. The modular home's assembly lines allow the waste generation to be reduced through precise cutting and effective machine utilization. In this regard, the modular home fabrication material utilization efficiency is 97.1%, compared to the conventional home's efficiency of 92.3%. Even though the modular home requires more material input for marriage walls and bigger studs (2X6), the reduced waste from the modular home fabrication balances material consumption between the modular and conventional house.

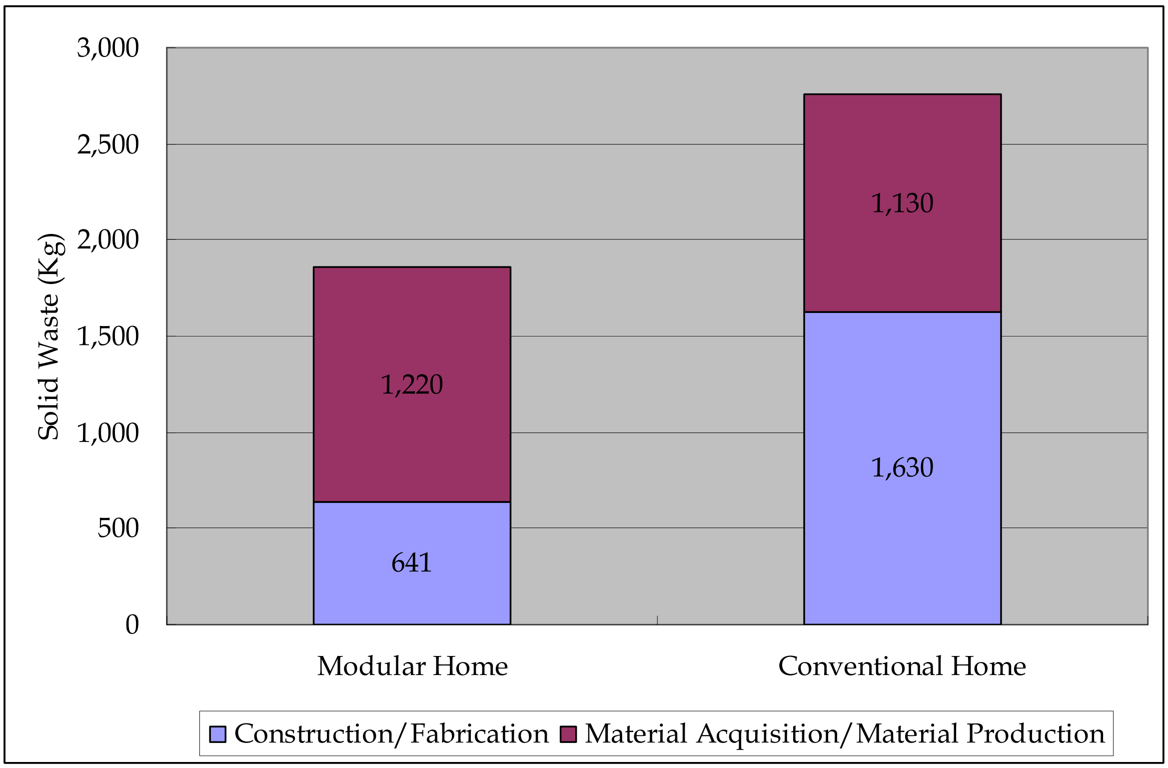

Figure 19 Life Cycle Solid Waste Generation (except the building use phase)

