S9-3

Quantification of the CO_2 Footprint in Residential Construction

Don Mah[1] P.Eng., Juan D. Manrique[2], Haitao Yu[3], Mohamed Al-Hussein.ASCE[4] P.Eng., PhD and Reza Nasseri[5]

1 PhD Candidate and Research Assistant at the University of Alberta, Department of Civil and Environmental Engineering, Hole School of Construction. 1-080 Markin/CNRL Natural Resources Engineering Facility. Edmonton, Alberta, Canada T6G 2W2. E-mail: dbmah@ualberta.ca
2 PhD Candidate and Research Assistant at the University of Alberta, Department of Civil and Environmental Engineering, Hole School of Construction. 1-080 Markin/CNRL Natural Resources Engineering Facility. Edmonton, Alberta, Canada T6G 2W2. E-mail: jdm19@ualberta.ca
3 PhD Candidate and Research Assistant at the University of Alberta, Department of Civil and Environmental Engineering, Hole School of Construction. 1-080 Markin/CNRL Natural Resources Engineering Facility. Edmonton, Alberta, Canada T6G 2W2. E-mail: hyu@ualberta.ca
4 Associate Professor at the Department of Civil and Environmental Engineering, Hole School of Construction. 3-011 Markin/CNRL Natural Resources Engineering Facility. Edmonton, Alberta, Canada T6G 2W2. E-mail: malhussein@ualberta.ca
5 CEO Landmark Group of Builders, 9765-54 Ave, Edmonton, Alberta, Canada, T6E5J4.

Abstract

The current residential process adheres to a traditional method of construction involving wood framing on-site on poured concrete foundations which has been widely applied in North America. A conventional residential construction process can include seventeen distinct stages ranging from stake-out to pre-occupancy inspection. The current practice possesses short comings including high construction material wastes, long scheduling timelines, adverse weather conditions, poor quality, low efficiencies and negative environmental impacts from transportation and equipment use. Over CAN $5 billion dollars was spent in the construction sector during 2007 in Canada. Previous findings in CO_2 emissions during the construction process of a conventional dwelling emphasize more than 45 tonnes of CO_2 emissions. Hence, in Alberta alone during 2007, almost 50,000 residential units would release more than two million tonnes of CO_2. These numbers demonstrate the economical and environmental impact in building construction and its relationship with CO_2 emissions. The aim of this paper is to quantify the CO_2 emissions from the current residential construction process in order to establish the baseline for CO_2 emission reduction opportunities. The quantification collection methodology will be approached by identifying the seventeen various stages of construction and quantifying the contributions of CO_2 from specific activities and their impacts of work for each stage. The approach of separating these into separate stages for collection will allow for independent opportunities for analysis from various independent contractors from the entire scope of work. The use of BIM will be implemented to efficiently quantify CO_2 emissions. Based on the CO_2 quantification baseline, emission reduction opportunities such as an industrialized construction process will be introduced that allows homebuilders to reduce the environmental and economical impact of home construction while enabling them to produce higher quality, more energy efficient homes in a safer and shorter period of time.

Introduction

The North American method of residential construction involving wood framing on-site on poured concrete foundations. This conventional construction process can be broken down into seventeen distinct stages, ranging from stake-out to pre-occupancy inspection as used by Landmark Homes in Edmonton, Alberta, Canada (Landmark Group of Builders, 2008). The current practice, however, entails a number of short-comings, including high material waste, long scheduling timelines, adverse weather conditions, poor quality, low efficiency, work pressure and negative environmental impacts from transportation and equipment use (Nepal et al., 2006). The time spent during the planning stage for constructing residential facilities is relatively short compared to other types of construction projects. It has become common practice in this industry to rely on trades personnel and their experience to deal with constructability details at construction sites rather than consultants detailing all information required for the project before construction starts. This lack of planning affects construction performance and the project scheduling. As a solution, information technology can produce accurate information in brief periods of time, from design to construction (Lee et al., 2006).

Over $5 billion dollars were spent in the construction sector during 2007 in Canada (Statistics Canada, 2008). Previous findings have shown that CO_2 emissions during the construction of a conventional dwelling amount to more than 45 tons of CO_2 (Gonzalez & Navarro, 2006). In Alberta alone during 2007, almost 50,000 residential units would have released more than two million tons of CO_2. These numbers demonstrate the economical and environmental impact on building construction and its relationship with CO_2 emissions due to current construction practices. On the other hand, the residential sector alone is the third-largest energy user, after the industrial and transportation sectors, accounting for 17% of secondary energy use in Canada and 16 percent of related GHG emissions (77 megatonnes). US Energy Information Administration (2008), illustrates that buildings operations are responsible for 43% of total U.S. CO_2 emissions and 76% of electricity consumption. The scope of work of this paper centers its attention in the construction of stick-frame dwellings, not in the operational implications of already constructed homes in North America. Considerable amount of information can be obtained from the operational portion of a household, but not many researchers have focused on the implications of current building processes and their relationship with GHG emissions.

