

Research Article

# A framework for the evaluation of the decision between onsite and offsite construction using life cycle analysis (LCA) concepts and system dynamics modeling

Adekunle Mofolasayo \*

Civil and Environmental Engineering Department, University of Alberta, Edmonton, Canada

\*Correspondence: Adekunle Mofolasayo (madekun@ualberta.ca)

**Abstract:** The decision to choose between onsite and offsite construction is important in the effort toward sustainable construction. Offsite construction is often promoted as an environmentally friendly approach to construction operations. However, previous studies have shown that there is a lack of clarity on the environmental trade-offs between onsite and offsite construction. Factors that can affect the decision to build onsite or offsite include the availability of a local offsite manufacturing facility, the distance of the offsite factory to the final place of use, the proximity of the site to the local supply of material and labor, etc. This study provides a framework to apply the system dynamic modeling technique to evaluate how various factors can affect the environmental impact of the building construction phase (for onsite or offsite construction methods). The system dynamic model (using Vensim software) that was developed provides a platform that allows users to input variables such as the distance that is expected for transportation of labor, material, and equipment to both the onsite facility and the offsite construction location, factors associated with the use of equipment for construction, the distance needed for transportation of building panels or modules from the offsite facility to the final site, etc. Among other things, the model showed that an increase in the distance from the offsite yard to the final construction site increases the total impacts of transportation of completed modules. An increase in the number of trips for the transportation of material to the onsite construction location increases the total impact of onsite construction. In terms of the environmental impact of construction, none of the two methods of construction gives an absolute superiority over the other. The environmental performance of offsite and onsite depends on various associated factors. It is recommended that building practitioners review various factors that are peculiar to their projects to make an informed decision on the best construction methods.

## How to cite this paper:

Mofolasayo, A. (2023). A framework for the evaluation of the decision between onsite and offsite construction using life cycle analysis (LCA) concepts and system dynamics modeling. *World Journal of Civil Engineering and Architecture*, 2(1), 1–31. Retrieved from <https://www.scipublications.com/journal/index.php/wjcea/article/view/569>

**Keywords:** Onsite Construction; Offsite Construction; System Dynamics; Environmental Impact; Life Cycle Analysis (LCA); GHG/CO<sub>2</sub> Emissions; Modeling

Received: December 12, 2022

Accepted: January 26, 2023

Published: January 28, 2023



**Copyright:** © 2023 by the author. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

The construction industry touches the daily lives of everyone as the quality of life is strongly influenced by the built environment that surrounds people [1]. There is an enormous demand for the construction of infrastructures and buildings to accommodate the growing population of the world [2, 3]. Meanwhile, concerns about the environmental impacts of construction in various places give rise to the need to continuously evaluate various methods of construction to ensure that the best method of construction is applied in various scenarios. Construction-related energy issues are a worldwide concern because of the intensive construction that is involved in the urbanization process [4]. Various methods of building construction include traditional onsite construction and offsite

construction. 3D printing of buildings onsite is also an evolving method of construction. However, material printability, buildability, and open time are the most cited challenges for 3D printing in construction [5]. In communities where wood structures are the desirable material for construction, 3D printing will not be applicable. This will be classified under material printability and buildability issues. Open time in 3D printing is the period of time in which the cementitious material is dispensed continuously through the nozzle without stopping or clogging. After the open time limit, it is expected that the material is not extrudable [6]. On-site construction refers to site-built construction; it is also called conventional, traditional, and stick-built construction [3]. Onsite construction has been around for ages. The construction of shelters using local materials has also been in practice for ages. The prefabricated building system is one of the methods of construction that is an alternative to traditional on-site stick-built construction [7]. Some scholars [8] defined offsite construction (also known as offsite fabrication, offsite production, pre-assembly, and fabrication) as the manufacture and pre-assembly of components, elements, or modules before installation into their final location. Offsite construction is commonly used interchangeably with terms such as industrialized building systems, modern methods of construction, prefabrication, industrialized building, and industrial construction [9]. Panelized and modular wood building systems are part of an expanding domain that is called "off-site construction" [7]. Among all other offsite products, modular construction is the most complete in factory finish. It can be up to 95% completed offsite in some cases [10]. Offsite construction has also been around for many centuries. To reduce the weight of transportation, building blocks for Egyptian pyramids were prefabricated at the quarry [9]. 1 Kings also preserved a long-detailed description of the construction of a temple and palace in Jerusalem by King Solomon in the 10th century BCE" [11]. In order to erect the magnificent temple [12] built during King Solomon's era, every portion was so carefully fabricated, far away from the construction site, that the building could be completely erected in reverent silence. And the king commanded, and they brought great stones, costly stones, and hewed stones, to lay the foundation of the house" (1 Kings 5:17). In today's terms, the construction method for the temple built in Jerusalem during King Solomon's reign will be described as offsite prefabrication, and onsite assembly.

There have been various other descriptions of offsite construction. Britain has begun the export of prefabricated timber cottages as early as 1624 [13]. In 1908, in the United States, Sears Roebuck & Company began to sell kit homes through its popular catalog [14]. The global modular construction market was USD \$72.11 billion in 2020. This was projected to grow from USD 75.89 billion in 2021 to USD 114.78 billion in 2028 at a compound annual growth rate, CAGR of 6.1% for the 2021 - 2028 period [15]. Both onsite and offsite construction has advantages and disadvantages.

### **Pros and cons of onsite construction**

#### *Advantages of onsite construction*

- Onsite construction does not require the need for transportation logistics to move bulky modules from the factory to the site.
- In some instances, onsite construction may be more suitable where there is a need for some special customization or where there are space constraints for panel/module delivery.
- Those who enjoy working outdoors may be more in favor of onsite construction.

#### *Disadvantages of onsite construction*

- Multiple trips for material delivery may be needed, depending on the storage space that is available on site.
- Onsite construction may require the need for security for a longer period of time.

- Workers in onsite construction are more exposed to weather elements and hazardous conditions that may be associated with ‘trips and falls’ on wet or slippery surfaces.

### **Pros and cons of off-site construction**

#### *Advantages of offsite construction*

- Some scholars [16] reported that prefabrication can show advantages in terms of time and material efficiency.
- Typically, the construction waste for a prefabricated building is less than that of conventional construction largely because of efficient procurement processes, the ability for offsite facilities to conveniently reuse some waste material in the next project going down the line, and the convenience of recycling from one facility in contrast with the difficulties that are involved with separation of recyclables at on-site construction locations [17].

#### *Disadvantages of offsite construction*

- Transportation restrictions could limit module and panel size in addition, spans and configurations of designs are restricted to an extent
- There is a lack of transparency in overhead and profit margin. [10].
- Prefabrication allows for the disassembly of the entire building, enabling the reuse of module components, relocation of the whole building, or separation of materials that can be recycled or reused [16].

Given the above pros and cons for onsite and offsite construction, the decision to choose between these two construction methods may be challenging in some instances. From a sustainability point of view, this decision will be viewed through the three pillars of sustainability (Social, economic and environmental impacts). Sustainable construction also includes the evaluation of technical factors that are associated with the construction (in addition to the triple bottom-line evaluation for sustainability). Given the lack of clarity on the environmental trade-offs between onsite and offsite construction as mentioned in previous work [16], this study provides a framework on how to apply system dynamics’ principles and life cycle analysis, LCA in the choice between offsite and onsite construction.

## **2. Literature review**

### **2.1. Life cycle analysis in building construction**

Life cycle analysis (LCA) is a scientific technique that is used to quantify the environmental impact of various production or construction processes. The goal of LCA is to assess the environmental impact of a system or product [18]. Life cycle impact assessment (LCIA) uses quantifiable indicators to show the potential environmental impacts of products and materials [7]. Life cycle assessment (LCA) is recognized as a powerful method for the evaluation of environmental burdens. Four major stages in LCA include goal and scope definition, inventory analysis, life cycle impact assessment, and interpretation [19, 20, 25-27]. In the first stage of LCA, the goals and scope are defined. The level of detail and the system boundary is dependent on the subject and purpose of the study [20]. Lifecycle inventory involves the compilation of all the input and output flows that are associated with the goal and scope that is defined [21]. Life cycle inventory (LCI) quantifies all the raw materials, diesel, electricity, and other similar resources that are needed to make the final goods [22]. Life cycle impact assessment is meant to provide additional information for the assessment of the results of the life cycle impacts in order to better understand their environmental significance [20]. Life cycle impact assessment involves the use of the result of the inventory analysis to quantify the energy and environmental impacts of the building [21]. However, to be robust and accurate, LCA

must be performed with close-to-reality inputs [23]. Interpretation in LCA involves explaining and presenting the result in a way that can be easily understood. In the interpretation phase, the results of LCI, LCIA, or both are discussed and summarized to form a basis for conclusions, recommendations, and decision-making in line with the scope and defined goals [20]. This study attempts to expand on the LCA inputs in model development for the comparison of the environmental impacts of onsite and offsite construction. Development of a complete life cycle assessment can be time-consuming, difficult, and particularly discouraging to non-experts [24]. A user-friendly model such as a system dynamic model will help various stakeholders understand the rationale behind the decision to choose a specific construction method. LCA is applicable for decision-making in various fields. LCA is also a useful tool that can be used to evaluate the environmental impacts of both onsite and offsite construction methods in various municipalities. The stages in the LCA process for onsite and offsite construction have some slight variations. The variations are between stages A3 and A5 of the LCA system boundaries that are described in Figure 1 and Figure 2.

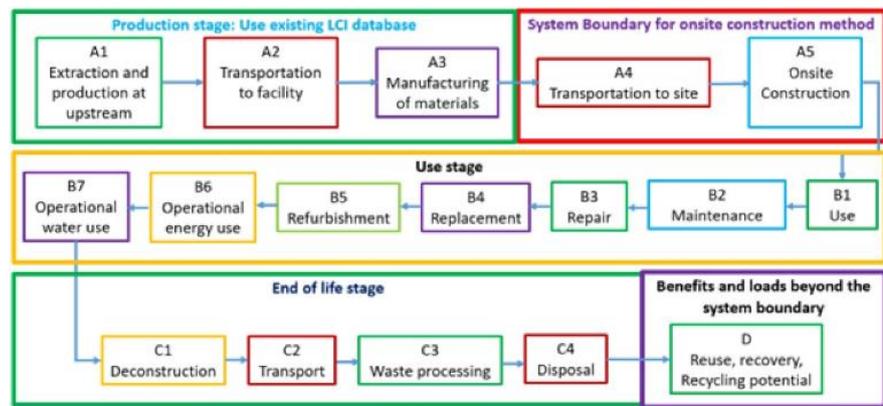


Figure 1. LCA system boundary for the onsite construction method [Adapted from 27, 28].

While the LCA system boundary for the construction phase for onsite construction includes only stages A4 and A5 (as shown in Figure 1), the LCA system boundary of the construction phase for offsite construction includes phases, A3.2 (transportation of materials to the offsite production facilities), A3.3 (offsite prefabrication of materials), A4 (transportation of completed modules or panels to the site), and A5 (Installation of panels or building modules onsite and completion of the onsite portion of the work).

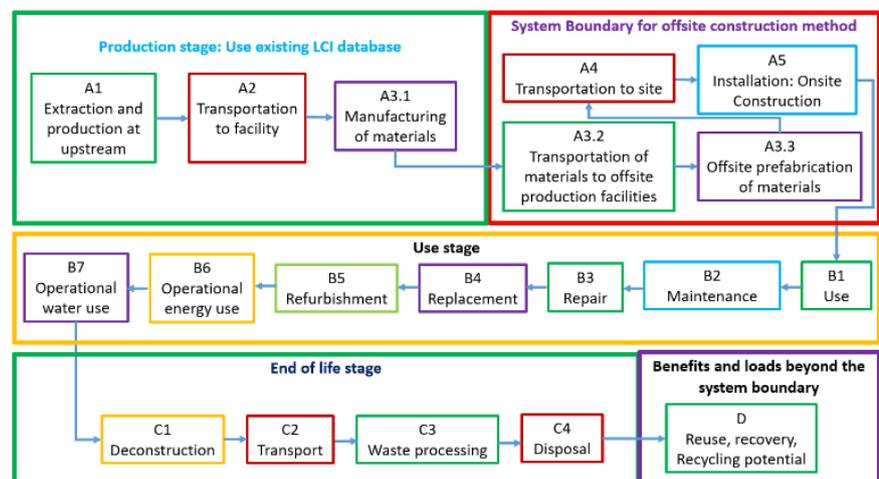


Figure 2. LCA system boundary for the offsite construction method (Adapted from 27, 28).