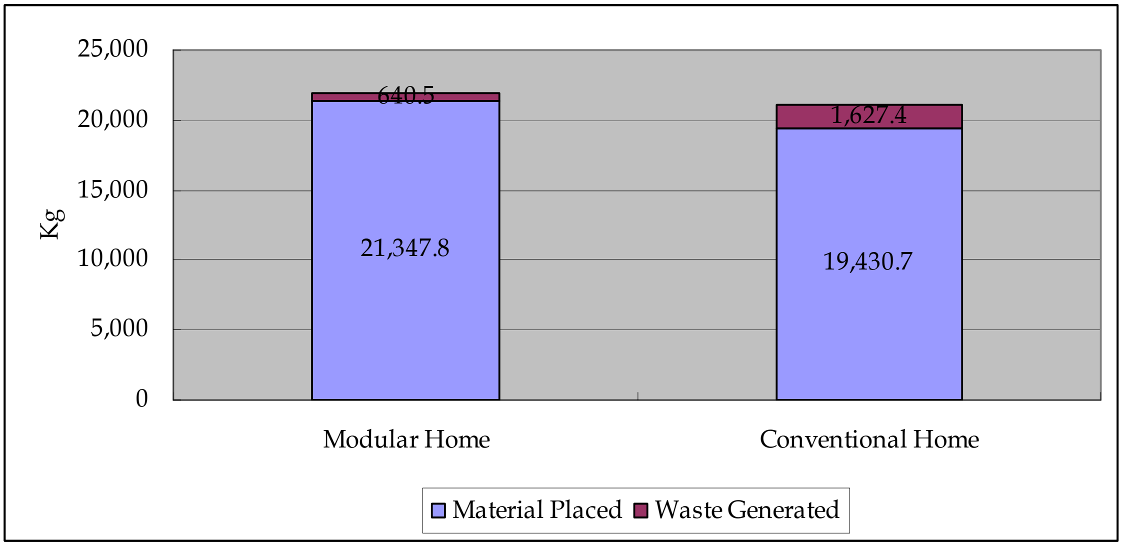

Figure 20 Modular and Convention Home Building Material Consumption

4. Conclusion

4.1. Findings

Based on this study, the modular home is expected to provide better environmental performance than the conventional home. The modular home consumes 4.6% less life cycle energy and emits 3% less greenhouse gas than the conventional home. The modular home's better performance in construction time, quality, and cost are factored into the sustainability context. The reduced construction time of the modular home contributes to reducing employee transportation energy consumption. The efficient assembly line fabrication allows the modular home to have greater air tightness, which attributes to energy savings on the building use phase.

The modular home delivery may require additional transportation energy compared to the conventional home, depending on the location of the construction site in relation to the location of the factory. The further the modular home is delivered, the more energy is consumed and the more greenhouse gas is emitted in transportation. Therefore, limiting the modular home delivery distance will be a key factor, in maintaining a better environmental performance over the conventional home. Therefore, the modular home can successfully meet the economic, environmental and social sustainability.

4.2. Future Study

The life cycle assessment conducted in this study excludes replacement and end-of-life phases of each home. The site-work and on-site assembly of the modular home are not taken into account in this study. There is limited information and data to complete a more comprehensive analysis at this stage. The material quantification for the conventional home employs many assumptions basically modeled after the modular home, due to difficulty in finding a conventional site built home. This estimated quantification may involve uncertainty or inaccuracy. Therefore, the future study requires extensive data gathering on replacement and end-of-life of each home as well as on the real material and design information of a conventional home. The extensive data will lead the study to be comprehensive and integrative.

In addition, the material transportation energy is unable to trace up to the raw material acquisition stage. The shipment information of each material is not available in this study. Information regarding fuel efficiency or size of truck was not fully provided from manufacturers or transporters. The transportation energy analysis is limited to the specific site location selected in this study. More comprehensive study, which can model transportation energy depending on different locations, would require an extensive amount of effort to obtain such data. It may also be of value to compare modular housing with other types of site built conventional housing to obtain a broader spectrum of environmental performance in the overall housing market. This would require a much greater collaboration with other suppliers, builders and providers of conventional site built housing.

5. Appendix

A. Modular Home Material Energy

Table 17 Primary Energy of Modular Home Materials

Materials	MJ LHV/kg	Total energy (MJ LHV)	Data Sources
Douglas Fir	9.87	91,320.0	IDEMAT 2001
Plywood	9.56	11,931.4	ETH-ESU 96 System
OSB	9.56	24,555.3	ETH-ESU 96 System
Gypsum Board	16.13	72,192.5	USA Input Out Database 98
Fiber glass	18.3	6,977.2	ETH-ESU 96 System
Cellulose insulation	17.1	13,160.9	BEES 3.0
Shingle	45.94	87,100.0	BEES 3.0
PVC	93.7	36,828.6	Industry Data (Sima Pro 6.0)
Carpet	158	28,914.0	BEES 3.0
HD urethane	99.8	12,528.5	Industry data (Sima Pro 6.0)
Polyethylene	108	1,966.8	Industry data (Sima Pro 6.0)
Galvanized steel	34.8	1,931.0	IDEMAT 2001
Western oak	9.02	2,365.3	IDEMAT 2001
Total		391,771.6	