BIM in Construction Engineering

With the advancement in building information modeling (BIM) software, it is possible to create an efficient analysis for building processes, types, sizes, materials effects and coordinate complex MEP systems (Korman, et al., 2008). Through the utilization of intelligent data repositories, any 3D model can be frontloaded with complex information in regards to construction materials, crew types and sizes, and equipment transportation and installation (Vilkner et al., 2007). Process documentation for construction activities and their relationship with cost estimates, construction schedules, quantity takes offs and in this case, CO_2 emissions can be easily incorporated, manipulated, updated and depicted through the use of BIM (Goedert and Meadati, 2008).

With BIM, homebuilders have eased the process of gathering relevant information to reduce the economic impact of home construction while enabling them to produce higher quality homes. Nevertheless, solutions for fostering sustainable residential construction are required in order to address environmental concerns such as CO_2 emissions and energy efficiency. The need to address sustainable development has become ostensible as the demand for resources and energy requirements has grown. There are many approaches that could be followed to meet the need for action in this regard. For instance, many new products, processes, and regulations have emerged in the marketplace and have enjoyed some success. The justification for sustainable construction is now well-established in our society. Sustainable facilities are becoming an increasingly favorable prospect for many forward-thinking organizations (Buchanan, 2007).

The rapid increase in the concentration of Green House Gas (GHG) emissions is widely acknowledged as the major cause of climate change. Based on data provided by Natural Resources Canada (NRC) (2006), total Canadian GHG emissions are estimated to have been 758 megatons in 2004; of this, 67 percent resulted from secondary energy use. Based on a survey conducted by researchers at the University of Alberta, the direct CO_2 emissions (i.e., material transportation, workforce travel, and construction equipments) in wood frame house construction in Edmonton area from stake-out to drywall completion are 10.6 tons per house (Yu et al., 2008). The GHG emissions from the operation of a new home have been reduced by 20 percent—about 3 tonnes per household per year (NRC, 2006).

The reality today is that current construction practices are being challenged by technological innovations, higher costs, and sustainable construction issues. There has been a significant increase in GHG emissions due to construction-related activities. This environmental issue is of paramount concern to society and thus it needs to be addressed by introducing new construction techniques. Panelized and modular constructions for stick-frame dwellings can significantly reduce construction costs, increase product quality, reduce construction time and enhance labour safety (Morse-Fortier, 1995) and NAHB (2000). Significant efficiencies can be gained by manufacturing buildings in components (panels) or complete in factory units (modules) and shipping these prefabricated pieces to the construction site for erection and installation (Landmark Group of Builders, 2008). Although the manufacturing components for the homebuilding industry can significantly reduce material waste and better utilize labour and equipment, the customer acceptance can put on hold the development of these construction techniques (Mullens and Arif, 2006). This paper provides the means for construction companies to measure their current practice and derive better procedures to reduce the amount of CO_2 emissions through the utilization of BIM.

Motivation and Rationale

Research has shown the possibility of a 30% reduction in CO_2 emissions from selection of low environmental impact materials (Gonzales & Navarro, 2005). Other works by researchers have highlighted the relationship between construction materials and CO_2 emissions in terms of life cycle, ranging from manufacturing to construction to operation and finally demolition (Seo & Hwang, 2001). As well, there is a body of literature which provides CO_2 emissions rates based on embodied energy from different materials (Upton & et al., 2008). However, there has been only limited research on CO_2 emissions directly from the construction process, although Nassen et al., (2007) have highlighted the need to address the issue of CO_2 emissions resulting from house production. Hence, there is a need to fill the gap in the literature and this research aims to address it.

A study done by the Landmark Group of Builders (LGB) and the University of Alberta (U of A) has suggested that a manufacturing process based on panelized construction technique may be a practical solution. The large scale and factory-built nature of panel production allows for the use of a number of energy-conservative technologies that are currently cost-prohibitive or skill-prohibitive in the context of site-built applications. This approach satisfies the customer demand for uniqueness, reason that has impeded market acceptance of other systems such as manufactured or modular housing. Panelized construction has been identified by U.S. Department of Housing and Urban Development (HUD) as one of three technologies with the highest level of potential benefits with respect to the HUD's goals of affordability, energy-efficiency, environmental impact, quality, durability, and labour safety. The aim of this paper is to demonstrate the benefits of manufacturing building components and its relationship with the reduction of CO_2 emissions. The need for delivering vital information on-time to residential constructors becomes the keystone for this research. The supply of accurate information can be provided by information technologies that can connect real-life complex and long processes with information management repositories. The utilization of BIM for quantifying CO_2 emissions due to construction processes can provide the vital information needed for decision makers to enhance current practices. With the use of an intelligent repository, many flaws in the construction of residential dwellings can be noticed and corrected before construction starts. With the results of this research, residential construction companies can improve their current practice by utilizing the proposed methodology.