## *2.2. How LCA has been used in previous works*

The design of green buildings is a complex interrelationship between many factors. However, LCA can be helpful in prioritizing and evaluating design options [29]. Some scholars [30] conducted an LCA to determine the environmental impacts of the production and construction stages of an average prefabricated timber house (including the building elements: 1 m<sup>2</sup> roof element, 1 m<sup>2</sup> ceiling element, and 1m<sup>2</sup> inner/outer wall) that is produced in Germany. Among other things, the authors reported that from an environmental viewpoint, it is better to choose a house manufacturer that is closer to the building site [30]. Some researchers [29] used life cycle assessment modeling to determine top design priorities that can quantitatively inform sustainable design decision-making for a prefabricated modular building. From a scenario analysis of lifecycle environmental impacts of various energy, material design substitutions and a structural design change of a case-study LCA for a 5000 square ft building in San Francisco, California, a previous study [29] found that the top design priority is the minimization of operation energy impacts (even for a highly energy-efficient modular building). However, as an energy-efficient building approaches net zero energy, impacts from the manufacturing phase become dominant generating a new set of design priorities. Some scholars [31] investigated the life-cycle energy use of prefabricated components and its effect on the total embodied energy use for some real building projects. Among other things, the report indicated that apart from the reusability of precast construction, energy savings are also achieved from waste reduction and high-quality control yielding a savings of 4 to 14% of the total life cycle energy consumption. Some other scholars [32] used an integrated method for process-based hybrid life cycle assessment and scenario-based energy simulation methods to evaluate the life cycle energy performance of prefabricated buildings. The results showed that prefabrication has better energy reduction potential during the embodied phase. Due to improved thermal performance, prefabrication also has environmental gains during the building operations phase.

## *2.3. Arguments on the move toward industrialized buildings*

Challenges in the construction industry include productivity (declining productivity), scarcity of labor, different building standards, conflicts of interest from different stakeholders, carbon footprint, utilities (huge consumers of energy and water, especially in the case of hotels), huge waste generation, lack of understanding [33]. The concept of industrialization was introduced to address the issue of poor productivity rate that has been seen in the construction industry (in comparison with other industries) in the past century [34]. Due to its energy and environmental benefits, modular construction has attracted increased attention [21]. In the modern-day context, prefabrication has been shown to be an effective method of construction [35]. A previous work [36] investigates whether a greater adoption of modern methods of construction (i.e., offsite construction) can help to achieve the UK's 2025 four key targets (reduction in the duration of construction projects, level of greenhouse gas emissions, operational cost, and import/export trade gap). The authors used a questionnaire approach to solicit responses from 134 professionals that are working in the Architectural, engineering, and construction sectors in the UK. The majority of the respondents believe that the Modern method of construction (MMC) could help in the achievement of the construction 2025 targets. According to the extent of prefabrication, off-site construction (OSC) can be categorized into sub-assembly, non-volumetric pre-assembly, volumetric pre-assembly, and modular construction [37]. Some scholars [35] noted that although much progress has been made in the development of prefabricated steel, timber, and reinforced concrete elements/structures, the prefabrication of masonry wall systems has not received a lot of attention in the past. When compared to traditional masonry construction, prefabricated masonry systems can have nearly 15% and 30% savings respectively as regards CO<sub>2</sub>

emissions and energy savings [35]. The study noted that some of the benefits of prefabrication include consistent quality at a competitive cost, speedy construction, and high-volume output. The authors cited some other works that indicated that prefabrication helps achieve environmental benefits like the reduction of construction wastes and CO<sub>2</sub> emissions. Prefabrication also helps to achieve less constraint at the construction site by minimizing onsite waste, dust, and noise.

Some researchers [38] noted that one step towards a more sustainable construction industry during the production stage is the production of precast construction components in manufacturing facilities but most precast facilities are not yet able to track value losses like wastes from time and scrap. When it comes to material use and environmental impacts prefabrication or offsite construction is seen as more sustainable than traditional methods [39]. Another study [40] also reported that as a game-changing technology with lots of economic, social, and environmental benefits, prefabricated technology has attracted attention and has seen increasing adoption in the construction industry. Although it has been reported that as an alternative construction method, offsite construction (OSC) has a variety of benefits, there is a lack of critical review of the performance of the offsite built facilities in terms of energy consumption and carbon emissions [37]. Some scholars [41] analyzed the rationale for using prefabricated straw bale construction (PSBC). The result indicated that for the regions that were evaluated, when compared with conventional construction, PSBC helped to reduce both cooling and heating energy uses and heating intensities in the severe cold and cold regions. When compared to conventional construction, the advantages of modular construction include greater certainty on building costs, times, and quality, less waste, and accelerated building schedules [42]. Prefabrication involves the production of parts in an offsite factory or workshop before onsite installation [43]. New technologies to suit modern world prefabricated construction have been developed. New technologies are not only helping owners and contractors get their buildings more economically and faster, but they also help in the reduction of construction waste and they produce high-efficiency energy buildings that bring long-term benefits to the project [43]. A previous study [44] reported that by shifting some operations from onsite to offsite, the environmental impacts show an average decrease ranging from 5 to 10. It is important to note that the level of prefabrication alone is not the only factor that affects the environmental impacts of construction. Other factors need to be considered too.

Citing some previous works some researchers [45] mentioned that the manufacturing approach to building construction can harness economics of scale, improve workplace safety, help achieve waste reduction, help achieve a reduced construction time, minimize onsite operation and duration, help achieve higher product longevity, and facilitate tighter management control. The authors also mentioned that manufactured buildings are cheaper than conventional buildings. Substantial benefits of prefabrication include a reduction in construction waste, material waste, labor demands, delivery time, and energy use, and an improvement in the constructability of projects and cost certainty. Improvement of the performance of prefabrication is necessary given the increasing demand for sustainable development in the architecture, engineering, and construction industries [46]. During the pandemic, modular construction became a preferred option for the construction of medical and quarantine facilities [47]. Modular designs facilitate future design and structure adaptations [48]. A scholar [49] investigated the effect of prefabricated materials and equipment on the cost efficiency of a building. The author reported that in addition to better quality, the use of prefabricated construction material brings lots of financial and time advantages over conventional construction. Steel prefab is specifically noted to be advantageous with respect to cost, recovery, time, and operation. In terms of the cost efficiency of buildings in Ethiopia, the study shows why the use of prefabricated construction is very advantageous over conventional construction. A list of strengths, weaknesses, opportunities, and threats (SWOT) analysis

of prefabricated construction in Ethiopia was presented. It was noted that without question, there are economic benefits that are associated with prefab construction. However, developers should carefully study the opportunities and challenges before adoption.

#### ***2.4. Reduction of emissions in the construction industry***

Some scholars [50] investigated current industry practices in managing emissions in construction projects and found that despite growing awareness and commitment to the development of low-carbon growth, emission management, and monitoring are still underdeveloped. It was reported that the primary constraint to the adaptation of emission-reduction strategies in the industry exists at the individual, organizational and institutional levels. The authors proposed government support, capacity building, and emission monitoring technologies and techniques that are important for minimizing emissions. The authors mentioned key barriers to the implementation of emissions management. Among others, this includes limited resources to invest in the implementation of emission mitigation strategies, lack of information on the availability of green technologies, alternative construction products, and materials in the market, lack of tools and mechanisms to monitor the implementation of emissions management on construction projects, etc. If emissions in the construction processes will be reduced, it is important that the hotspots for emissions are identified during the planning phase, and that applicable mitigation strategies are implemented during the construction phase. This study attempts to bridge some of the gaps in ensuring that construction practitioners have reasonable tools and techniques for the evaluation and applicable planning for emissions management for construction operations.

The system boundary for the present study is the construction phase of the LCA for onsite and offsite construction. Previous construction LCA research mostly focused on the comparison of various structural systems with little emphasis on the contribution of construction methods on the impacts [17]. Meanwhile, the environmental impacts are not dependent only on the structural systems. The environmental impacts are also dependent on various individual variables that are involved in the construction methods. Variations in these factors/variables can affect the overall impact of the construction method. This study provides a system dynamic framework to evaluate how variations in each individual factor affect the overall environmental impacts of the selected construction method. This model can provide a visual illustration of how a change in different variables in the system can result in a change in the overall environmental impacts. Using simulation methods, the model can allow for a visual illustration of areas for potential improvement. The System dynamic model will also show the construction method with minimal environmental impact. This is dependent on inputs that are specified by the user.

#### ***2.5. System dynamics modeling***

"A model is a substitute for a real system. Models are used when it is easier to work with a substitute than with the actual system" [51]. Dynamic models help to see the interaction between multiple variables in a system. Dynamic simulation methods such as system dynamics can be applied in planning and addressing issues that pose significant challenges to resource planners and managers. These issues include new agenda items of sustainability, multiple bottom lines, stakeholder participation, and efficient management of scarce and contested water resources [52].

##### **2.5.1. Why should we evaluate the environmental impacts of onsite and offsite construction through a system dynamics approach?**

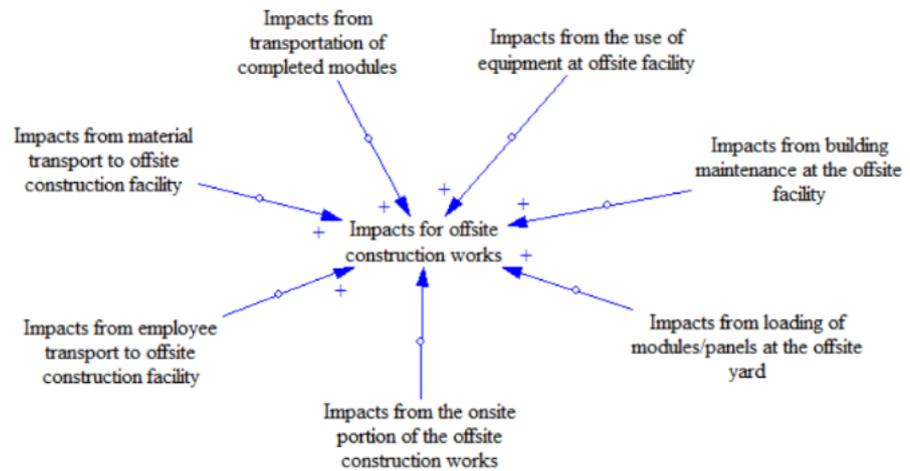
System dynamics, systems thinking and soft operations research all aim at understanding and improvement of systems [53]. Models should become part of a more persuasive communication process that interacts with people's mental modes, unifies

knowledge, and create new insights [54]. Various factors could result in communication challenges with stakeholders: Understanding the way a resource system works sometimes requires some technical knowledge that may not be common to all stakeholders. Stakeholders in a resource management system may not have the same mental models about how the system works leading to difficulty in reaching an acceptable solution. System dynamics modeling is one approach that can help managers with communication challenges with stakeholders. A system dynamics model can be used to explain the dynamics of the resource system. It can also be used to illustrate the effects of strategies that are suggested by forum participants or proposed by managers. An interactive system dynamic model can help stimulate stakeholder interest in the structure of the system, create more engagement from participants and increase stakeholder understanding of the basis for the decisions that are made by management [55]. Indirectly, as regards the decision between offsite and onsite construction, considering every constraint, a good system dynamic model can be used to show transparency in decision-making.

Dynamic modeling starts with an advantage over purely statistical or empirical modeling schema. It does not rely on historical or empirical modeling schema to show relationships between input and output in industrial and biological processes [56]. This study has developed an interactive model for the evaluation of the impacts of both offsite and onsite construction works. Given the nature of system dynamics modeling, real-life data is not required to show the relationship between variables, as various relationships can be seen through the use of a wide range of numbers. However, for a direct comparison of two scenarios, to obtain results that are within a reasonable degree of accuracy, there will be a need to have the expected input parameters (that is within a reasonable degree of accuracy) to feed the model. The relationships reported in this report were based on variations of a wide range of numbers for some of the variables in the model. Further study is recommended using 'real data' that shows the detail of works according to the work breakdown structure for both onsite and offsite construction. This data can be an aggregate of information that is collected from previous projects and reserved for a forecast for future works. The data for modeling can also be based on expected variables on the project, based on what exists at the time of evaluation. "In system dynamics, description leads to equation of a model, simulation to understand the dynamic behavior, evaluation of alternative policies, education and choice of a better policy, and implementation" [53]. Some researchers [3] also reported that regardless of the different advantages and disadvantages of onsite and offsite construction methods, the environmental trade-offs between these construction methods are still not clear. This study develops an interactive model that can help bring clarity to the environmental trade-offs between the two construction methods.