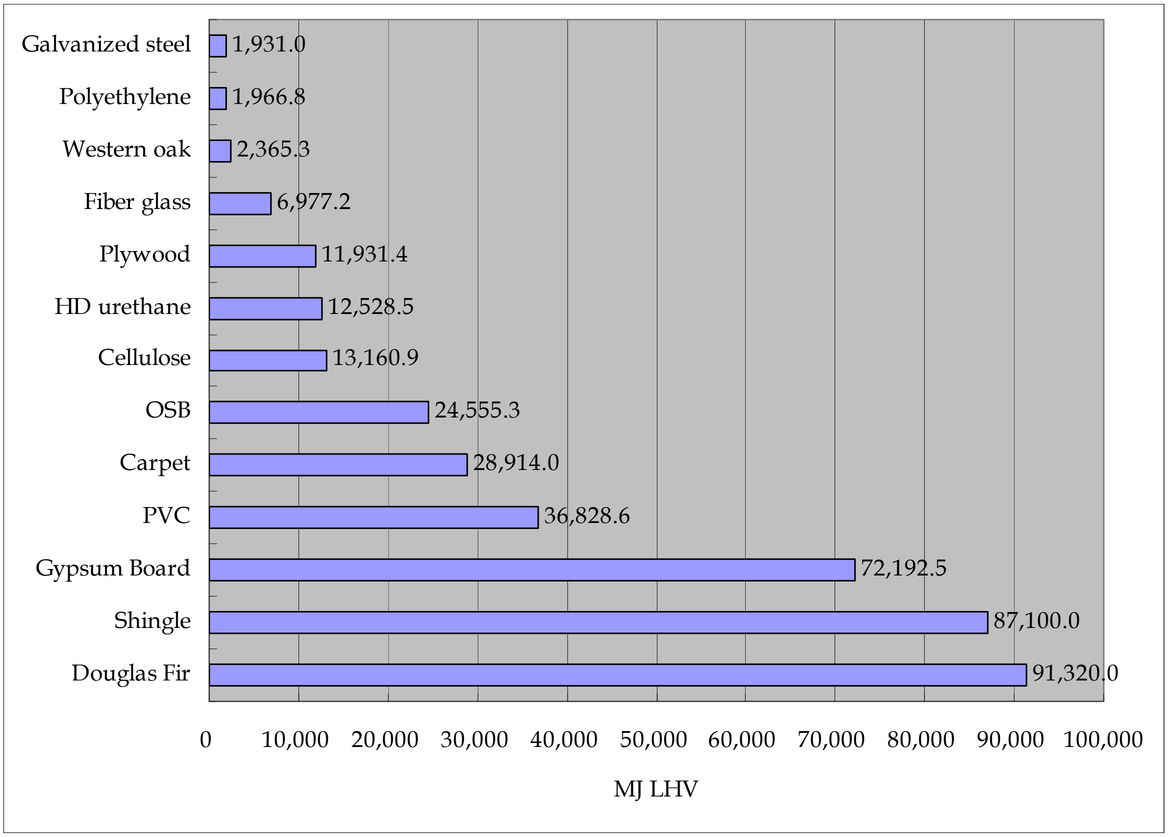

Figure 21 Primary Energy of Modular Home Materials

B. Conventional Home Material Energy

Table 18 Primary Energy of Conventional Home Materials

Materials	MJ LHV/kg	Total energy (MJ LHV)	Data Sources
Douglas Fir	9.87	81,955.49	IDEMAT 2001
Plywood	9.56	13,112.77	ETH-ESU 96 System
OSB	9.56	27,270.39	ETH-ESU 96 System
Gypsum Board	16.13	63,703.88	USA Input Out Database 98
Fiber glass	18.3	7,470.97	ETH-ESU 96 System
Cellulose insulation	17.1	14,092.19	BEES 3.0
Shingle	45.95	92,543.10	BEES 3.0
PVC	93.7	40,674.25	Industry Data (Sima Pro 6.0)

