International Journal of Innovation, Creativity and Change. www.ijicc.net
Volume 10, Issue 7, 2019

Developing a Framework for Life Cycle Assessment of Construction Materials through Building Information Modelling (BIM)

Nurshuhada Zainon[a], Goh Wei Lun[b], Noor Suzaini Mohamed Zaid[c], Nik Elyna Myeda[d], Nur Mardhiyah Aziz[e], [a,b,e]Department of Quantity Surveying, Faculty of Built Environment, University of Malaya, Kuala Lumpur, Malaysia, [c,d]Department of Building Surveying, Faculty of Built Environment, University of Malaya, Kuala Lumpur, Malaysia, Email: [a]zshuhada@um.edu.my, [b]simongoh1997@gmail.com, [c]suzaini_zaid@um.edu.my, [d]elyna@um.edu.my, [e]nurmardhiyah@um.edu.my

Buildings are responsible for up to 50% of greenhouse gas emissions worldwide, and more than 30% of energy use. Studies show that 90% of building life span occurs during operation and maintenance. Hence, construction professionals should address life cycle environmental considerations. The Life Cycle Assessment (LCA) is crucial in achieving sustainable building design, as it offers an objective and consistent measurement of environmental impacts from construction materials and assemblies. Building Information Modelling (BIM) technology could automate LCA into one single platform. This research proposes a BIM-enabled Life Cycle Assessment Framework, to trade-off embodied energy against predicted operational energy consumption in construction projects. The research identified assessment parameters for LCA. It then mapped out in the digital construction process using BIM as a platform. The conceptual framework was validated by BIM experts and Quantity Surveyors who are knowledgeable in this area. They were selected using snowball sampling methodology. Ultimately, recognizing the environmental impact encourages the use of materials with low environmental impact. It will also echo our government's various efforts to assist industry players in embracing Industry 4.0, through the adoption of digital technologies.

Key words: *Life Cycle Assessment (LCA), Building Information Modelling (BIM), Construction, Materials, Quantity Surveyors, Carbon footprint.*

Introduction

The Malaysian economy grew 4.5% in the first quarter (Q1) of 2019 (Ministry of Finance, 2019). The construction industry is a major productive sector. It contributed about 4.5% to the Gross Domestic Product (GDP) (at constant 2010 prices) in Q1 2019 (Ministry of Finance, 2019). The 11th Malaysia Plan (2016-2020) estimates that construction will increase by 10.3% per year from 2016 to 2020, outpacing the anticipated average growth of Malaysia by 5.0% to 6.0% per annum. To date, construction has continued to register positive growth.

Recently, Malaysia's climate is changing with global climate change (Shahid et al., 2017). It has been recognised as a global issue and is being discussed all over the world. This is due to greenhouse gas emissions growing in tandem with economic growth, particularly in a developing country like Malaysia (Rashidi et al., 2014). Climate change shall be taken into consideration as it comprises a range of potential indirect effects; for instance, the economic and ecological loss due to habitat loss, as well as an increased flood risk to the community.

Unfortunately, there is still a huge ambition gap between the reality and the climate change targets, in reducing greenhouse gases (Caytas, 2018). If the emissions gap is not closed by 2030, the average global temperature increase target of just two degrees Celsius is unlikely to be kept (United Nations Environment Programme, 2018).

In fact, the BP Statistical Review of World Energy 2019 (BP Energy Economic, 2019) reported that the amount of carbon dioxide emission is growing per annum, especially in 2017. Between 2013 and 2017, Malaysia's carbon emissions grew by 1.7%. The construction sector contributed a high amount of greenhouse gas emissions compared to other industries, which consist of 24% of total carbon emissions. Hence, it is crucial for construction industry players to consider environmental impacts.

In the construction industry, Quantity Surveyors (QS) are the main players who calculate the embodied carbon of the construction material, and manage the sector's environmental impacts (Royal Institution of Chartered Surveyors, 2012). With a European database, QS assess carbon footprint as part of standard cost planning services. For instance, they can give a client the option to select material with lower costs and smaller carbon emissions. This can enhance sustainability in the construction industry, by measuring the carbon footprint of products.