### 2.5.2. Causal loop diagram

Causal loop diagrams in system dynamics show how different variables affect one another. A "+" on the arrow that connects two variables shows that the variable at the bottom of the arrow causes a change in the variable at the head of the arrow in the same direction while a "-" on the arrow that connects two variables shows a change in the opposite direction [55]. Sometimes interrelationships could be seen among the variables and the illustration may reflect a (circular) loop. At other times, different variables may have some independent contribution to the overall environmental impact of a process or operation. Sometimes, this may not be a circular loop. Variables in Figure 3 can be further broken down with the sub-variables in Table 2. A similar diagram to Figure 3 can also be drawn for traditional onsite construction using the sub-variables in Table 2.



**Figure 3.** Variables that contribute to the environmental impacts of offsite construction.

A previous study [57] noted that for new building construction, (based on the scope definition for their study), the total energy consumption can be divided into four parts (Energy consumption during raw material extraction and transportation, energy consumption during manufacturing of materials, energy consumption during the transportation of building materials, and energy consumption during the onsite construction). It is crucial to have a holistic investigation of the energy requirement involving the direct energy input from both the onsite production process and the indirect energy consumption from the upstream process [4]. The present study expanded on these factors to include energy use during worker transport to onsite and offsite construction locations, energy used during equipment transport to the site, etc. A breakdown of the variables included in the model is presented in Table 2.

### ***2.6. Contentions on the method of construction with less environmental impact during the construction phase and how the system dynamics modeling approach to LCA can help bring clarity to the conflict of opinions***

In terms of the environmental impacts of construction works, various contentions exist about whether onsite construction is better than offsite construction and vice versa. Some scholars [39] noted that when it comes to the use of energy resources and the consequent environmental pollution, the literature mentioned that prefabrication can help achieve savings in both energy and CO<sub>2</sub> emissions. However, the authors found that the efficient use of energy resources in a construction project is more dependent on the design approach, the amount and type of materials that are used, and whether the construction is onsite or offsite. In current research, there is no clear conclusion on whether prefabricated buildings reduce the environmental impacts of construction more than cast-in-place buildings [58]. Prefabrication has been reported as more environmentally friendly when compared with traditional cast-in-situ because of its advantages in reducing environmental impact [59]. Prefabrication can be more advantageous in terms of time and material efficiency, but the overall environmental and cost trade-offs between conventional and prefabricated construction are not clear [16]. Another study [60] mentioned that due to the need for the transportation of heavier components, prefabrication was found to have more environmental impacts than conventional buildings. A previous work [61] reported that as the rate of prefabrication increases, there is a shift in carbon emission during the construction cycle toward manufacturing and transportation. Some researchers [3] evaluated the environmental impacts of three buildings (two prefabricated buildings and one conventional building) using eight

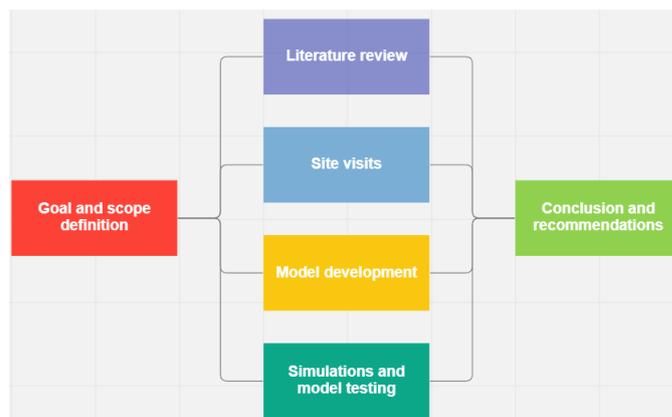
environmental impact indicators from Athena LCA software. The indicators considered include global warming potential, acidification potential, eutrophication potential, human health effects, ozone depletion potential, fossil fuel consumption, eco-toxicity effect, and smog potential. The results showed that the environmental impact of the conventional building is better than one of the two modular buildings while the second modular building has a better environmental impact than the conventional construction. The report noted that modular construction is not always the most environmentally friendly choice. This lack of consensus on which of the two methods of construction is better shows the need for a more holistic review of the construction methods from a system's perspective.

### 3. Materials and Methods

The study methods include a literature review that allows for the identification of various factors that contribute to the environmental impacts of onsite and offsite construction. The goals and scope of the project are:

- (1) Provide a framework for the application of system dynamics and LCA in the evaluation of how different variables contribute to the environmental impacts of onsite and offsite construction,
- (2) Provide a framework to choose a method with lesser environmental impact based on user-specified inputs from local conditions.

The project also includes site visits and discussions with some workers in the construction industry to have more knowledge about the work process and more knowledge about the life cycle inventory of some of the work processes. Model development involves the development of mathematical models and the development of the system dynamic model for the evaluation of the environmental impact of onsite and offsite building construction using Vensim software. Simulation and model testing helps to see how the model can work and how different variables can have an effect on the environmental impact of the construction phase of the two construction methods.



**Figure 4.** Project methodology.

Various efforts have been made to improve the environmental impacts of construction. Considering construction activities such as transportation and installation of building materials, temporary works, construction machinery, waste management, person-transport, and energy use, some scholars [62] aimed at presenting the main challenges and opportunities from the construction phase of two near-zero emission construction sites in Norway. Table 1 shows different variables that affect the LCA of a building that was presented in some of the previous works.

**Table 1.** Variables relating to the LCA of a building

<b>Reference Number</b>	<b>Year</b>	<b>Notes on variables relating to LCA of building</b>
[3]	2019	<p>The data requirement for a cradle-to-gate analysis of conventional versus traditional onsite construction includes raw materials, workforce and material transportation, and energy sources.</p> <p>The activities in the material production phase are categorized into:</p> <ol style="list-style-type: none"> <li>1. Material extraction and process A1,</li> <li>2. Material transportation.</li> </ol> <p>The construction phase is categorized into</p> <ol style="list-style-type: none"> <li>1. Construction and installation, A3, and</li> <li>2. Product and worker transportation, A4.</li> </ol> <p>For stages A1, and A2 of LCA for both conventional and Modular construction, the data variable includes:</p> <p>Materials and products (types and quantities).</p> <p>In phase A3 for conventional construction, data variables include:</p> <ol style="list-style-type: none"> <li>1. Onsite energy (heating, machinery, and cooling).</li> </ol> <p>In phase A4 for conventional onsite construction, the data variable includes</p> <ol style="list-style-type: none"> <li>1. Worker transport (commute modes, number, workdays),</li> <li>2. Material/product transport (transport modes, supplier-site distances).</li> </ol> <p>For modular construction stage A3, the data variables include</p> <ol style="list-style-type: none"> <li>1. Offsite energy (machinery in the factory, cooling, and heating),</li> <li>2. On-site energy (machinery for site work, cooling, and heating).</li> </ol> <p>For phase A4 of the LCA for modular construction, the data variables include:</p> <ol style="list-style-type: none"> <li>1. Worker transport to the factory and worker transport to the site (number, workdays, commute modes)</li> <li>2. Material/product transport to the factory (transport modes, supplier-factory distance), and</li> <li>3. Module transport (transportation mode, factory-site distance.</li> </ol>
[18]	2020	<p>The carbon footprint of precast concrete piles was divided into three sources</p> <ol style="list-style-type: none"> <li>1. Material transportation</li> <li>2. Construction equipment, and</li> <li>3. Office area</li> </ol>

[23]	2020	<p>For embodied impacts, the variables include:</p> <ol style="list-style-type: none"> <li>1. Transport of materials,</li> <li>2. Materials used for the construction, etc.,</li> </ol> <p>For the operational impacts, the variables for energy demand include those for:</p> <ol style="list-style-type: none"> <li>1. Heating,</li> <li>2. Ventilation,</li> <li>3. Lighting, etc.,</li> </ol>
[57]	2019	<p>The total energy consumption can be divided into four parts</p> <ol style="list-style-type: none"> <li>1. Energy consumption during raw material extraction and transportation</li> <li>2. Energy consumption during the manufacturing of materials,</li> <li>3. Energy consumption during the transportation of building materials, and</li> <li>4. Energy consumption during the onsite construction</li> </ol>
[63]	2012	<p>The data submitted for the project include:</p> <ol style="list-style-type: none"> <li>1. Worker commuting information,</li> <li>2. Utility bills,</li> <li>3. Building materials,</li> <li>4. Waste procedures,</li> <li>5. Construction schedules,</li> <li>6. Employee schedule and other relevant information</li> </ol>

The environmental impacts that are evaluated in this study are the emissions. Although the model presents an illustration using impact factors for greenhouse gas GHG/CO<sub>2</sub> emissions, the model has the capability to be easily modified to evaluate other environmental impacts such as acidification potential, ozone depletion potential, eutrophication potential, etc. The impact per unit rate that was used for GHG emissions from the electricity grid in the model is based on the GHG emission for the electricity grid for a jurisdiction for the year 2020 [87]. The CO<sub>2</sub> emission (per liter of diesel and gasoline) used in the model is reported in previous work [68]. To convert to CO<sub>2</sub>e, this value was divided by 0.994 with an assumption that the ratio of carbon emissions to the total greenhouse gas emissions (including carbon dioxide, nitrous oxide, and methane, all expressed as carbon dioxide equivalence) is 0.994. A previous work [69] indicated that in 2019, the ratio of carbon dioxide emissions to the total greenhouse gas emissions (including methane, carbon dioxide, and nitrous oxide, all expressed as carbon dioxide equivalents) for passenger vehicles was 0.994. Further study is recommended on the amount of carbon dioxide equivalence that is emitted from various vehicles that are manufactured in different years. This may be included in the information for model expansion in the future.

**Table 2.** Model Parameters (Variables) - Offsite and Onsite Construction

Model parameters (Main variables)	Sub-Variables
Impacts from the transportation of completed modules	<ol style="list-style-type: none"> <li>1. Energy use rate of the vehicle for transport of module and equipment</li> <li>2. Impact per unit rate for the energy use for the transportation of completed modules</li> </ol>

	<ol style="list-style-type: none"> <li>3. Number of trips from the offsite yard to the final site</li> <li>4. Round trip distance from offsite yard to site.</li> </ol>
Impacts from material transport	<ol style="list-style-type: none"> <li>1. Number of trips during material transport</li> <li>2. Roundtrip distance for material delivery to the offsite construction yard</li> <li>3. Energy use rate of the vehicle for material transport</li> <li>4. Impact per unit rate for the energy used in the transportation of materials.</li> </ol>
Impacts from employee transport	<ol style="list-style-type: none"> <li>1. Number of employees</li> <li>2. Energy use rate by the vehicle that is used for employee transport</li> <li>3. Impact per unit rate for energy that is used by employee's vehicle</li> <li>4. Average round trip distance for employees to the offsite construction facility</li> <li>5. Number of trips by employees to the offsite facility</li> </ol>
Impacts of the use of equipment	<ol style="list-style-type: none"> <li>1. Duration of use for the equipment at the offsite construction facility</li> <li>2. Energy use rate for the equipment</li> <li>3. Impact per unit rate for the energy that is used by the equipment</li> </ol>
Impacts of building maintenance	<ol style="list-style-type: none"> <li>1. Area of the building</li> <li>2. Energy use per square area of the building</li> </ol>
Impacts from the loading of modules	<ol style="list-style-type: none"> <li>1. Number of loads</li> <li>2. Energy used for each load of building modules or panels</li> <li>3. Impact per unit rate for the energy that is used in loading operation.</li> </ol>

---

**Impacts for the onsite portion of work for the offsite construction project (includes foundation construction and miscellaneous onsite works)**

---

	<ol style="list-style-type: none"> <li>1. Round trip distance for transportation of all equipment that are used during the foundation work</li> <li>2. Number of trips for transportation of equipment for the foundation work on site</li> </ol>
Impacts of the construction of the foundation for the building	<ol style="list-style-type: none"> <li>3. Energy use rate for the equipment for foundation works.</li> <li>4. Impact per unit rate for the energy for the equipment that are used for the foundation work.</li> <li>5. Energy use rate for the material transport for foundation works</li> <li>6. Round trip distance for material transport for foundation works</li> <li>7. Number of trips for material transport for foundation works</li> <li>8. Impact per unit rate for energy used for material transport for foundation works</li> </ol>

9. Energy use rate for employee transport for foundation works
10. Roundtrip distance for employee transport for foundation works.
11. Number of trips for transportation of employees during foundation works
12. Energy use rate for employee transport for foundation works.
13. Impact per unit rate for employee transport for foundation works.

Impacts for assembly of prefabricated modules/panels onsite

1. Duration of module assembly
2. Energy use rate during the assembly process for modules onsite
3. Impact per unit rate for the energy that is used for module assembly.