Carpet	158	28,914.0	BEES 3.0
HD urethane	99.8	13,414.86	Industry data (Sima Pro 6.0)
Polyethylene	108	2,106.05	Industry data (Sima Pro 6.0)
Galvanized steel	34.8	2,067.73	IDEMAT 2001
Western oak	9.02	2,532.72	IDEMAT 2001
Total		389,858.40	

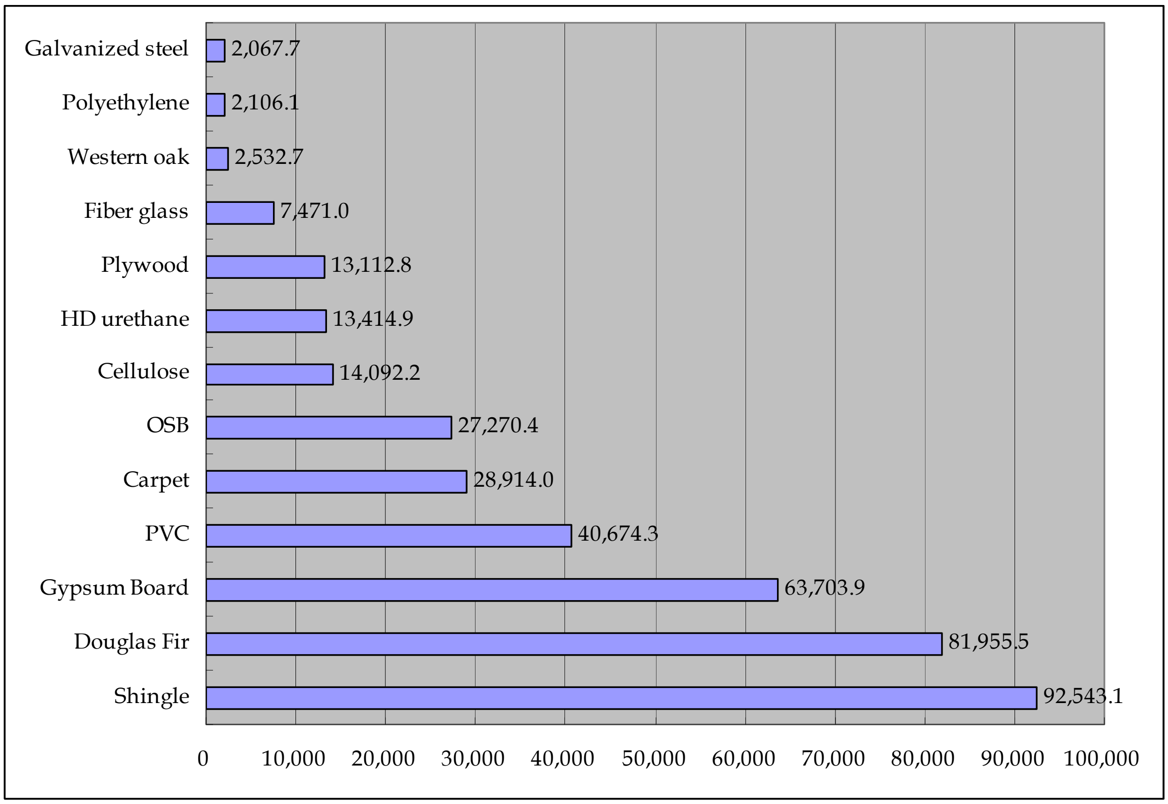

Figure 22 Primary Energy of Conventional Home Materials

C. eQuest Building Energy Modeling Data

Table 19 eQuest Energy Modeling Data

Category	**Input Data**
Location	Benton Harbor, MI

Building Area	1,456 ft^2
Cooling/Heating	DX Coils/Furnace
Roof Insulation	R-40 cellulose
Wall Insulation	R-19 fiberglass batts
Ground floor insulation	R-10
Infiltration	0.35 ACH (Conventional Home) 0.194 ACH (Modular Home)
Window	Low-emissivity glazing (Double Low-E (e3=0.4) clear window) ✓ U-factor: 0.46 ✓ SHGC: 0.72 ✓ SC: 0.84
Building operation schedule	Weekday unoccupied: 7am~5pm Weekend unoccupied: 10am~4pm
Lighting	Residential area (0.5W/ft^2) Storage are (1.19W/ft^2) Laundry (1.28 W/ft^2)
Miscellaneous Loads	Residential area (0.3W/ft^2) Laundry (0.15W/ft^2)
Thermostat set-points	Occupied: 70˚F for cooling and heating Unoccupied: 80˚F for cooling and 65˚F for heating
Water heating	Type: Natural gas boiler Storage : 27 gallon capacity with R-12 insulation Supply temperature: 135˚F

Table 20 Modular Home Material Inventory (P164 Ranch Model)

P164 RANCH		Material Quantity			Material Weight (lbs)				
Floors	**UOM**	**Module A**	**Module B**		**Weight A**	**Weight B**	**Total**		**Description**
Open-Web Floor Joist -9 1/4" X 150"	EA	35.00	40.00		1474.4	1685.0	3159.4	lbs	2X10, Douglas Fir