In order to establish the baseline for CO_2 emission reduction initiatives with the aid of BIM, the need for micro-detailing every activity related to the construction of a typical stick-frame dwelling becomes evident. Factors such as transportation, equipment, weather, scheduling, material handling, and other contributing factors can be built-in as criteria for quantification. Based on the CO_2

quantification baseline, emission reduction opportunities such as an industrialized construction processes can be obtained.

This paper has combined the power of Parametric Modeling and the inclusion of an intelligent repository system to quantify the effect of CO_2 in the home building construction industry. The quantification of GHG emissions from the current residential construction process can be automatically obtained from the analysis of rich 3D models and comprehensive lists of construction methods. The proposed methodology is applicable to any other type of construction process, where materials, labour and equipment are utilized for any building technique.

The significance of this research to housing is significant, especially considering the contribution of the housing industry to Canada's GDP. Furthermore, the relationship between housing construction and CO_2 emissions has been made evident: the residential sector is the third largest energy user in Canada accounting, for 17% of secondary energy and 16% of GHG emissions or 77 megatons (NRC, 2006). A recent project funded through the Canadian Mortgage and Housing Corporation (CMHC) on Net Zero Housing has provided the impetus for this application through its goals of reducing environmental impact and encouraging sustainable construction. More broadly, all citizens and companies must contribute to mitigating climate change while providing value to society (Yu et al., 2008).

Proposed Methodology

The proposed methodology commenced with a review of the residential construction process by identifying all activities and stages for stick-frame houses. In order to model accurately the current construction practice, it was necessary to shadow one of the largest home builders in the local area: Landmark Homes, an Edmonton-based homebuilder. The research plan is based on the following phases:

Phase 1: Gather information and document sources of CO_2 emissions from standard activities for the various stages of home construction.

Phase 2: Quantify the current CO_2 emissions from various activities in each stage, including emissions from equipment, transportation, handling and material waste.

Phase 3: Quantify the current CO_2 emissions during the operational use of a residential dwelling and find solutions to minimize them.

Phase 4: Develop a repository with the data obtained in phase 2 and link it to a parametric model (BIM).

Phase 5: Analyze the nature of CO_2 emissions and explore opportunities for reduction, such as the industrialized housing concept.

Phase 6: Document the benefits of the proposed industrialized housing methodology and facilitate dissemination to the housing industry.

The quantification collection methodology was approached by identifying seventeen various stages of construction and quantifying the contributions of CO_2 from those specific activities and their impacts on work for each stage (See Table 1).

The approach of identifying separate stages for collection allowed for independent opportunities for analysis with various independent contractors from the entire scope of work. Factors such as transportation, equipment, weather, scheduling, material handling and other contributing factors were used as criteria for quantification as well. Data was collected through detailed field observations and in-depth interviews with site superintendents.

Table 1, 17 construction stages for residential construction

Stage	Description	co2 (kg)
1	Stake Out	23
2	Deep Services & Foundation Walls	2257
3	Backfill & Shallow Trenching	926
4	Capping Shallow Services	1057
5	Framing Main & Second Joists	482
6	Framing Second & Roof	778
7	Roofing	514
8	Siding & Rough-Ins	381
9	Electrical RI & Slabs	344
10	Insulation & Boarding	562
11	Drywall Taping & Texture	420
12	Stage 1 Finishing & Cabinets	167
13	Railing & Painting	763
14	Tile & Vinyl Flooring	326
15	Hardwood & Stage 2 Finishing	270
16	Carpet & Finals	326
17	Touch-Ups & Pre-Occupancy	311
	Total	9908

The proposed methodology for this research is shown in Figure 1. The input parameters to the system start with the recompilation of all designs required for construction. The structural, architectural, landscape, mechanical, electrical and plumbing designs are gathered at the initial stage in conjunction with the customer requirements for construction.

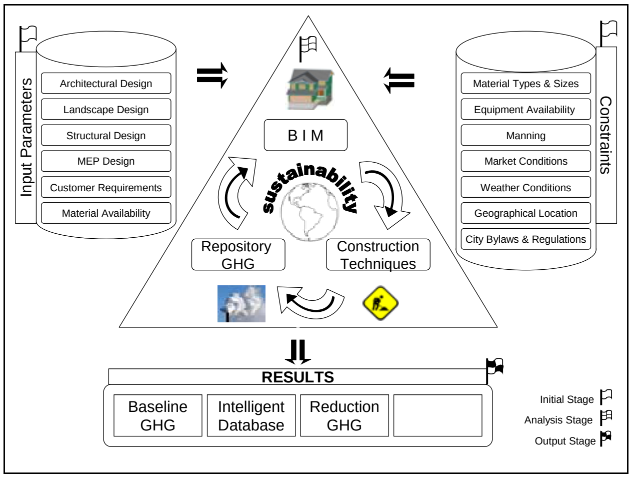


Figure 1, Proposed Methodology

These parameters are bounded by the local City bylaws and regulations, and the materials available in the area. It is important to notice that special items not produced or manufactured in the local region of construction will increase the CO_2 emissions due to transportation and material handling. The system is also constrained by the equipment and means for transportation required by the workforce. Depending on the type of construction methodology to be followed, the geographical location will also affect the CO_2 emission output of the model since either men and/or materials will have to travel to the site on a daily bases. The amount of labour and the weather conditions during the building stage have a significant impact for task durations; this fact links to the energy required for heating the facility during low temperatures.