1. Roundtrip distances for material transport for all miscellaneous works
2. Number of trips for material transport for miscellaneous works
3. Energy use rate for material transport for miscellaneous works
4. Impact per unit rate for material transport for miscellaneous works.
5. Energy use rate for transportation of equipment for miscellaneous works

Impacts from miscellaneous onsite portion of work for the offsite construction project.

6. Round trip distance for equipment transport for miscellaneous works
7. Number of trips for equipment transport for miscellaneous construction works
8. Impact per unit rate for energy that is used for material transport.
9. Round trip distance for employee transport for miscellaneous construction works
10. Number of trips for employee transport for miscellaneous construction works
11. Impact per unit rate for the energy that is used for employee transport for miscellaneous construction works.
12. Energy use rate for the vehicle that is used for employee transport for miscellaneous construction activities

Impacts from the transportation of equipment for module installation to the site

1. Round trip distance from the offsite construction yard to the site (while transporting equipment for panel/module installation)
2. Number of trips for transportation of equipment for installation of panels/modules on site.
3. Energy use rate for the vehicle to transport the equipment for module/panel installation
4. Impact per unit rate for the energy that is used by the vehicle transporting the module/panel installation equipment to the final site location

---

**Onsite construction (Variables for the foundation works, superstructure works, and miscellaneous construction activities)**


---

Total impacts for onsite construction	<ol style="list-style-type: none"> <li>1. Round trip distance for employee transport for the foundation, superstructure, and miscellaneous finishes onsite.</li> <li>2. Energy use rate for the vehicle for employee transportation for foundation, superstructure, and miscellaneous construction works</li> <li>3. Number of trips for employee transport for the foundation, superstructure, and miscellaneous finishes</li> <li>4. Impact per unit rate for energy that is used for employee transport for the foundation, superstructure, and miscellaneous construction works.</li> <li>5. Round trip distance for equipment transport for the foundation, superstructure, and miscellaneous finishes on-site.</li> <li>6. Energy use rate for the vehicle for the transportation of equipment for foundation, superstructure, and miscellaneous construction works</li> <li>7. Number of trips for equipment transport for the foundation, superstructure, and miscellaneous finishes</li> <li>8. Impact per unit rate for energy that is used for equipment transport for the foundation, superstructure, and miscellaneous construction works.</li> <li>9. Round trip distance for material transport for the foundation, superstructure, and miscellaneous finishes on the site.</li> <li>10. Energy use rate for the vehicle for the transportation of materials for the foundation, superstructure, and miscellaneous construction works</li> <li>11. Number of trips for material transport for the foundation, superstructure, and miscellaneous finishes</li> <li>12. Impact per unit rate for energy that is used for transportation of material for the foundation, superstructure, and miscellaneous construction works.</li> </ol>
---------------------------------------	---

---

The sub-variables for onsite construction in [Table 2](#) can be further broken down into smaller units. Ideally, for both onsite and offsite construction, the impact of the construction methods can be evaluated in detail using each item on the work breakdown structure, (WBS).

## 4. Results

### 4.1. Model equations

#### 4.1.1. Model equations for offsite construction

It is important to assess the emissions and energy use of the building sector in order to achieve energy security and carbon emission reduction [57]. The total impact for offsite construction is the sum of the impacts from material transport, employee transport (including any occasional inspector transport to the fabrication yard for code compliance), equipment transport, use of equipment, building operation, module transport, and onsite work for foundation construction, the final installation of modules, fencing, landscaping, and other miscellaneous activities.

$$TI_{OSC} = I_{OSC} + I_{ONS\_OSC} \quad (1)$$

Where:

$TI_{OSC}$  is the total impact of offsite construction.

$I_{ONS\_OSC}$  is the impact of the onsite portion of the offsite construction. This includes the construction of the foundation onsite  $I_{FDN}$ , the assembly of the modules or panels onsite  $I_{MASB}$  i.e., panel/module installation on site, and the other associated onsite works like landscaping, fencing, connection to utilities, etc.  $I_{MISC}$

$$I_{ONS\_OSC} = I_{FDN} + I_{MASB} + I_{MISC} \quad (2)$$

$I_{OSC}$  is the impact of the offsite portion of the construction. This includes the impact of the offsite facility's building maintenance ( $I_{BM}$ ), round-trip material transportation to the offsite construction factory ( $I_{MT\_OSC}$ ), all employee transportation (round-trips) to the offsite facility ( $I_{EPT\_OSC}$ ), the use of equipment in the offsite facility ( $I_{EQU\_OSC}$ ), loading of completed modules at the offsite factory ( $I_{LD}$ ), transportation of equipment for module/panel installation to the site,  $I_{EQT}$  and transportation of completed modules to the site ( $I_{TCM}$ ).

$$I_{OSC} = I_{BM} + I_{MT\_OSC} + I_{EPT\_OSC} + I_{LD} + I_{TCM} + I_{EQT} + I_{EQU\_OSC} \quad (3)$$

The energy for the offsite building maintenance,  $E_{BM}$  and equipment use can be obtained from the monthly energy bill. An alternative will be to record the individual energy use rate of the equipment.  $I_{BM}$  includes the energy used for the provision of lightning for the offsite facility, the energy used for heating and cooling of the facility, and the energy for general building maintenance. It can also be estimated by the energy required for heating, cooling, lighting, and the energy for general building maintenance per area of the building multiplied by the total area of the building.

$$E_{BM} = E_{HC\_PA} \times A_B \quad (4a)$$

Where

$E_{HC\_PA}$  is the energy required for heating, cooling, lighting, and the energy for general building maintenance per square area of the offsite construction facility.

$A_B$  is the building area for the offsite construction facility.

$$I_{BM} = E_{HC\_PA} \times A_B \times I_{u_{BM}} \quad (4b)$$

$I_{u_{BM}}$  is the impact per unit for the energy type that is used for the maintenance of the building.

#### 4.1.2. The impact of the round-trip material transportation to the offsite construction factory

The impact of the round-trip material transportation to the offsite construction factory ( $I_{MT\_OSC}$ ) is a function of the distance between the offsite factory and the material supply yard, the energy use rate by the vehicle for material transport, the number of trips for material transport, and the impact per unit rate for the transportation of materials to the offsite fabrication yard,  $I_{u_{MT}}$ . Ideally, this should also include the impact from the material manufacturing production yard to the material supplier.

$$I_{MT\_OSC} = \sum_{i=1}^n D_{RMP\_OSC} \times E_{urv_{MT}} \times N_t \times I_{u_{MT}} \quad (5)$$

Where

$D_{RMP\_OSC}$  is the round-trip distance from the material production yard to the offsite construction facility.

$E_{urv_{MT}}$  is the energy use rate for the vehicle used for material transport

$N_t$  is the number of trips for materials for the building

$I_{u_{MT}}$  is the impact per unit for the energy type that is used for the transportation of the materials.

#### 4.1.3. The impacts from employee transportation (round-trips) to the offsite facility

The impacts from employee transportation (round-trips) to the offsite facility ( $I_{EPT}$ ), is a function of the distance between the offsite factory and the residences for the employees, the energy use rate of the vehicle that is used for employee transport, the number of trips made by employees during the building construction, and the impact per unit rate for the energy that is associated with each employee transport,  $I_{u_{EPT}}$ . This impact will be high when employees have to travel a long distance to reach the offsite facility.

$$I_{EPT\_OSC} = \sum_{i=1}^n D_{EPT\_OSC} \times E_{urv_{EPT}} \times N_t \times I_{u_{EPT}} \quad (6)$$

Where

$D_{EPT\_OSC}$  is the average round-trip distance from employees' residences to the offsite construction facility.

$E_{urv_{EPT}}$  is the energy use rate for the vehicle used by the employees

$N_t$  is the number of trips for employee transport for the duration of the building construction.

$I_{u_{EPT}}$  is the impact per unit for the energy type that is used for employee transportation to the offsite facility.

$n$  is the number of employees involved in the building construction work.

Some scholars [39] mentioned that when compared with conventional methods, offsite manufacturing has extra transportation and this could affect emissions. The authors also mentioned that more investigation is needed to see how significant this may be. However, contrary to this, it is important to note that the transportation impact for both offsite and onsite construction is dependent on how the movement of material, equipment, and manpower is planned and executed. Hence, proper planning and good execution are needed. Further research is needed for optimal transportation requirements to achieve minimum impact on worker, equipment, and material transport for both offsite and onsite construction.

#### 4.1.4. The impacts of loading the completed modules

The impact of loading the completed modules ( $I_{LD}$ ) at the offsite yard is a function of the energy use per load  $E_{UPL}$ , the number of loads  $N_L$  for the building, and the impact per unit for the energy type that is used for the loading of the materials,  $I_{u_{LD}}$ .

$$I_{LD} = \sum_{i=1}^n E_{UPL} \times N_L \times I_{u_{LD}} \quad (7)$$

#### 4.1.5. The impact from the transportation of completed modules to the site

The impact from the transportation of completed modules to the site ( $I_{TCM}$ ) is a function of the distance of the site to the offsite construction factory, the number of trips to the site, and the impact per unit for the energy type that is used for the transportation of the finished modules or panels to the site,  $I_{u_{TCM}}$ .

$$I_{TCM} = \sum_{i=1}^n D_{OSC_{ST}} \times E_{urv_{TCM}} \times N_t \times I_{u_{TCM}} \quad (8)$$

Where

$D_{OSC_{ST}}$  is the round-trip distance from the offsite construction facility to the site.

$E_{urv_{TCM}}$  is the energy use rate for the vehicle used to transport the modules to the site

$N_t$  is the number of trips for module transport from the offsite location to the site.

Note that during the evaluation of impacts for module transport, the associated impact with equipment transport (for installation of the modules on site) will also be considered as below.

#### 4.1.6. The impacts from the transportation of equipment to install modules on the site

The impacts from the transportation of equipment to install modules on the site ( $I_{EQT\_OSC}$ ) is a function of the distance of the site to the offsite construction factory, the number of trips to the site, and the impact per unit for the energy type that is used for the transportation of the equipment for the installation of finished modules or panels to the site,  $I_{UEQT}$ .

$$I_{EQT\_OSC} = \sum_{t=1}^n D_{OSCST} \times E_{urvEQT} \times N_t \times I_{UEQT} \quad (9)$$

Where

$D_{OSCST}$  is the round-trip distance from the offsite construction facility to the site.

$E_{urvEQT}$  is the energy use rate for the vehicle used to transport the equipment for module- installation to the site

$N_t$  is the number of trips for the equipment for module installation from the offsite location to the site.

##### 4.1.6.1. Case study: Illustrative example for module transport

A certain offsite construction facility supplies prefabricated buildings to communities that are about 100 to 200 Km away (on average) from the offsite manufacturing facility. A previous report indicated that the average fuel efficiency of trucks is 39.5 liters / 100km (in 1999). This excludes fleets operating B trains that have a substantially lower average fuel efficiency [64]. There are reports about improved fuel efficiency in the trucking industry [65, 66]. The example given here assumes the average roundtrip fuel efficiency for module transport is 39.5 liters/ 100 Km = 0.395 liters /km (for illustrative purposes only).

As described by previous work [67], for simplicity, the fuel consumption for the trip can be represented as

$$F_c = R_u \times d_t \quad (10)$$

Where

$R_u$  is the rate of fuel use, and  $d_t$  is the distance travelled.

If the roundtrip distance for a delivery is 200 km, and assuming historical records indicate that the average fuel use is 0.395 liters/km for such journey. Assume a diesel-powered truck is used for the module delivery, and no additional equipment was transported for the module delivery.

The fuel usage for this aspect of the project can be estimated as:

$$0.395 \frac{\text{liters}}{\text{km}} \times 200\text{km} = 79 \text{ liters.}$$

Note that this is just an illustrative example, the actual fuel usage can be obtained by evaluation of the quantity of fuel that is required to refill the tank after the trip (If the trip started with a full tank of fuel). The CO<sub>2</sub> emissions from the module delivery operation,  $E_c$  can be estimated as a product of the amount of fuel used and the CO<sub>2</sub> emissions per liter of fuel. The CO<sub>2</sub> emission per liter of diesel as reported by previous work [68] is 2.7KgCO<sub>2</sub>/liter of diesel.

$$\text{i.e.,} \quad E_c = F_c \times E_l \quad (11)$$

where:

$E_l$  is the emissions per liter of fuel used, and  $F_c$  is the amount of fuel consumed.