2 X 10 X 16' #2 SYP Rim Joist	LF	208.00	240.00		701.0	808.8	1509.8	lbs	2X10, Douglas Fir
2 X 4 X 16' #2 Floor Backer	EA	52.00	60.00		832.0	960.0	1792.0	lbs	2X4, Douglas Fir
Ledger Strip (1-1/2" x 1-1/2" x 12) MW Side	LF	104.00	120.00		57.2	66.0	123.2	lbs	2X2, Douglas Fir
19/32" Plywood Floor Decking 4x8 TG	SF	676.00	780.00		1216.8	1404.0	2620.8	lbs	19/32" thick, Plywood
25 OZ. Carpet - High Sierra	LF	68.00	54.00		226.8	180.1	407.0	lbs	12' W X 68' L or 54' L
7# Rebond Carpet Pad	LF	68.00	54.00		151.0	119.9	270.8	lbs	7/16" thick, high-density urethane, 5~6lbs/cf
Clear Poly Film 3 Mill 14x300	LF	52.00	60.00		2.4	2.8	5.2	lbs	0.0098' X 14" X 52, polyethylene
Left Sidewall:	**UOM**	**Module A**	**Module B**		**Weight A**	**Weight B**	**Total**		**Description**
34 x 57 Window Framing	EA	5.00	0.00		4.6	0.0	4.6	lbs	1/4" X 4", PVC
Studs 2 X 6 X 8' (PET 91-5/8")	EA	50.00	0.00		800.0	0.0	800.0	lbs	2X6, Douglas Fir
Top Plate - Double 2 X 6 X 12 #2	LF	52.00	0		208.0	0.0	208.0	lbs	2X6, Douglas Fir
Bottom Plate - 2 X 6 X 12 #2	LF	52.00	0		104.0	0.0	104.0	lbs	2X6, Douglas Fir
Plate Splice 2 X 6 X 14-1/2"	EA	3.25	0		7.9	0.0	7.9	lbs	2X6, Douglas Fir
Misc. Lumber	BF	48.00	0.00		1354.6	0.0	1354.6	lbs	BF= 10"X 1' X 1', Douglas Fir
1/2 X 4 X 8 Raw Gyp	SF	416.00	0		832.0	0.0	832.0	lbs	1/2" thick, Gypsum board
Insulation R-19	SF	382.72	0		175.3	0.0	175.3	lbs	5-1/2" thick, Fiber glass
Right Sidewall:	**UOM**	**Module A**	**Module B**		**Weight A**	**Weight B**	**Total**		**Description**
30 x 37 Window Framing	EA	0.00	1.00		0	3.8	3.8	lbs	1/2" X 6"X 1/16", PVC