The analysis stage of the proposed methodology combines the development of a building information model (BIM) of the residential facility with an intelligent repository of GHG emissions of construction activities and methods as explained before (Table 1). These two processes are also linked with the construction methodology chosen by the homebuilder: Panelized or On-site construction. The core purpose of this methodology is to create a baseline for sustainability in the homebuilding industry. These processes should be analyzed altogether in order to have a better perspective between materials, building techniques, labour and others.

Once these cornerstones are set, the quantification of CO_2 emissions and their implications per installed material are stored in the repository system. Since the system is based on emission rates per unit of installed material, the quantification for any other residential facility within the same building technique can be also analyzed with accurate results. In order to have an ample range of analysis within the homebuilding industry, panelized and on-site framing construction techniques were broken down and stored in the repository system. It is important to mention that the proposed methodology is applicable to any other building technique and construction industry. An evaluation of the current practice in terms of its potential for CO_2 emissions reduction is a product of this research final output stage.

The sections below will describe the following various CO_2 emission analysis and comparison for residential construciton: CO2 emissions during construction and CO2 emissions during operational lifecycle.

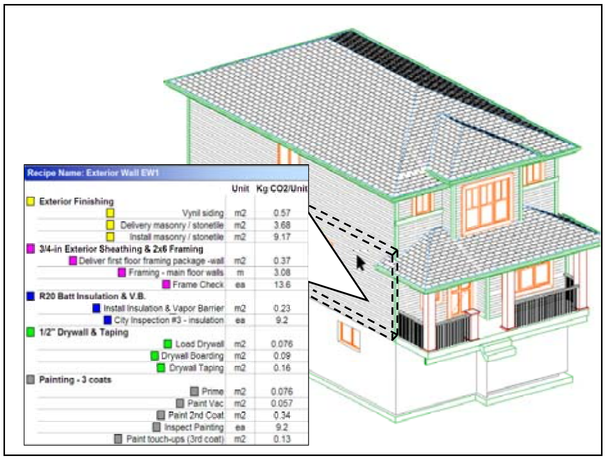
CO_2 Emissions during Construction

As described in the proposed methodology, every of the 17 stages required for construction were broken down into all tasks required for material installation in combination with demanded workforce (see Table 1). Over 9900 CO_2 kg of emissions is used for conventional on-site construction. As an example, stage 5 consists of framing the main floor and second floor joists which contributes about 482 kg of CO_2. Table 2 shows the various tasks associated with stage 5 and its corresponding CO_2 emissions by task and by unit rates. Task durations and trip counts were established through field observations and interviews conducted with Landmark Homes site superintendents. The material trips and crew trip contribution to emissions are based on averaged travel distance and type of vehicle used. Established CO_2 emissions for various vehicle types were used as well as equipment types such as generators and compressors. Vehicle emissions rates were between 0.23 kg/km of CO_2 and 2.68 kg/hr of CO_2 for generators and compressors. An average travel distance of 40 km was used in this analysis. Based on a typical house, unit rates such as per linear meter or square meter were established for inclusion into BIM for quantification purposes. For instance, the unit rate for wall framing CO_2 emissions is 3.08 kg/m.

Table 2, Stage 5 CO_2 Computations

Stage 5 - Framing		Material		Labour		Installation				
Tasks	Duration (hr)	Trips	Equipment	Trips	Equipment	Equipment	CO2 (kg)	Unit	Qty / Model	Amt (kg/unit)
Framing Main & Second Joists										
Deliver first floor framing package -wall	1	0.5	5t truck				23.2	linear m of wall	63.1	0.37
Deliver first floor framing package -floor	1	0.5	5t truck				23.2	m2 of floor	82.3	0.28
Framing - main floor	16			8	0.5t truck	1 generator, 1 compressor	194.56	m2 of floor	82.3	2.36
Framing - main floor walls	16			8	0.5t truck	1 generator, 1 compressor	194.56	linear m of wall	63.1	0.32
Deliver second floor framing package -floor	1	0.5	5t truck				23.2	m2 of floor	82.3	0.28
Deliver second floor framing package -wall	1	0.5	5t truck				23.2	linear m of wall	63.1	0.37

Figure 2 illustrates the input into BIM for quantification purposes. The construction stages mentioned before relate only to specific tasks during the building process. For the analysis with BIM, it was necessary to group these tasks into assemblies for construction. As an example, Figure 2 shows a common assembly for an exterior load bearing wall composed of vinyl siding or brick veneer, exterior sheathing and wood studs, thermal insulation, drywall and final paint. These tasks happen at different stages, but for quantification purposes and CO_2 emission analysis, it was required to create an assembly that can be linked to a parametric object in the BIM.