For the illustration above, for the module delivery, the carbon dioxide emissions can be estimated as:

$$E_c = F_c \times E_l = 79 \text{ liters} \times 2.7 \frac{\text{KgCO}_2}{\text{liter}} = 213.3 \text{ KgCO}_2$$

To use equation 8 above,

$$I_{TCM} = \sum_{i=1}^n D_{OSCST} \times E_{urvTCM} \times N_t \times I_{U_{TCM}} \quad (8)$$

In the example above,  $I_{U_{TCM}} = 2.7 \frac{\text{KgCO}_2}{\text{liter}}$ ,  $E_{urvTCM} = 0.395 \frac{\text{liters}}{\text{km}}$ ,  $D_{OSCST} = 200 \text{ km}$   
 $N_t = 1 \text{ trip}$

$$I_{TCM} = 200 \text{ km} \times 0.395 \frac{\text{liters}}{\text{km}} \times 1 \times 2.7 \frac{\text{KgCO}_2}{\text{liter}} = 213.3 \text{ KgCO}_2$$

Note that the above estimation for the CO<sub>2</sub> emissions does not include other GHG such as N<sub>2</sub>O, CH<sub>4</sub>, etc. that may be emitted during a trip (The above result is not carbon dioxide equivalent, CO<sub>2</sub> eq). As earlier mentioned, in 2019, for passenger vehicles, the ratio of carbon dioxide to total greenhouse gas emissions (including carbon dioxide [CO<sub>2</sub>], methane [CH<sub>4</sub>], and nitrous oxide [N<sub>2</sub>O]), expressed as carbon dioxide equivalents for passenger vehicles is 0.994." [69]. To convert the CO<sub>2</sub> emissions to carbon dioxide equivalent CO<sub>2</sub> eq, (accounting for N<sub>2</sub>O and CH<sub>4</sub> that is emitted) for passenger vehicles, the report [69] showed that CO<sub>2</sub> emissions is divided by 0.994 to obtain the CO<sub>2</sub> equivalent.

#### 4.1.7. The impact of the use of equipment in the offsite facility

The impact of the use of equipment in the offsite facility ( $I_{EQU\_OSC}$ ), is a function of the duration of equipment use, the energy use rate of the equipment at the offsite construction facility, and the impact per unit rate for the energy type that is associated with the use of each equipment at the offsite construction facility  $I_{u_{EQU}}$

$$I_{EQU\_OSC} = \sum_{i=1}^n DR_{EQU\_OSC} \times E_{ur_{EQU}} \times I_{u_{EQU}} \quad (12)$$

Where

$DR_{EQU\_OSC}$  is the duration for the use of equipment at the offsite construction facility.

$E_{ur_{EQU}}$  is the energy use rate of the equipment

$n$  is the number of such equipment

#### 4.1.8. The impact from the assembly of modules or panels onsite

The impact from the assembly of modules or panels onsite ( $I_{MASB}$ ), is a function of the duration for the use of equipment, the energy use rate of the equipment during the onsite assembly works, and the impact per unit rate for the energy type that is associated with activities in module assembly,  $I_{u_{MASB}}$

$$I_{MASB} = \sum_{i=1}^n DR_{EQU\_MASB} \times E_{ur_{EQU\_MASB}} \times I_{u_{MASB}} \quad (13)$$

Where

$DR_{EQU\_MASB}$  is the duration of the equipment use during the module/panel assembly onsite.

$E_{ur_{EQU\_MASB}}$  is the energy use rate of the equipment that is used for module assembly onsite.

$n$  is the number of such equipment.

#### 4.1.9. The impact of other miscellaneous activities onsite

The impact of other miscellaneous activities onsite ( $I_{MISC}$ ), is a function of the duration of equipment use, the energy use rate of the equipment during those onsite activities, and

the impact per unit rate for the energy type that is associated with the use of equipment for those miscellaneous activities,  $I_{u_{MISC}}$

$$I_{MISC} = \sum_{i=1}^n DR_{EQU_{MISC}} \times E_{ur_{EQU_{MISC}}} \times I_{u_{MISC}} \quad (14)$$

Where

$DR_{EQU_{MISC}}$  is the duration of the use of equipment during those miscellaneous onsite activities.

$E_{ur_{EQU_{MISC}}}$  is the energy use rate of the equipment that is used for those miscellaneous onsite activities.

$n$  is the number of such equipment/activities.

$I_{OSC}$  is subject to the impacts of the variables that are involved in the offsite portion of the work and  $I_{ONS_{OSC}}$  is subject to the impacts of the variables that are involved in the onsite portion of the work.

#### 4.2. Model equations for onsite construction

The total impact for onsite construction is the sum of the impacts from material transport to the final site ( $I_{MT_{ONS}}$ ), employee transport ( $I_{EPT_{ONS}}$ ) to the site (including inspector transport to the site for code compliance), equipment transport to the site ( $I_{EQT_{ONS}}$ ), the use of equipment for the building construction on site ( $I_{EQU_{ONS}}$ ). The total impact for onsite construction can be summarized as the total impact for the construction of the foundation,  $I_{FDN}$  and the total impacts for all the superstructure work onsite,  $I_{SPT}$ .

$$TI_{ONS} = I_{FDN} + I_{SPT} \quad (15)$$

$$TI_{ONS} = I_{MT_{ONS}} + I_{EPT_{ONS}} + I_{EQT_{ONS}} + I_{EQU_{ONS}} \quad (16)$$

$$I_{FDN} = (I_{MT_{ONS}} + I_{EPT_{ONS}} + I_{EQT_{ONS}} + I_{EQU_{ONS}})_{FDN} \quad (17)$$

##### 4.2.1. The impact of the round-trip material transportation

The impact of the round-trip material transportation to the onsite construction location ( $I_{MT_{ONS}}$ ) is a function of the distance between the onsite location and the material manufacturing yard, the energy use rate of the vehicle for material transport, the number of trips for material delivery, and the impact per unit rate for the energy that is associated with the vehicle for material delivery,  $I_{u_{MT}}$ . If the material supply yard is different from the material manufacturing facility, the impact of the distance through the retailer should be added.

$$I_{MT_{ONS}} = \sum_{i=1}^n D_{RMP_{ONS}} \times E_{ur_{v_{MT}}} \times N_t \times I_{u_{MT}} \quad (18)$$

Where

$D_{RMP_{ONS}}$  is the round-trip distance from the material production yard to the building construction site.

$E_{ur_{v_{MT}}}$  is the energy use rate for the vehicle used for material transport

$N_t$  is the number of trips for materials for the building construction works.

The impact of employee transportation (round-trips) to the offsite facility ( $I_{EPT}$ ), is a function of the distance between the offsite factory and the residences for the employees, the number of trips for the employees to the building construction site, the energy use rate for the vehicle that is used by the employee, the impact per unit rate for the energy that is associated with employee transport  $I_{u_{EPT}}$ , and the number of employees that travel alone to site. This impact will be high when employees have to travel a long distance to reach the offsite facility.

$$I_{EPT\_ONS} = \sum_{i=1}^n D_{EPT\_ONS} \times E_{urv_{EPT}} \times N_t \times I_{u_{EPT}} \quad (19)$$

Where

$D_{EPT\_ONS}$  is the average round-trip distance from employees' residences to the building construction site (onsite).

$E_{urv_{EPT}}$  is the energy use rate for the vehicle used by the employees

$N_t$  is the number of trips for employee transport for the duration of the building construction.

$n$  is the number of employees that travel alone to the site. Those who travel together (like in a carpool) can be counted as one.

#### 4.2.2. The impact of equipment transportation (round-trips) to the onsite facility

The impact of equipment transportation (round-trips) to the onsite facility ( $I_{EQT\_ONS}$ ), is a function of the distance between the equipment storage yard and the building construction site, the energy use rate for the vehicle that transports the equipment to the storage yard, number of trips for equipment transport, and the impact per unit rate for the energy that is associated with round-trip transportation of equipment to the site  $I_{u_{EQT}}$ . This impact will be high where the distance between the locations for equipment storage is very far from the construction site.

$$I_{EQT\_ONS} = \sum_{i=1}^n D_{EQT\_ONS} \times E_{urv_{EQT}} \times N_t \times I_{u_{EQT}} \quad (20)$$

Where

$D_{EQT\_OSC}$  is the round-trip distance from equipment storage yard to the building construction site.

$E_{urv_{EQT}}$  is the energy use rate for the vehicle used by the vehicle that is used to transport the equipment

$N_t$  is the number of trips for the transportation of the equipment to the building construction site.

$n$  is the number of equipment types that are to be transported to the building construction site.

The above equation is with the assumption that the energy use rate is the same for all the trips. The actual amount of fuel can be determined by the amount of fuel that is needed to refill the tank after starting the trips with a full tank of fuel. When using electricity, the actual rate of energy use can be determined by the amount of energy that is required to cover a certain distance.

#### 4.2.3. The impact of the onsite use of equipment

The impact of the use of equipment onsite ( $I_{EQU\_ONS}$ ), is a function of the duration of equipment use, the energy use rate of the equipment during those onsite activities and the impact per unit rate for the energy that is associated with equipment use onsite.

$$I_{EQU\_ONS} = \sum_{i=1}^n DR_{EQU\_ONS} \times E_{ur_{EQU\_ONS}} \times I_{u_{EQU}} \quad (21)$$

Where

$DR_{EQU\_ONS}$  is the duration of the use of equipment during those onsite activities.

$E_{ur_{EQU\_ONS}}$  is the energy use rate of the equipment that is used for those onsite activities.

$n$  is the number of such equipment/activities.

$I_{u_{EQU}}$  is the impact per unit rate for the energy that is used by the equipment on the site.

Depending on the available information, the impact of the use of equipment can also be estimated by a product of the impact per unit for a task, and the number of tasks (for both onsite and offsite construction).

The total impact for all the foundation works onsite,  $I_{FDN}$  is the summation of the individual impacts that are defined above

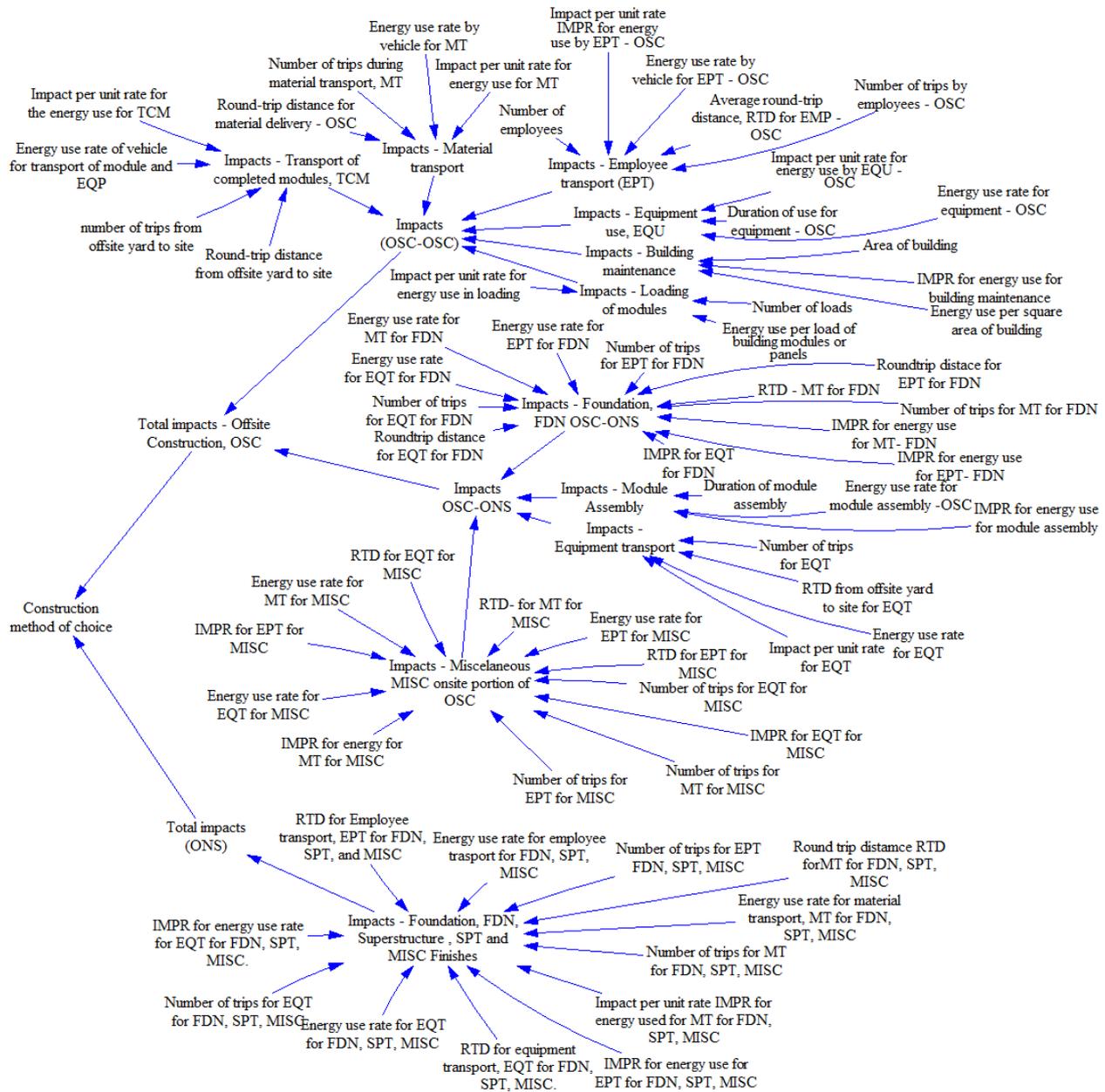
$$I_{FDN} = (I_{MT_{ONS}} + I_{ET_{ONS}} + I_{EQT_{ONS}} + I_{EQU_{ONS}})_{FDN} \quad (22)$$

The total impacts for all the superstructure work onsite,  $I_{SPT}$  is the summation of the individual impacts that is defined above

$$I_{SPT} = (I_{MT_{ONS}} + I_{ET_{ONS}} + I_{EQT_{ONS}} + I_{EQU_{ONS}})_{SPT} \quad (23)$$

The final selection for the system dynamic model that is presented in this study uses a command function to choose the construction method with minimum environmental impacts. Note that the multi-variable system dynamics model for the evaluation of the environmental impacts of onsite and offsite construction that is presented in [Figure 4](#) is designed to compare the environmental impact of two construction methods (onsite and offsite construction) for buildings with the same design and specifications. If it is desirable to compare impacts for similar buildings with different floor areas, the model can be modified to normalize the output to compare impacts per unit area of the building. Interested readers can look up the user guide and tutorial for the Vensim system dynamic modeling software on the applicable website [\[89\]](#).