34 x 57 Window Framing	EA	0.00	1.00		0	5.1	5.1	lbs	1/2" X 6"X 1/16", PVC
Exterior Door Framing	EA	0.00	1.00		0	59.9	59.9	lbs	(36" X 80") X 7/4"X 7"X1/16", Steel
Studs 2 X 6 X 8' (PET 91-5/8")	EA	0.00	44.00		0	704.0	704.0	lbs	2X6, Douglas Fir
Top Plate - Double 2 X 6 X 12 #2	LF	0	60.00		0	240.0	240.0	lbs	2X6, Douglas Fir
Bottom Plate - 2 X 6 X 12 #2	LF	0	60.00		0	120.0	120.0	lbs	2X6, Douglas Fir
Plate Splice 2 X 6 X 14-1/2"	EA	0	3.75		0	9.1	9.1	lbs	2X6, Douglas Fir
Misc. Lumber	BF	0.00	48.00		0	1354.6	1354.6	lbs	BF= 10"X 1' X 1', Douglas Fir
1/2 X 4 X 8 Raw Gyp	SF	0	480.00		0	960	960	lbs	1/2" thick, Gypsum board
Insulation R-19	SF	0	441.60		0	202.3	202.3	lbs	5-1/2" thick, Fiber glass
Front Wall:	**UOM**	**Module A**	**Module B**		**Weight A**	**Weight B**	**Total**		**Description**
34 x 57 Window Framing	EA	2.00	2.00		1.851036	1.9	3.7	lbs	1/4" X 4", PVC
Exterior Door Framing	EA	0.00	1.00		0.0	59.9	59.9	lbs	3' X 6.7' Door, 2" X 1/4", Steel
Studs 2 X 6 X 8' (PET 91-5/8")	EA	8.00	8.00		128.0	128.0	256.0	lbs	2X6, Douglas Fir
Top Plate - Double 2 X 6 X 12 #2	LF	13.00	13.00		52.0	52.0	104.0	lbs	2X6, Douglas Fir
Bottom Plate - 2 X 6 X 12 #2	LF	13.00	13.00		26.0	26.0	52.0	lbs	2X6, Douglas Fir
Plate Splice 2 X 6 X 14-1/2"	EA	1.00	1.00		2.4	2.4	4.8	lbs	2X6, Douglas Fir
1/2 X 4 X 8 Raw Gyp	SF	104.00	104.00		208	208	416	lbs	1/2" thick, Gypsum board
Insulation R-19	SF	95.68	95.68		43.8	43.8	87.6	lbs	5-1/2" thick, Fiber glass
Rear Wall:	**UOM**	**Module A**	**Module B**		**Weight A**	**Weight B**	**Total**		**Description**
26 x 37 Window Framing	EA	1.00	0.00		0.6	0.0	0.6	lbs	1/4" X 4", PVC
34 x 57 Window Framing	EA	0.00	1.00		0.0	0.9	0.9	lbs	1/4" X 4", PVC
Studs 2 X 6 X 8' (PET 91-5/8")	EA	11.00	11.00		176.0	176.0	352.0	lbs	2X6, Douglas Fir
Top Plate - Double 2 X 6 X 12 #2	LF	13.00	13.00		52.0	52.0	104.0	lbs	2X6, Douglas Fir