Recipe Name: Exterior Wall EW1

	Unit	Kg CO2/Unit
🟨 Exterior Finishing		
🟨 Vynil siding	m2	0.57
🟨 Delivery masonry / stonetile	m2	3.68
🟨 Install masonry / stonetile	m2	9.17
🟪 3/4-in Exterior Sheathing & 2x6 Framing		
🟪 Deliver first floor framing package -wall	m2	0.37
🟪 Framing - main floor walls	m	3.08
🟪 Frame Check	ea	13.6
🟦 R20 Batt Insulation & V.B.		
🟦 Install Insulation & Vapor Barrier	m2	0.23
🟦 City Inspection #3 - insulation	ea	9.2
🟩 1/2" Drywall & Taping		
🟩 Load Drywall	m2	0.076
🟩 Drywall Boarding	m2	0.09
🟩 Drywall Taping	m2	0.16
⬜ Painting - 3 coats		
⬜ Prime	m2	0.076
⬜ Paint Vac	m2	0.057
⬜ Paint 2nd Coat	m2	0.34
⬜ Inspect Painting	ea	9.2
⬜ Paint touch-ups (3rd coat)	m2	0.13

Figure 2, BIM CO_2 Assembly

After obtaining and grouping the related tasks for construction into object assemblies, the BIM will transfer the quantities per object into an intelligent repository. The repository, based on logical rules and model constraints, will determine the emissions produced per assembly. This information is stored according to the work breakdown structured (WBS) defined in the BIM. The assemblies are classified in the WBS based on location within the building. In this case, the WBS for the 3D model is: Basement, Main Floor, Second Floor and Roof. Each storey in the building is also broken down into areas, such as leaving spaces, mechanical and service rooms, corridors, and so forth.

This research examines prefabrication of various house components as an approach to mitigate CO_2 emissions through higher productivity, inclusion of better energy efficient equipment and higher quality. This industrialized housing concept has been proposed and initial findings definitely highlight its benefits. The scope of work for the prefabrication manufacturing shop will be wall panels, floor and roof components. Siding, building wrap, sheathing, panel framing, insulation, vapor barrier, drywall and taping, door and windows installation, and electrical components will be installed at the shop. Floor sections will have joists and subfloor sheathing. The roof sections will have shingles, sheathing, and roof trusses. Figure 3 shows the various building components manufactured at the shop.

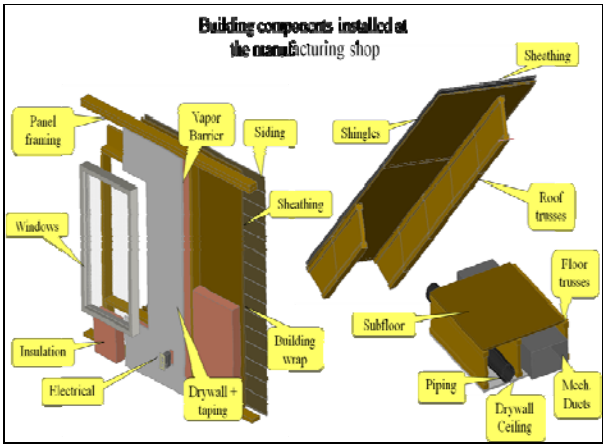


Figure 3, Building components manufactured at the shop.

The positive impact of adopting a prefabricated panelized system versus on-site construction is apparent. First, there is reduced site construction activity which would minimize on-site material waste, transportation and idle time. Second, there will be a reduction of operational costs and emissions for houses. The efficiencies and process integration advantages of the panelized component system will reduce current obstacles of diminishing returns when integrating materials and components that significantly improve energy efficiency and reduce GHG emissions. The panelized component system will enable the construction of a 1600 sq.ft. home that emits 4.4 t CO_2/yr less than a standard home for a third of the conventional cost premium during its operational lifecycle. This reference home mitigates 2.87 t CO_2/yr during its operational lifecycle. This research study concludes that the panelized component system will eliminate 6.21t CO_2 emissions per house (See Table 3). Third, there is a drastically shortened construction time. What is normally a 9 month long construction process for a 2000 sq.ft. house will take a mere 2 months when the panelized component system is fully operational. Emissions from winter heating can be reduced by an average of 4.2 t CO_2 per house and costs of construction are much lower as a result of reduced carrying costs and reduced heating fuel costs. Additionally, a shorter construction time requires fewer construction supervision trips, saving 0.26 t CO_2 per house. Fourth, there is a potential to reduce material waste by 50%.