In the model development, this study considered the environmental impacts of onsite and offsite construction, using LCA criteria (in terms of GHG/CO<sub>2</sub> emissions). Further research is recommended on the development of a system dynamic model that includes social and economic criteria into a model for choosing between onsite and offsite construction at various locations. The inclusion of social and economic factors in the system dynamics model may require the inclusion of a weighting factor which may be peculiar to each project. This study provided a framework for a user-friendly and interactive system dynamic model for comparison of the environmental impact of onsite and offsite construction. Further development of the model is welcomed by other researchers and other stakeholders in the industry. Other areas for further contributions and improvement includes the expansion of the variables that are labeled as miscellaneous works for offsite and onsite construction, the inclusion of variables to account for a reduction of the impact from employee transport when a company provides a shuttle (ride share) for employees that reside in different parts of the city, a reduction in transportation impacts if some employees travel with public transit, etc.



**Figure 5.** Multi-variable system dynamics model for the evaluation of the environmental impacts of onsite and offsite construction.

The abbreviations in the model in Figure 5 includes transportation of completed modules (TCM); material transport (MT); offsite construction (OSC); employee transport (EPT); impact per unit rate (IMPR); round trip distance (RTD); equipment use (EQU); foundation (FDN); equipment transport (EQT); miscellaneous works (MISC); superstructure (SPT); onsite construction (ONS).

**5. Other potential areas for future studies**

**5.1. Consideration for impacts beyond LCA review of the construction phase**

Although a model like this can estimate the environmental impact during the construction works, it is important to also consider the environmental impacts from other phases of the building lifecycle. Prefabricated construction has been shown to come with some good attributes such as air tightness that brings good benefits during the use phase

of the building. This can be especially important in parts of the world where it is desirable to keep the heat inside during the winter months. Some other researchers [39] mentioned that with the present knowledge, it is not possible to claim that prefabrication is more sustainable than traditional methods in all aspects as everything is dependent on the choice of materials and how the building performs. The authors noted that a full LCEA be done to be sure that both pollution and energy are minimized. Hence, further study is recommended on the environmental impacts through the whole building life cycle for both offsite and onsite construction.

### *5.2. Reducing the embodied impacts of building materials*

More opportunities exist in the evaluation of embodied impacts of building materials. Further study is recommended on how the embodied impacts of building materials can be reduced in the effort to achieve net-zero emission buildings. Focusing on embodied CO<sub>2</sub>, some scholars [70] attempt to look at the LCA of a specific magnesium oxide structural insulated panel (MgO SIP) that was used for a home in North England. In addition, the LCA compares six indicators including global warming, eutrophication, acidification, primary energy, formation of ozone, and depletion of ozone. The result showed that the product being reviewed does not have a higher score than the conventional structural insulated panel as it is manufactured at a place that is far away from the UK (Although it was assembled in the UK). The authors noted that if the product had been manufactured locally, it could have received a higher score than the conventional structural insulated panel. The authors also highlighted the potential of the MgO SIP in attaining the objective of the UK's nearly Zero energy building. The authors reported that the total embodied CO<sub>2e</sub> of the MgO SIP house is 18KgCO<sub>2e</sub>/m<sup>2</sup>/year but this number could have been nearly zero if the material was sourced locally.

Some scholars noted that while the sustainability of wood as a building material is complex as it is dependent on sustainable forestry and end-of-life treatment of the wood, fast-growing bio-based materials are valuable alternatives for insulation of buildings as the biogenic carbon can be stored in the built environment for relatively long time. If extended on a large scale, the combination of sustainable bio-based building materials and prefabrication could offer a lot of benefits at different levels [71]. Further evaluation of how bio-based products (that would have otherwise been dumped at the landfill) could be better applied to reduce the environmental impacts of construction will be beneficial for both onsite and offsite construction. Opportunities exist in the evaluation of the type of material that is most suitable for the construction of different components of building in different jurisdictions. Many sectors are trying to capitalize on the renewability of wood for the reduction of environmental impacts [72].

While wood is seen as an environmentally friendly material because of desirable factors such as carbon sequestration, more trees can be planted through sustainable forestry, a scholar [73] described some situations in which concrete may also be a preferred choice, especially for structures in which moisture damage may be of concern. Some scholars [74] noted that timber cannot completely replace other building materials such as concrete and steel. However, by maximizing the use of timber with other materials and components, the sustainability of future developments can be improved. In terms of thermal behavior, a researcher [44] presented the results for a comparison of the timber-framed wall, cross-laminated-timber wall, and masonry wall. It was reported that timber-framed wall has the highest capacity to slow down the propagation of temperature waves from the outer surface to the inner surface (time lag), the masonry wall performs best in reducing the amplitude of temperature oscillation on the inner surface (decrement factor). Relative to the other two walls, the CLT wall shows an intermediate value of both the decrement factor and the time lag. Local availability of construction materials, equipment, and labor, as well as local availability of offsite construction companies, is also a very important factor to consider in the decision about the method of construction.

### ***5.3. Evaluation of the end-of-life impacts of the construction materials***

More studies on how the materials can be put to good use at their end of life will be beneficial. For permanent buildings, Architects keep designing in the same manner as before. However, the concept of recyclable architecture at the beginning of the construction project is very necessary to address the need for more buildings to accommodate new generations while reducing the use of natural resources and minimizing the amount of materials that are wasted during construction [75]. When the focus is on material substitution, other phases of the lifecycle of a product should be accounted for, especially the reuse and recycling potential of the product after its useful lifetimes [38]. A previous work [75] presented three building prototypes for new recyclable architectural typologies i.e., (1) a demountable prototype that is characterized by the entire demountability of the building, (2) a slab prototype that is designed as a shelf structure in which wooden housing modules can be plugged in and out, (3) a tower prototype that allows for an easy change of layout and uses for different floors. The prototypes combine flexibility, modularity, and disassembling to address the increasing demands for reusable multi-use and resource-efficient constructions.

In line with the circular economy framework, designing modular buildings for disassembly and reuse can help decrease waste production and material depletion [76].

### ***5.4. Design for manufacture and ease of assembly***

The design phase is of great significance for ensuring construction quality, low environmental impact, and economic efficiency [77]. A previous work [78] presented a review of design for manufacture and assembly and their application in manufacturing and prefabrication. In design for manufacture and assembly projects, components of the building are manufactured in the factory and delivered to the project site for installation [78]. Offsite manufacturing can be structured in such a way that facilitates the ease of assembly of building components. This can be especially beneficial in places where there is an accommodation crisis, or where there is a need for urgent housing situations in an effort to respond to the impacts of natural disasters. Such housing modules should be designed in a way that the building can be easily assembled by a few people with few instructions. The assembly instructions can be supplemented with pictures to ensure that even those who are not literate can follow the pictorial instructions to assemble the building. Design for manufacture is an important part of the construction industry's future, due to the promise of the speed of project delivery, worker safety, quality control, and onsite waste minimization through purposeful design for manufacture and assembly [79]. While millions of people are displaced by disasters, billions of people globally are believed to lack adequate housing. The adoption of economically and environmentally sustainable practices for the construction industry is important [42]. Further study on how to adequately implement design for ease of manufacturing, ease of assembly, and ease of disassembly of building components for reuse and recycling is recommended.

### ***5.5. Consideration for other sustainability factors that are not often accounted for in building LCA***

Sustainability is often approached from a three-dimensional perspective (covering social, economic, and environmental factors). Adverse impacts of construction on the environment typically include dust and gas emissions, waste generation, noise pollution, air pollution, and water consumption [38]. Further study is recommended on how factors such as noise disturbance to neighbors, dirt on the street, safety, availability of maneuver space for equipment to lift modules, etc. may affect the choice of the method of construction, especially for infill projects in residential neighborhoods. Some scholars, [47] provided a focused review of modular medical quarantine facilities covering the structural forms, equipment arrangement, and floor layout design. The construction

management strategies were also highlighted. The scholars reported that disturbance of neighboring buildings during the construction process was mitigated as most of the buildings were constructed offsite, minimizing onsite work.

### ***5.6. Addressing various factors that may affect the uptake of sustainable construction***

Analysis of the environmental impacts of onsite and offsite construction alone is not sufficient to change how construction will be done. The construction industry constantly has a low score on sustainable development and innovation although the industry is one of the biggest and long-standing industries [80]. Further study on how the construction industry can become more flexible to good innovations is recommended. Some other scholars [81] also noted that further research is needed in the integration of digital construction technology, lean construction, integrated project delivery method, and issues of sustainability of offsite construction. In a complex and fragmented construction industry, the adoption of sustainable construction technology may not happen by chance. Unless the situational context is provided, it is likely to be met with uptake problems [82]. There is a need for more education of construction stakeholders. More studies and implementation of good strategies to ensure adequate uptake of sustainable construction principles will be beneficial for the construction industry. BIM is considered an information technology-enabled platform that can help to achieve the integration of interdisciplinary collaboration [83]. Some scholars [76] provided a design for the manufacture and assembly DfMA framework that is aimed at achieving integration with BIM and allowing for customer participation in the process. Further study is recommended on how the BIM technology can be further adapted (with system dynamics principles) as one of the visual means of education for construction stakeholders on the concept of sustainable construction. The construction industry will have to learn new processes to become more productive and efficient [45].

Some researchers [84] aimed at identifying the factors that affect the adoption of industrialized building systems in Malaysia. The 14 factors identified include project condition, procurement setup, decision-making style, economic conditions, management approach, communication process, technology development, experience, government involvement, sustainability feature, stakeholders' participation, bounded rationality, awareness, and attitude. The authors also mentioned that the intensity and influence of the factors may be different from one country to the other as such there is a need for a targeted approach in the effort to develop a strategy for the improvement of the adoption of industrialized building systems. To promote modular construction, an important aspect that must be addressed is the cultural mindset toward the method of construction and a wider collaboration between all actors that are involved in the planning, construction, maintenance, and refurbishment of a modular building [1]. The scholar recommended education and training for skillsets that will be useful in modular construction. Political strategies and incentives to boost modular construction were also recommended.

Some scholars [79] reported that the reasons for the slow uptake of DfMA in Australia include government regulations and incentives, community mindset, planning, and building codes, finance and supply chain management, unionization, and business politics. Further study on how government regulations and incentives can facilitate the principles for design for manufacture, ease of assembly, and disassembly of building components for reuse and recycling is recommended.

### ***5.7. Compilation and sharing of knowledge on emission reduction strategies for the construction industry***

Some scholars [62] presented the emission reduction strategies for two Norwegian low-emission construction sites and recommended further studies to have more

information about emission reduction strategies from other building typologies. Further study on the achievement of zero-emission construction sites is recommended.

### **5.8. Cost of buildings**

From a sustainability perspective, economic factor such as the cost of buildings is important. A researcher [86] developed a universal methodology for cost-optimal zero-energy lightweight construction. Life cycle costing portrays the cost that will be incurred for a project for its whole building life cycle [86]. Further study is recommended on how to ensure that the cost of the building becomes affordable for all (toward the goal of ensuring that adequate housing is an international human right [88]). In addition, to the social and environmental aspects of building construction, more studies and continuous improvement on the reduction of the life cycle cost of residential buildings are important.