A Life Cycle Assessment (LCA) can assess a carbon footprint. Carbon footprint is the release of greenhouse gases by human activities, measured in tonnes of carbon dioxide (Ramachandra & Mahapatra, 2015). LCA identifies the environmental effects of construction material from cradle-to-grave, in a wide range of operations. It takes the process into consideration, from the extraction of raw material until the disposal of the construction product (Nyári, 2011).

Digital construction provides opportunities to assess carbon footprint, in each building element during the design stage, by superimposing multi-disciplinary information on a model (Sanguinetti et al., 2012). It digitally enhances information delivery and operational procedures in the construction industry (Singh, 2019).

Recently, the construction sector has become more concerned with designing and constructing environmentally-friendly buildings, to provide monetary savings and high performance (Jrade & Jalaei, 2013). Designers are integrating BIM with sustainability, during the conceptual stage of project design. They identify materials through selected rating systems, such as Leadership in Energy and Environmental Design (LEED) or Building Research Establishment Environmental Assessment Method (BREEAM) in Europe. However, they are unable to identify and calculate the materials' environmental impacts. Databases lack information on sustainable materials. Interoperability between BIM and LCA is also lacking.

Digital technology in the construction industry can act as a platform for QS. It allows them to calculate the carbon embodied in construction material. BIM can estimate, monitor and manage the environmental impacts of projects, via visualisation technology. It shall add value to QS practice in assessing carbon footprints. QS could use different methods to assess carbon footprints, as part of their standard cost planning.

This paper proposes a BIM-enabled LCA framework for QS, to digitally calculate the carbon emissions embodied in construction materials, using BIM as a platform. The objectives are as follows: 1) to identify the LCA methodology for QS, and 2) to map the LCA methodology in digital construction processes, using BIM.

Literature Review

Carbon Footprint

Buildings now dominate energy consumption in cities, accounting for 30% - 40% of total consumption of energy and 70% of total consumption of electricity (Pandey, 2015). Thus, the construction industry should adopt energy efficiency principles, to minimize buildings' energy consumption.

Carbon footprint commonly serves as a conceptual obligation regarding global climate change, in public debate (Wiedmann & Minx, 2008). Baldwin (2006) defines carbon footprint the total amount of emissions of greenhouse gases (GHGs) or carbon dioxide over a product's entire life cycle. It is measured as kilograms (kg) of carbon dioxide equivalent per kilowatt hour (kWh). It thereby accounts for various impacts of global warming of other greenhouse gases (GHGs). GHGs are the gases trapping heat inside the atmosphere. There are six common GHGs: carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4), sulphur hexafluoride (SF6), hydrofluorocarbon (HFC) and perfluorocarbon (PFC). The unit of carbon footprint is carbon dioxide equivalent (CO2e). It is the amount of all GHG emissions, converted to carbon dioxide (Neitzert, Olsen, & Collas, 1999).

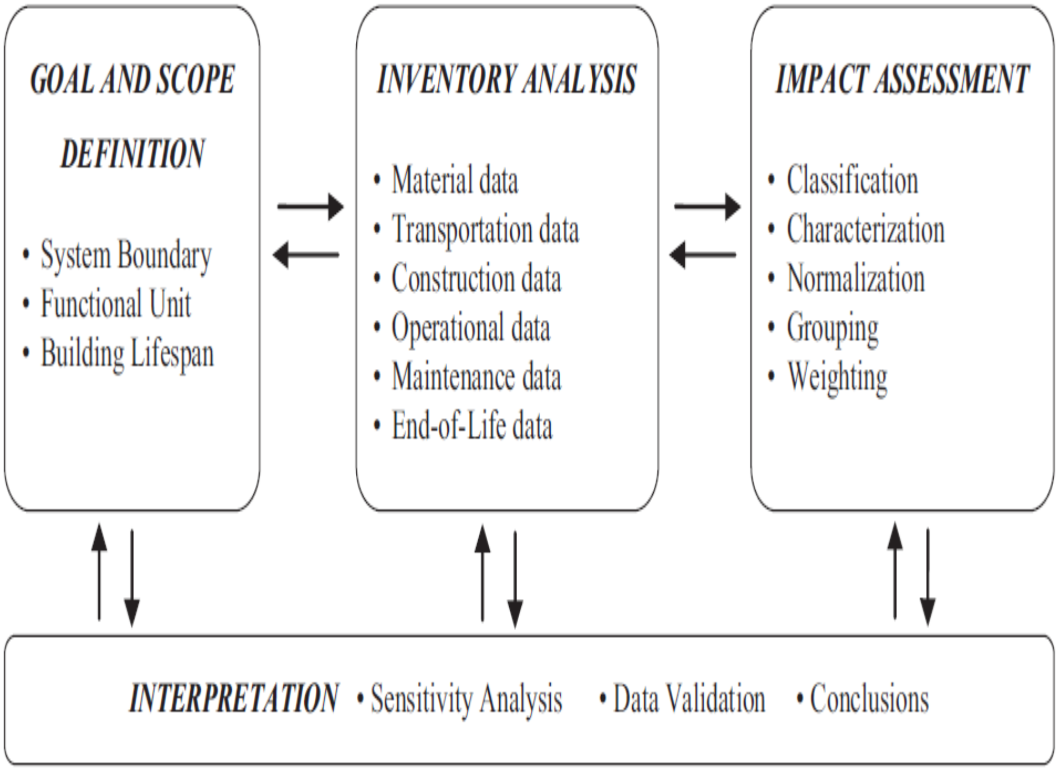
Carbon footprint measures the impact of relative GHGs towards global warming, or the 'global warming potential' (Stocker TF, Qin D, Plattner GK et al, 2013). For instance, the global warming potential of N2O is 265. This means that one kilogram of N2O has a climate change impact similar to 265 kilograms of CO2. Hence, one kilogram of N2O is equal to 265 kilogram of CO2 equivalent (Royal Institution of Chartered Surveyors, 2012).