Bottom Plate - 2 X 6 X 12 #2	LF	13.00	13.00		26.0	26.0	52.0	lbs	2X6, Douglas Fir
Plate Splice 2 X 6 X 14-1/2"	EA	1.00	1.00		2.4	2.4	4.8	lbs	2X6, Douglas Fir
Misc. Lumber	BF	8.00	0.00		225.8	0.0	225.8	lbs	BF= 10"X 1' X 1', Douglas Fir
1/2 X 4 X 8 Raw Gyp	SF	224.25	258.75		448.5	517.5	966	lbs	1/2" thick, Gypsum board
Insulation R-19	SF	206.31	238.05		94.5	109.0	203.5	lbs	5-1/2" thick, Fiber glass
Partition:	**UOM**	**Module A**	**Module B**		**Weight A**	**Weight B**	**Total**		**Description**
Top Plate 2 X 4 X 16' #2	LF	91.17	65.08		116.7	83.3	200.0	lbs	2X4, Douglas Fir
Bottom Plate 2 X 4 X 16' #2	LF	91.17	65.08		116.7	83.3	200.0	lbs	2X4, Douglas Fir
Top Plate 2 X 6 X 16' #2	LF	0.00	12.50		0.0	25.0	25.0	lbs	2X6, Douglas Fir
Bottom Plate 2 X 6 X 16' #2	LF	0.00	12.50		0.0	25.0	25.0	lbs	2X6, Douglas Fir
2 X 4 X 93-1/8" Studs	EA	82.00	66.00		814.5	655.6	1470.1	lbs	2X4, Douglas Fir
2 X 6 X 93-1/8" Studs	EA	0.00	8.00		0.0	124.2	124.2	lbs	2X6, Douglas Fir
Misc. 2 X 4 Lumber	LF	56.00	88.00		71.7	112.6	184.3	lbs	2X4, Douglas Fir
7/16" OSB Backers	SF	20.00	20.00		28.0	28.0	56.0	lbs	7/16" thick, OSB
1/2 X 4 X 8 Raw Gyp	SF	1,458.67	1,241.33		2917.3	2482.7	5400	lbs	1/2" thick, Gypsum board
Marriage Wall:	**UOM**	**Module A**	**Module B**		**Weight A**	**Weight B**	**Total**		**Description**
2 X 4 X 91 5/8" Marriage Wall Stud	EA	56.00	56.00		547.6	547.6	1095.3	lbs	2X4, Douglas Fir
Marriage Wall Top Plate 2 X 4 X 16' #2 (X2)	LF	59.00	59.00		151.0	151.0	302.1	lbs	2X4, Douglas Fir
Marriage Wall Bottom Plate 2 X 4 X 16' #2	LF	59.00	59.00		75.5	75.5	151.0	lbs	2X4, Douglas Fir
Misc. 2 X 4 X RL	LF	56.00	32.00		71.7	41.0	112.6	lbs	2X4, Douglas Fir
1/2 X 4 X 8 Raw Gyp	SF	472.00	472.00		944	944	1888	lbs	1/2" thick, Gypsum board
Roof:	**UOM**	**Module A**	**Module B**		**Weight A**	**Weight B**	**Total**		**Description**
MC02746 68-7/16 X 154-1/2 MP HG 5/12	EA	28.00	30.00		1040.2	1114.5	2154.7	lbs	2X6, 5.7' X 12.875', Douglas Fir

Rafter									
MC02791 68-7/16 Fly Rafter	EA	2.00	2.00		22.8	22.8	45.6	lbs	2X6, 5.7', Douglas Fir
MC02745 48-11/16 Fly Rafter	EA	0.00	2.00		0.0	16.2	16.2	lbs	2X6, 4.06', Douglas Fir
Ceiling Board 1/2" Raw Gyp 48 X 150	SF	650.00	750.00		1300	1500	2800	lbs	1/2" thick, Gypsum board
Furrow Strip MW side15/32" Plywood 2-3/4"	SF	23.83	27.50		33.4	38.5	71.9	lbs	Plywood
Strong Back (2) 1 X 3	LF	52.00	52.00		20.8	20.8	41.6	lbs	Douglas Fir
Fascia Board - Sidewall 2 X 6 X 12'	LF	54.00	62.00		108.0	124.0	232.0	lbs	2X6, Douglas Fir
Fascia Board - Endwall 2 X 6 X 12'	LF	30.00	30.00		60.0	60.0	120.0	lbs	2X6, Douglas Fir
Subfascia Board 1 X 6 X 12'	LF	52.00	60.00		44.2	51.0	95.2	lbs	1X6, Douglas Fir
Top of MW 2 X 4 X 12'	LF	52.00	60.00		66.6	76.8	143.4	lbs	2X4, Douglas Fir
Bottom of Hinge Post 2 X 4 X 12'	LF	52.00	60.00		66.6	76.8	143.4	lbs	2X4, Douglas Fir
Top Of MW (no beam) 2 X 4 X 12'	LF	52.00	60.00		66.6	76.8	143.4	lbs	2X4, Douglas Fir
Bottom of MW (no beam) 2 X 6 X 12'	LF	52.00	60.00		104.0	120.0	224.0	lbs	2X6, Douglas Fir
Wall Backer 1 X 6 X 12'	EA	5.00	4.00		51.0	40.8	91.8	lbs	1X6, Douglas Fir
Roof Decking 7/16" OSB	SF	782.60	903.00		1095.6	1264.2	2359.8	lbs	7/16" thick, OSB
Ply Dry 8' X 300' / roll	SF	837.00	961.00		5.4	6.2	11.7	lbs	0.0055" thick, 1.18lbs/cf, Polyethylene fabric
Rolled Roofing ICE/WATER 36" x 65' / roll	LF	52.00	60.00		12.1	14.0	26.2	lbs	1/6" thick X 36" wide, rubberized membrane
25 YR 3-1 Royal Sovereign Shingle	SF	782.60	903.00		164346	189630	4214.0	lbs	2.5 lb/sf
R-19 Batt Insulation on MW	LF	52.00	60.00		71.4	82.4	153.9	lbs	14.58' X 52' or 60' X 5-1/2"
Blown Insulation R-40	Bag	29.00	32.50		783.0	877.5	1660.5	lbs	Weight/bag, Cellulose
Vapor Barrier (1GA = 300SF)	GA	2.60	3.00		10.4	12.0	22.4	lbs	1mil thick, polyethylene