### **5.9. Efficiency of onsite and offsite construction in waste minimization**

Various studies have mentioned about enormous waste from construction operations. Further study on how various methods of construction can help to achieve a significant waste reduction is recommended. Potential reduction in the environmental impact as a result of a reduction in construction waste can be included in the decision to choose between methods of construction in the future.

## **6. Conclusions and recommendations**

This study addressed the decision to use either offsite or onsite construction through the lens of system dynamics, and LCA. Simplified model equations for the estimation of environmental impacts of construction works were presented for the model development. The model presented helps to bring more clarity to the environmental trade-offs in the construction phase between the two construction methods (onsite and offsite construction). The model equations can be useful for construction stakeholders (including both onsite and offsite building contractors) to have a good knowledge of areas of hot spots to have a significant reduction in the environmental impacts of construction works. This study also presents various potential areas for future studies in the effort towards the reduction of environmental impacts and achievement of more sustainable construction. Among other things, the model showed that an increase in the number of trips for material transport increases the total impacts of onsite construction. However, this is also affected by the energy use rate (and the other variables described in model equations) for the transportation medium. An increase in the round-trip distance from the offsite yard to the final construction site increases the total impacts from the transportation of completed modules. An increase in distance for material delivery for offsite construction increases the total impact of material transport for offsite construction. The decrease in the number of trips of material transport results in a reduction in the impact of onsite construction. The overall impacts have some dependency on the energy use rate of the transportation medium and other variables that were described in the model parameters. The system dynamics model that is described in this study has the capability to show how changes in various variables affect the environmental impact. With the right inputs, the model can help with the selection of a construction method that has the least environmental impact during the construction process (as described in the study). Further study is recommended on the differences in the environmental impact of the two construction methods while considering the whole life cycle of the building (i.e., in addition to the environmental impacts during the material production and construction stage, the inclusion of consideration of the differences in environmental impact during the use stage and the end-of-life stage will be a good area for further studies). Due consideration also needs to be given to the reduction in environmental impacts due to the potential for the reuse and recycling of buildings. The dismantlability, reuse, and recycling potential can

be affected by the design and construction of the building. Further study is recommended on the evaluation of how the two methods of construction can be applied to reduce waste in construction operations. In situations where the standard member sizes for the building structures are pre-cut into customized sizes for various projects (at upstream production/supplier facilities) before shipping to the offsite construction yard. A holistic review of the waste management for construction materials will also include the waste management at the upstream supplier yard for the offsite construction approach. This will also be applicable to the onsite construction method. Further study on the incorporation of the impact of this waste on the overall environmental impact of construction works is recommended. Although the environmental impact of both offsite and onsite construction can be affected by a change in various associated factors that are described in this study, it is important to note that sustainable construction also considers social, economic, and technical factors. In addition to technical feasibility in various locations, further research is recommended on a holistic evaluation of onsite and offsite construction through the lens of the three pillars of sustainability.

**Funding:** This research received no external funding that is specifically assigned to this study.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

- [1] Tzourmakliotou, D., 2021. Modular Disruption in Construction Industry—The Environmental Benefits. *J. Civil Eng. Archit.* **2021**, 15, 318 - 329. doi: 10.17265/1934-7359/2021.06.004
- [2] Lim, Y. S.; Xia, B.; Skitmore, M.; Gray, J.; Bridge, A. Education for sustainability in construction management curricula. *Int. J. Constr. Manag.* **2015**, 15, 4.
- [3] Kamali, M.; Hewage, K.; Sadiq, R. Conventional versus modular construction methods: A comparative cradle-to-gate LCA for residential buildings. *Energy Build.* **2019**, 204.
- [4] Jingke, H. A study of embodied energy assessment of China's construction sector and construction projects. *The Hong Kong Polytechnic University*. Thesis. 2016.
- [5] El-Sayegh, S.; Romdhane, L.; Manjikian, S. A critical review of 3D printing in construction: benefits, challenges, and risks. *Archiv.Civ.Mech.Eng.*, **2020** 20, 34. <https://doi.org/10.1007/s43452-020-00038-w>.
- [6] Jo, J.H.; Jo, B W.; Cho, W.; Kim, J-H. Development of a 3D Printer for Concrete Structures: Laboratory Testing of Cementitious Materials. *Int J Concr. Struct. Mater.* **2020**, 14, 13, <https://doi.org/10.1186/s40069-019-0388-2>
- [7] Smith, R. E.; Hamedani, M. N.; Griffin, G.; Developing Timber Volume Calculators Through a Comparative Case Study Analysis of Wood Utilization in On-Site and Off-Site Construction Methods". *Technology | Architecture + Design*, 2018, 2, 1, 55-67.
- [8] Goodier, C.; Gibb, A. Future opportunities for offsite in the UK. *Constr. Manag. Econ.* **2007**, 25, 585-595.
- [9] Nawi, M. N. M.; Hanifa, F. A. A.; Kamar, K. A. M.; Lee, A.; Azman, M.N. A. Modern Method of Construction: An Experience from UK Construction Industry". *Aust. j. basic appl. sci.*, **2014**, 8, 5, Special 2014: 527-532.
- [10] Smith, R. E. Off-Site and Modular construction explained. Whole building design guide. **2016**, Available online at <https://www.wbdg.org/resources/site-and-modular-construction-explained> Accessed June 16, 2022.
- [11] Garfinkel, Y.; Mumcuoglu, M. The Temple of Solomon in Iron Age Context. *Relig.* **2019**, 10 (198). doi:10.3390/rel10030198
- [12] Morris, H. M. The Temple's Silent Construction. Institute for creation research. 2009, Available online at <https://www.icr.org/article/4247> Accessed June 16, 2022.
- [13] Crowther, P. Historic trends in building disassembly. *Int. sci. technol. conference*. Technology in transition: mastering the impacts, Montreal. June **1999**. Available online at <https://eprints.qut.edu.au/2837/1/Crowther-ACSA1999.PDF> accessed June 17, 2022
- [14] Na, L. Investigation of the designers' and general contractors' perception of offsite construction techniques in the United States construction industry. Ph.D. Thesis. Clemson University. **2007**, Available online at <https://www.proquest.com/pagepdf/304888018?accountid=14474> Accessed June 16, 2022.
- [15] Fortune Business Insights. 2021. "Modular construction market size, share & COVID-19 impact analysis, by type (Permanent modular construction and relocatable modular construction), by application (Commercial, health care, education & Institutional, hospitality and others), and regional forecast, 2021-2028". Available online at <https://www.fortunebusinessinsights.com/industry-reports/modular-construction-market-101662> Accessed June 17, 2022.
- [16] Tavares, V.; Soares, N.; Raposo, N.; Marques, P.; Freire, F. Prefabricated versus conventional construction: Comparing life-cycle impacts of alternative structural materials. *J. Build. Eng.* 2021, 41. <https://doi.org/10.1016/j.job.2021.102705>
- [17] Quale, J. D. Onsite vs. Offsite "Comparing environmental impacts". In *Offsite Architecture: Constructing the future*, Edited by Smith R. E., and Quale, J. D., Routledge. Taylor and Francis Group. London and New York, 2017, ISBN: 978-1-315-74333-2.

- [18] Li, X.-J.; Zheng, Y.-D. Using LCA to research carbon footprint for precast concrete piles during the building construction stage: A China study. *J. Clean. Prod.* **2020**, *245*. <https://doi.org/10.1016/j.jclepro.2019.118754>
- [19] ISO 14044:2006E. Environmental management life cycle assessment requirements and guidelines- first edition. International Organization for Standardization.
- [20] International Organization for Standardization, ISO 14040:2006E. Environmental management: Life cycle assessment, principles and framework.
- [21] Ansah, M. K.; Chen, X.; Yang, H.; Lu, L.; Lam, P. T. I. Developing an automated BIM-based life cycle assessment approach for modularly designed high-rise buildings. *Environ. Impact Assess. Rev.* **2021**, *90*, 106618. <https://doi.org/10.1016/j.eiar.2021.106618>
- [22] Balasbaneh, A. L.; Sher, W.; Yeoh, D.; Yasin, M. N. Economic and environmental life cycle perspectives on two engineered wood products: comparison of LVL and GLT construction materials. *Environmental Science and Pollution Research.* **2022**, <https://doi.org/10.1007/s11356-022-24079-1>.
- [23] Vuarnoz, D.; Hoxha, E.; Nebrini, J.; Jusselme, T.; Cozza, S. Assessing the gap between a normative and a reality-based model of building LCA. *J. Build. Eng.* **2020**, *31*. <https://doi.org/10.1016/j.jobte.2020.101454>
- [24] Famiglietti, J.; Toosi, H. A. T.; Denarie, A.; Motta, M. Developing a new data-driven LCA tool at the urban scale: The case of the energy performance of the building sector. *Energy Convers. Manag.* **2022**, *256*. <https://doi.org/10.1016/j.enconman.2022.115389>.
- [25] Hollberg, A.; Genova, G.; and Habert, G. Evaluation of BIM-based LCA results for building design. *Autom. Constr.* **2020**, *109*.
- [26] Wolodko, J. Life Cycle Assessment Part 2 (Into to the LCA Method & Life Cycle Mapping). Lecture Notes. University of Alberta, Canada, 2019.
- [27] Mofolasayo, A., The environmental cost of hidden waste in design. 13th International conference on construction and project management, ICCPM, **2022**
- [28] American Wood Council and Canadian Wood Council. **2020**. Environmental Product declaration- North American Glued Laminated Timber.
- [29] Faludi, J.; Lepech, M. D. Using life cycle assessment methods to guide architectural decision-making for sustainable prefabricated modular buildings. *J. Green Build.* **2012**, *7*, 3.
- [30] Achenbach, H.; Wenker, J. L.; Ruter, S. Life cycle assessment of product- and construction stage of prefabricated timber houses: a sector representative approach for Germany according to EN 15804, EN 15978 and EN 16485. *Eur. J. Wood. Wood. Prod.* **2018**, *76*, 711 - 729.
- [31] Hong, J.; Shen, G. Q.; Mao, C.; Li, Z.; Li, K. Life-cycle energy analysis of prefabricated building components: an input output-based hybrid model. *Journal of Cleaner Production.* **2015**, *112*, 2198 - 2207.
- [32] Zhu, H.; Hong, J.; Shen, G. Q.; Mao, C.; Zhang, H.; Li, Z. The exploration of the life-cycle energy saving potential for using prefabrication in residential buildings in China. *Energy Build.*, **2018**, *166*, 561-570.
- [33] Noordzy, G.; Whitfield, R.; Saliot, G.; Ricaurte, E. Modular Construction: An important alternative approach for new hotel development projects. *J. Mod. Proj. Manag.* **2021**, *9*, 2. doi: 10.19255/JMPM02715.
- [34] Veiskarami, M. Modular construction and overview on its potential advantages and constraints in the project management perspective. Thesis. *Escola de Camins*, **2020**
- [35] Thamboo, J.; Zahra, T.; Navaratnam, S.; Asad, M.; Poologabathan, K. Prospects of Developing Prefabricated Masonry Walling Systems in Australia. *Buildings*, **2021**, *11*, 294. <https://doi.org/10.3390/buildings11070294>
- [36] Maqbool, R.; Namaghi, J. R.; Rashid, Y.; Altuwaim, A. How modern methods of construction would support to meet the sustainable construction 2025 targets, the answer is still unclear. *Ain Shams Eng. J.* **2022**, <https://doi.org/10.1016/j.asej.2022.101943>.
- [37] Ruoyu, J.; Jingke, H.; Jian, Z. Environmental performance of off-site constructed facilities: A critical review. *Energy and Buildings.* **2020**, *207*, 109567. <https://doi.org/10.1016/j.enbuild.2019.109567>
- [38] Drager, P.; Letmathe, P. Value losses and environmental impacts in the construction industry – Tradeoffs or correlates?" *J. Clean Prod.*, **2022**, *336*, 130435.
- [39] Moradiboustouni, M.; Vale, B.; Isaacs, N. Investigating the level of sustainability in off-site construction. International Conference on Sustainable Design and Manufacturing, Budapest, Hungary. In: Ball, P., Huaccho Huatuco, L., Howlett, R., Setchi, R. (eds) Sustainable Design and Manufacturing, KES-SDM. Smart Innovation, Systems and Technologies, 2019, 155. Springer, Singapore. [https://doi.org/10.1007/978-981-13-9271-9\\_10](https://doi.org/10.1007/978-981-13-9271-9_10).
- [40] Wu, Z.; Luo, L.; Wang, Y.; Bi, G.; Antwi-Afari, M. F. 2021. An Analysis on Promoting Prefabrication Implementation in Construction Industry towards Sustainability. *Int. J. Environ. Res. Public Health.* **2021**, *18*, 11493. <https://doi.org/10.3390/ijerph182111493>.
- [41] Yin, X.; Dong, Q.; Zhou, S.; Yu, J.; Huang, L.; Sun, C. Energy-Saving Potential of Applying Prefabricated Straw Bale Construction (PSBC) in Domestic Buildings in Northern China. *Sustainability*, **2020**, *12*, 3464; doi:10.3390/su12083464
- [42] Bhandari, S.; Riggio, M.; Jahedi, S.; Fischer, E. C.; Muszynski, L.; Luo, Z. 2023. A review of modular cross laminated timber construction: Implications for temporary housing in seismic areas. *J. Build. Eng.*, **2023**, *63*, Part A. <https://doi.org/10.1016/j.jobte.2022.105485>.
- [43] Ngoenchuklin, C. Feasibility of implementing prefabricated U.S. products and methods for residential construction in Thailand. *Georgia Institute of Technology*. Thesis. 2014.
- [44] Sanna, F. Timber modern methods of construction: A comparative study. Volume 1. *Edinburgh Napier University*. Thesis. 2018.