Table 3, CO_2 Emissions Comparison

GHG Emissions in House Construction

Construction Stage	GHG Emissions (tonne/house)	
	Stick-Built	Panelized Construction
Site Related Activities		
Main subfloor capping & shallow services	1.06	0.38
Framing main floor walls & second floor joists	0.48	
Framing second floor walls and roof	0.78	1.02
Roofing	0.51	
Siding & plumbing rough-in	0.39	0.24
Electrical rough-in & slabs	0.34	0.28
Insulation & drywall boarding	0.52	0.35
Drywall taping & texture	0.37	0.37
Winter Heating	6.30	2.10
Site Supervision	0.51	0.25
Factory operation		0.79
Elimination of embodied emissions through material use and waste reduction		-0.72
TOTAL (Tonnes)	11.27	5.06

Material usage can be maximised through computerised cutting algorithms (Manrique, et al. 2008). Indoor assembly protects materials from damage and weathering and what waste is generated can be readily recovered for recycling and all wood waste can be used onsite as heating fuel. The outcome of this material waste mitigation will yield a reduction of 0.72 t CO_2 per house. Fifth, quality will be enhanced. Modular and panelized construction is tighter and stronger compared to stick-built or traditional methods. The controlled indoor environment and experienced labor force can construct with consistent quality. Workers familiar with their product can easily integrate materials and techniques into the process when working side-by-side with individuals of other trade backgrounds. Finally, safety is enhanced. Items such as siding, roofing, flooring and windows that are usually installed using scaffolds, ladders and lifts will be installed on the assembly line, making these processes both safer and dramatically faster. On-site construction through the 17 stages resulted in approximately 9900 kg of direct CO_2 emissions. Additionally, winter heating contributes an additional 6300 kg of CO_2. The CO_2 emissions from operations are significantly higher when compared to the life cycle of the house. This will be detailed in a later section.

CO_2 Emissions during the Operational Lifecycle

The CO_2 emissions from construction were described in the previous section. Although the impacts are significant, the section below outlines and compares how much more operational CO_2 emissions are affecting the environment and sustainability. Capital costs have been a primarily concern for construction project budgets until the utilization of life cycle costs analysis for a building were introduced. With this onset, owners are now more cognizant of total life cycle costs in their financing. That is, the operational costs are included in decision making. This analogy is applicable to CO_2 emissions from buildings. In terms of higher capital investment in better energy efficient equipment, materials and practices, the overall CO_2 emissions can be reduced dramatically. As shown in Figure 4, the cumulative effects comparison of construction versus operations over a period of time highlights the significant impact of operational emissions. This figure highlights the CO_2 mitigations through the adaptation of a panelized building process. The projections are based on the manufacturing of 1000 housing units per year with a corresponding 4400 tonnes of savings through the life cycle operations and 5500 tonnes from construction. The operational emissions mitigations come from the shift to a manufacturing process and enhancement with building upgrades. The shift from on-site to factory-built has a tremendous impact on CO_2 emission reductions.

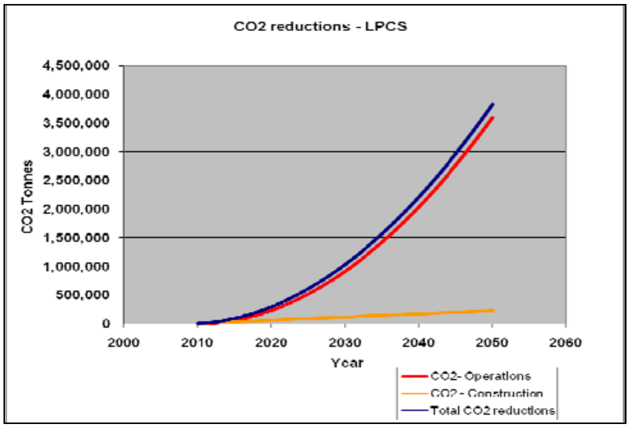


Figure 4, Cumulative CO_2 mitigation Landmark Panel Construction System until 2050.

Landmark Homes offers standard building features in their P model including the following examples: R12 wall insulation, single glazed windows, 5.5 air changes per hour, R34 ceiling insulation, and 80% efficient furnace. Upgrading from a P to N1 model would include the following as an example: wall insulation from R12 to R20, single glazed to double glazed windows, 5.5 to 3.5 air changes per hour R34 to R40 ceiling insulation and 80% to 90% efficiency furnace. An upgrade from a N1 to N2 model standard upgrades on those mentioned above such as moving from a 90% efficient furnace to a 95% efficient furnace. Figure 7 illustrates the changes from a P to N1 model and a N1 to N2 model. Although not shown in Figure 7, N3 model is yet another higher level of standard with appropriate upgrades.