Exterior Siding:	**UOM**	**Module A**	**Module B**		**Weight A**	**Weight B**	**Total**		**Description**
Exterior Sheathing 3/8" OSB - Sidewalls 8'6"	SF	442	510		530.4	612	1142.4	lbs	3/8" thick, OSB
Exterior Sheathing 3/8" OSB - Endwalls 10'6"	SF	273	273		327.6	327.6	655.2	lbs	3/8" thick, OSB
Exterior Sheathing 3/8" OSB - Mating Wall 9'	SF	468	540		561.6	648	1209.6	lbs	3/8" thick, OSB
Exterior Sheathing 3/8" OSB - Ship Loose	SF	64	64		76.8	76.8	153.6	lbs	3/8" thick, OSB
Vinyl Siding - Triple 3 - 1/3 Sides	SQ	4.16	4.8		208	240	448.0	lbs	3/8" thick, 1 SQ= 100 sf, PVC
Vinyl Siding - Triple 3 - 1/3 Ends (shiploose)	SQ	4	4		200	200	400.0	lbs	3/8" thick, 1 SQ= 100 sf, PVC
Exterior Doors & Windows:	**UOM**	**Module A**	**Module B**		**Weight A**	**Weight B**	**Total**		**Description**
26 X 37 Vinyl Window - Tempered (Baths)	EA	1.00	0.00		0.6413913	0	0.6	lbs	1/4" X 4", PVC
30 X 37 Vinyl Window	EA	0.00	1.00		0	0.6816843	0.7	lbs	1/4" X 4", PVC
36 X 61 Vinyl Window	EA	5.00	2.00		4.9346715	1.9738686	6.9	lbs	1/4" X 4", PVC
72 X 61 Vinyl Window (36 Twin)	EA	1.00	1.00		1.3532343	1.3532343	2.7	lbs	1/4" X 4", PVC
LS-5902 Comb-SS Emtrance Lockset	EA	0.00	2.00		0	5.6	5.6	lbs	2.8 lbs/EA, Galvanized steel
Interior Doors & Trim:	**UOM**	**Module A**	**Module B**		**Weight A**	**Weight B**	**Total**		**Description**
Interior Door 20" Western Oak Flat	EA	0.00	1.00		0.0	12.8	12.8	lbs	20" X 6.7' X 11/8", Western Oak
Interior Door 32" Western Oak Flat	EA	7.00	6.00		143.8	123.3	267.1	lbs	32" X 6.7' X 11/8", Western Oak
#1011 Door Casing 7' 2" Western Oak	EA	35.00	40.00		64.7	74.0	138.7	lbs	4-1/4" wide X 7/8" thick, Western Oak
#1011 Window Casing 10' Western Oak	LF	107.13	62.31		27.6	16.1	43.7	lbs	4-1/4" wide X 7/8" thick, Western Oak
#4634 Base Western Oak	LF	170.00	170.00		43.9	43.9	87.7	lbs	4-1/4" wide X 7/8" thick, Western Oak
Ceiling Cove #4051 10'/Ea 60pc/box	LF	20.00	20.00		7.8	7.8	15.6	lbs	4-1/2" wide X 1/4" thick, Western Oak

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