- [45] Datta, K.; Bunning, J.; Green, J.; Hargroves, K. Weaknesses, Review of the Strengths, Opportunities, and Threats of Manufactured Buildings for the Sustainable Built Environment National Research Centre, Curtin University Sustainability Policy Institute, 2014.
- [46] Zhao, L.; Liu, Z.; Mbachu, J. Optimization of the Supplier Selection Process in Prefabrication Using BIM. *Buildings*, 2019, 9, 222; doi:10.3390/buildings9100222.
- [47] Ding, C.; Bai, Y.; Fang, Y.; Huang, F. A Focused Review of Modular Construction for Medical and Quarantine Facilities. *J. Archit. Eng.* 2022, 28, 4.
- [48] Gunaydin, D. Modularity: Real diversity of notion. Thesis, *Cankaya Universitesi*. 2014.
- [49] Tesema, H. T. The Effect of Prefabricated Materials and Equipment on Cost Efficiency of a Building: The case of Ministry of National Defense Housing Projects in Addis Ababa. *Pretor Business College*, 2018.
- [50] Mustafa, N. K.; Isa, C.M M., Ekundayo, D., Joseph, V,R, A., 2022. Barriers and strategies for improving carbon emissions management approaches in Malaysian construction. *Construction Economics and Building* 22 (3). . <https://doi.org/10.5130/AJCEB.v22i3.7909>. pp. 99-123.
- [51] Ford, A. Modeling the environment: An introduction to system dynamics modeling of environmental systems. Island Press, Washington DC. 1999.
- [52] Winz, I.; Brierley, G.; Trowsdale, S., The use of system dynamics simulation in water resource management. *Water Resour Manage*, 2009, 23:1301-1323. DOI10.1007/s11269-008-9328-7
- [53] Forrester, J. W. System dynamics, systems thinking, and soft OR. *Syst. Dyn. Rev.* 1994, 10: (2-3): 254-256. <https://doi.org/10.1002/sdr.4260100211>
- [54] Forrester, J. W. Lessons from system dynamics modeling. 1987, <https://doi.org/10.1002/sdr.4260030205>.
- [55] Stave, K. A. A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. *J. Environ. Manage.* 2003, 67, 4, 303-313.
- [56] Costanza, R.; Ruth, M. Using Dynamic Modeling to Scope Environmental Problems and Build Consensus. *Environ. Manage.* 1998, 22, 183–195. <https://doi.org/10.1007/s002679900095>
- [57] Zhang, Y.; Yan, D.; Hu, S.; Guo, S. Modelling of energy consumption and carbon emission from the building construction sector in China, a process-based LCA approach". *Energy Policy*, 2019, 134.
- [58] Mingxiao, X.; Yan, L.; Environmental impact assessment of Materialization Stage of prefabricated buildings based on LCA and WTP". *IOP Conf. Ser.: Earth Environ. Sci.* 634 012020, DOI 10.1088/1755-1315/634/1/012020, 2021.
- [59] Cao, X.; Li, X.; Zhu, Y.; Zhang, Z. A comparative study of environmental performance between prefabricated and traditional residential buildings in China. *J. Clean. Prod.*, 2015, 109, 131 - 143
- [60] Tian, Y.; Spatari, S. Environmental life cycle evaluation of prefabricated residential construction in China". *J. Build. Eng.* 2022, 57. DOI10.1016/j.job.2022.104776.
- [61] Du, Q.; Bao, T.; Li, Y.; Huang, Y.; Shao, L. Impact of prefabrication technology on the cradle-to-site CO2 emissions of residential buildings. *Clean Technol Environ Policy*, 2019. 21, 7, 1499-1514.
- [62] Fufa, S. M.; Wiik, M. K.; Mellegard, S.; Andresen, I. Lessons learnt from the design and construction strategies of two Norwegian low emission construction sites. *IOP Conf. Ser.: Earth Environ. Sci.* 2022, 352 012021.
- [63] Quale, J.; Eckelman, M. J.; Williams, K. W.; Sloditskie, G.; Zimmerman, J. B. Construction Matters Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States, *J Ind Ecol.* 2012, 16, 2.
- [64] Government of Canada NRCAN Fuel efficiency benchmarking in Canada's trucking industry. Available online at <https://www.nrcan.gc.ca/energy/efficiency/transportation/commercial-vehicles/reports/7607> Accessed November 9, 2022.
- [65] Bulk Transporter. Cummins-Peterbilt SuperTruck hits 10.7 MPG in latest trial. 2014. Available online at <https://www.bulktransporter.com/fleet-management/features/article/21654316/cumminspeterbilt-supertruck-hits-107-mpg-in-latest-trial> Accessed December 12, 2022.
- [66] DieselNet. Cummins-Peterbilt SuperTruck achieves 10.7 mpg. 2014. Available online at <https://dieselnet.com/news/2014/03cummins.php> Accessed December 12, 2022.
- [67] Mofolasayo, A., A framework for evaluation of improvement opportunities for environmental impacts on construction works using life cycle assessment and value stream mapping concepts: offsite and onsite building construction. *World. J. Civil Eng. Archit.* 2023, In production..
- [68] Natural Resources Canada, NRCAN. Learn the facts: Emissions from your vehicle, 2014. Available online at [https://www.nrcan.gc.ca/sites/nrcan/files/oe/pdf/transportation/fuel-efficient-technologies/autosmart\\_factsheet\\_9\\_e.pdf](https://www.nrcan.gc.ca/sites/nrcan/files/oe/pdf/transportation/fuel-efficient-technologies/autosmart_factsheet_9_e.pdf) accessed, September 28, 2022
- [69] United States Environmental Protection Agency (EPA). "Greenhouse gases equivalencies calculator-Calculations and references". 2022. Available online at <https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references> Accessed December 06, 2022.
- [70] Al Derbi, B.; Finnegan, S. The embodied carbon analysis of a nearly Zero Energy Building (nZEB) MgOSIPs house in the UK. *PLEA*, Planning Post Carbon Cities. A coruna, Spain, 2020.
- [71] Carcassi, O. B.; De Angelis, E.; Iannaccone, G.; Malighetti, L. E.; Maser, G.; Pittau, F.; Bio-Based Materials for the Italian Construction Industry: Buildings as Carbon Sponges. S. Della Torre et al. (eds.), *Regeneration of the Built Environment from a Circular Economy Perspective*, Research for Development, 2020, [https://doi.org/10.1007/978-3-030-33256-3\\_23](https://doi.org/10.1007/978-3-030-33256-3_23).

- [72] Browne, X.; Larsen, O. P. L.; Friis, N. C.; Kühn, M. S. Material Value(s): Motivating the architectural application of waste wood. *Archit. Struct. Constr.*, **2022**. <https://doi.org/10.1007/s44150-022-00065-6>
- [73] Mofolasayo, A., A Comparison of Life Cycle Impact of Mass Timber and Concrete in Building Construction. *World. J. Civil Eng. Archit.* **2022**, *1*, 1, 47-72. Doi: 10.31586/wjcea.2022.449.
- [74] Stocchero, A.; Seadon, J. K.; Falshaw, R.; Edwards, M. Urban Equilibrium for sustainable cities and the contribution of timber buildings to balance urban carbon emissions: A New Zealand case study. *J. Clean. Prod.* **2017**, *143*, 1001-1010. <https://doi.org/10.1016/j.jclepro.2016.12.020>.
- [75] Silva, M. F.; Jayasinghe, L. B.; Waldmann, D.; Hertweck, F. Recyclable Architecture: Prefabricated and Recyclable Typologies. *Sustainability*, **2020**, *12*, 1342; doi:10.3390/su12041342.
- [76] O'Gardy, T. M.; Minunno, R.; Chong, H-Y.; Morrison, G. M.; Interconnections: An Analysis of Disassemblable Building Connection Systems towards a Circular Economy. *Buildings* **2021**, *11*, 535. <https://doi.org/10.3390/buildings11110535>.
- [77] Bakshi, S.; Chanaghlo, M R.; Rahimian, F. P.; Edwards, D. J.; Dawood, N. Integrated BIM and DfMA Parametric and Algorithmic Design Based Collaboration Framework for Supporting Client Engagement within Offsite Construction. *Autom. Constr.* **2022**, *133*,
- [78] Wasim, M.; Serra, P. V.; Ngo, T. D. 2020. Design for manufacturing and assembly for sustainable, quick and cost-effective prefabricated construction- a review. *Int. J. Constr. Manag.*, <https://doi.org/10.1080/15623599.2020.1837720>.
- [79] Langston, C.; Zhang, W. 2021. DfMA: Towards an Integrated Strategy for a More Productive and Sustainable Construction Industry in Australia. *Sustainability*, *13*, 9219. <https://doi.org/10.3390/su13169219>
- [80] Hamdan, H. The potential of public procurement to achieve low or zero-emission construction sites. Thesis. *Norwegian University of Science and Technology*, 2018.
- [81] Jin, R.; Gao, S.; Chechmehzangi, A.; Aboagye-Nimo, E. 2018. A holistic review of off-site construction literature published between 2008 and 2018. *J. Clean. Prod.*, **2018**, *202*. 1202-1219.
- [82] Martin, L.; Perry, F. Sustainable Construction Technology Adoption. In *Sustainable Construction Technologies: Life-Cycle Assessment*, Edited by Tam, V. W. Y., and Le, K. N. 2019, <https://doi.org/10.1016/B978-0-12-811749-1.00009-2>.
- [83] Li, X.; Wu, P.; Shen, G. Q.; Wang, X.; Teng, Y. Mapping the knowledge domains of Building Information Modeling (BIM): A bibliometric approach. *Automation in Construction*, **2017**, *84*, 195-206, <https://doi.org/10.1016/j.autcon.2017.09.011>.
- [84] Zakaria, S. A. S.; Gajendran, T.; Skitmore, M.; Brewer, G. Key factors influencing the decision to adopt industrialised building systems technology in the Malaysian construction industry: an inter-project perspective. *Archit. Eng. Des. Manag.* **2017**, *14*, issue 1-2. <https://doi.org/10.1080/17452007.2017.1298512>
- [85] Amer, M. DenCity: A methodology to design cost-optimal zero-energy lightweight construction for roof stacking. Thesis. *University of Liege*, 2019
- [86] Shamsuddin, S. M. B. S. 2020. Decision making tool for industrialised building system adoption through integrated life cycle cost analysis. PhD. Thesis. *School of Civil Engineering, Universiti Teknologi Malaysia*.
- [87] Canada energy regulator, 2022. "Provincial and Territorial Energy Profiles-Alberta". Available online at <https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-alberta.html#:~:text=Alberta's%20electricity%20sector%20produces%20more,GHG%20emissions%20from%20power%20generation>. Accessed June 22, 2022.
- [88] UN Habitat. The right to adequate housing: Fact sheet number 21 (Rev.1). Available online at [https://www.ohchr.org/sites/default/files/Documents/Publications/FS21\\_rev\\_1\\_Housing\\_en.pdf](https://www.ohchr.org/sites/default/files/Documents/Publications/FS21_rev_1_Housing_en.pdf) Accessed December 12, 2022.
- [89] Ventana Systems Inc., User Guide - Vensim Introduction and Tutorials. Available online at [https://www.vensim.com/documentation/users\\_guide.html](https://www.vensim.com/documentation/users_guide.html) Accessed January 2, 2023.