Landmark has modeled the GHG reductions from moving from a P Model through to N1 and N2 Models which is shown in Figure 5. This figure shows how many tonnes of GHG per year can be reduced through each type of house model. The Y-axis on the left of the chart shows how many tonnes of green house gas emissions per year can be reduced from the P-Model to the N3-Model. In terms of monetary cost upgrades, almost $ 18,600 CAD are required from the P-Model to the N3 (Y-axis on the right side of the chart), but through the factory, it will only cost a third ($6,300 CAD). The explanation for this is due to the higher productivity and cost savings generated through the prefabricated process. The savings can be passed onto the customer who can then upgrade to enhanced model at lower cost.

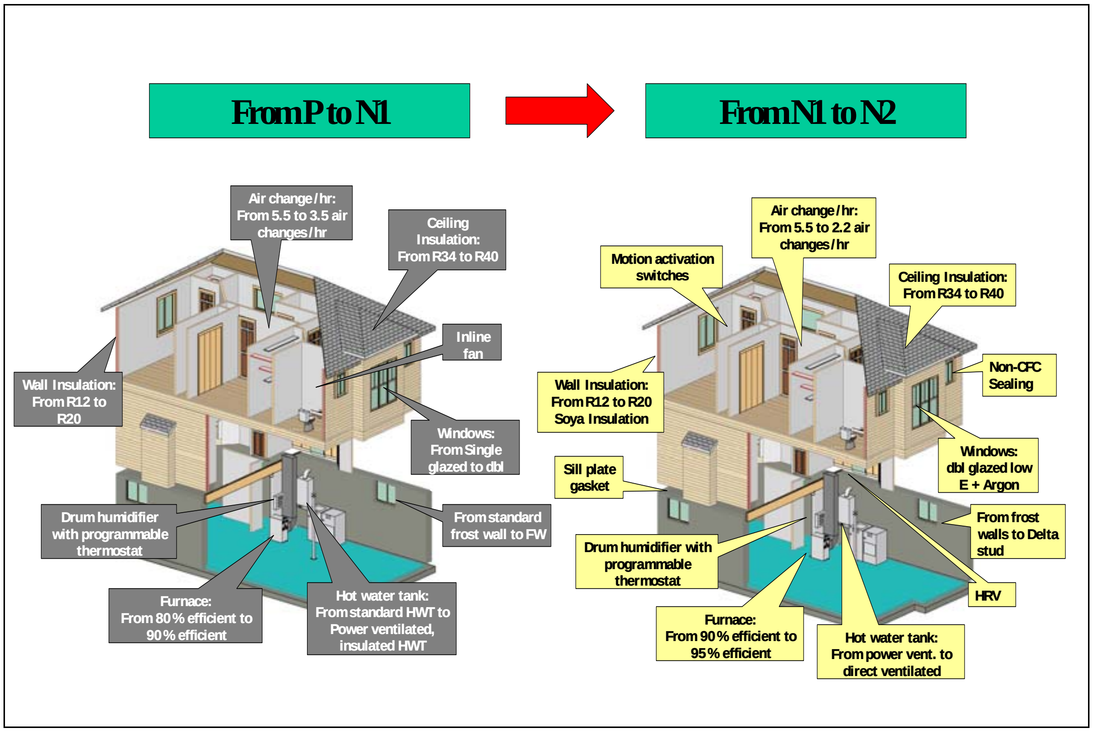


Figure 7, Building Upgrades.

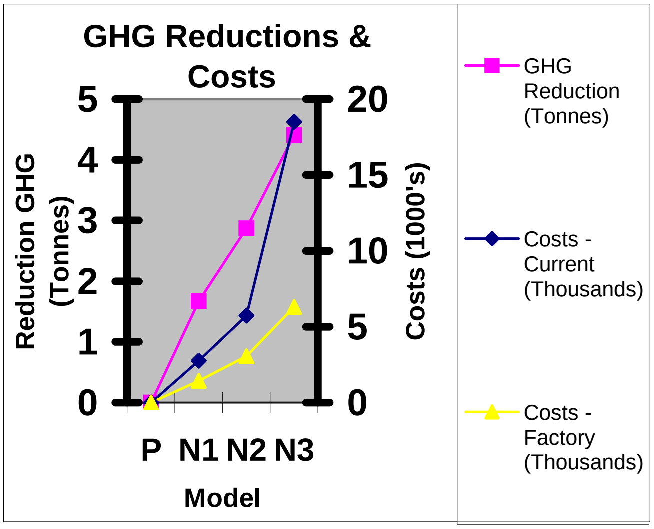


Figure 5, GHG Reductions and Costs.

Figure 6 highlights the energy saving per model type for natural gas and electricity use. The Y-Axis on the left shows how the N2 model can save up to 32% in natural gas and a 2% in electricity compared to the P model. The Energuide rating for the N2 model is 77 (Y-axis on the right). As clearly evident, the upgrade to a higher standard dramatically provides a significant energy saving. As mentioned, the various models in terms of building upgrades are shown in Figure 7. This figure shows the enhanced features from the P model to the N1 model, and from the N1 model to the N2 model. Landmark Homes can build a house under differing energy efficiency specifications ranging from P to N1 and N2 and N3 resulting in substantial emission reductions.

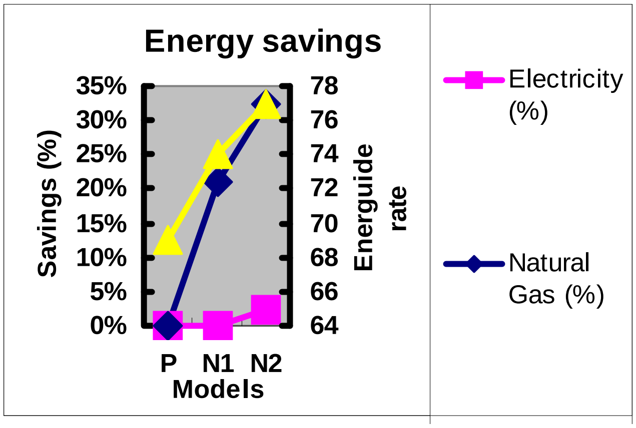


Figure 6, Energy Savings.

Contribution, Benefits and Significance to the homebuilding industry

The findings of this research have highlighted how the housing industry can contribute to a reduction of CO_2 emissions through the development and adoption of best practice concepts. The hypothesis being proposed in this research is that with a shift to an industrialized housing concept, such as a factory-built modular or panelized process, there will be a reduction of CO_2 emissions throughout the overall residential construction process by 55% (see Table 2).

This fact has been demonstrated through the development of building information model linked to a detailed description of manufacturing production processes. Different assemblies for construction have been modeled and stored in a repository system that allows end users to asses and control CO2 emissions for different dwelling models.

The contributions from this research to housing construction include the following: fostering of innovation in construction practices; lowering of CO_2 emissions through industrialization of processes; improvement of energy efficiency in house construction; reduction of emissions from winter construction heating; improvement of planning and decision making prior to construction; and positive impact on the environment due to reductions in CO_2 emissions and material disposal to landfills.

The panelized system represents a leap similar to that made by Henry Ford when he developed an industrialised mass production system for cars, making them affordable and vastly improving their quality. The panelized system will produce houses in panel components such as floors, roofs and interior and exterior walls complete with structural framing, exterior finishes, insulation, vapour barrier, wiring, plumbing and drywall. The controlled indoor factory setting will facilitate speed, quality control, safety, and waste reduction that is not achievable through conventional onsite construction. These panels will be packaged and transported by conventional means to a construction site in either rural or urban areas and assembled in 1 to 1.5 days by a specialised crew. The panelized system is distinct from modular home construction in that the architectural design possibilities highly flexible, not constrained by size, and the houses can be transported and installed anywhere (Landmark Group of Builders, 2008).

The panelized process consists of an automated production line that effectively eliminates most repetitive, strenuous work. Computer controlled machines facilitates the nailing, screwing, cutting and shaping of panel components while workers assemble and install the normal elements of a wall, roof or floor. Doors, hardware, wires, electrical boxes, HVAC ducting, plumbing, insulation, drywall and taping will also be installed by a combination of manual and automated processes. Once a package of panels is complete and ready for delivery, they are loaded onto trailers and transported to site. A dedicated erection crew will assemble the panels with the help of a crane, joining them together and connecting wires, pipes and installing tubs and showers. When the erection crew leaves the site, the house will be enclosed, insulated and ready for final finishing (Landmark Group of Builders, 2008).

Conclusion

This paper has provided the CO_2 emissions from the various stages of house construction ranging from stake-out through pre-occupancy inspection. As evidenced by identifying the stages which generates the CO_2 emissions, better practices and processes can be identified to mitigate the emissions. The adoption of a factory panelized system has shown to significantly reduce CO_2 emissions and provide additional benefits to the construction process including better quality, faster construction timelines, enhanced safety and lower costs. By shifting to a panelized construction process, lower production costs allow for better energy efficient equipment and products to be included in houses without increasing the house price to the buyer.

The implementation of BIM allows for rapid computations of CO_2 emissions from various house sizes, designs and materials. The use of BIM and the integration of an intelligent repository permit end-users to calculate the CO_2 emissions for any style of house with any style of construction process. Through the definition of CO_2 rates per unit of material delivered and installed, the quantification of GHG emissions per dwelling becomes much easier to address. BIM has facilitated the comparison process between two different construction techniques through activity definition and their GHG implications to the environment. The panelization manufacturing system has proven through BIM that is a more environmentally friendly technique than stick-frame on-site. A difference of 6.21 tonnes of CO_2 between the two construction methodologies was found as part of the results of this research. BIM provides to managers and decision makers with useful data that can be manipulated as the decisions are changed during the design stage.

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