Life Cycle Assessment (LCA)

LCA measures the environment impact of construction materials throughout their product life cycle (Khasreen, Banfill, & Menzies, 2009). It assesses the carbon embodied in a product. LCA identifies the environmental effects of a construction product from cradle-to-grave, for a potentially wide range of operations. It shall consider the process, starting from the extraction of raw material until the disposal of the construction material (Nyári, 2011). LCA has been widely used, because of it integrates different aspects of its framework with the quality of data and impact assessment (Klöpffer, 2006).

The standard ISO14040:2006 defines the methodology of LCA. It comprises four interrelated phases, each affects the other. The four main phases in LCA methodology are goal and scope definition, inventory analysis, impact assessment and lastly interpretation phase (Figure 1).

Figure 1. LCA Methodology (ISO14040:2006)



The goal and scope definition phase identifies the scope and determines the goals of the LCA study, consistently with project requirements. The scope of the LCA study may from time to time be refined, due to its iterative nature. It is a critical step. It will affect the outcome of the study. It shall take into consideration the system boundaries of the LCA study; either from cradle-to-site, cradle-to-gate or cradle-to-grave (Royal Institution of Chartered Surveyors 2012). Yet, cradle-to-grave is used in most cases. It ranges from raw material extraction to the end of the construction material's life cycle. The life cycle of a product is interconnected, and it is impossible to isolate it into single phases. In addition, the functional units of the LCA study of a building shall measure the performance characteristics of the selected material, to ensure comparability. An example is the number of occupants in a building or 1 m^2 of gross floor area (GFA). The purpose is to give a reference and guidance on the inputs and outputs of the product. That is essential for ensuring comparability of the LCA results. Furthermore, the building lifespan is consideration. It has the greatest impact on the outcomes of the LCA, particularly on the total energy consumption during operation.

Inventory analysis comprises the collection and calculation of data, to measure the related inputs and outputs of building materials. The data for every single unit process is collected within its system boundary and classified into raw material and energy requirements, solid wastes, waterborne and atmospheric emissions, and other environmental aspects

(ISO14040:2006). The collected data is then verified and assigned to selected functional units and unit processes. The energy flows of a product will be calculated in accordance with the electricity sources and fossil fuels used, conversion efficiency and energy flow distribution (Curran, 2015). The life cycle inventory has four main phases; pre-use, construction, operation and end of life (Iyer-Raniga & Wong, 2012).

During inventory analysis, it is crucial to identify the type of construction materials and their quantity. The average transportation distances, from the factories to the site, depend on communication between the contractor and the designer (Blengini & Di Carlo, 2010). The transportation data can also be obtained by identifying the distance between manufacturer and site (Ortiz-Rodríguez, Castells, & Sonnemann, 2010). The construction phase lowers impacts on the environment (Blengini & Di Carlo, 2010). Thus, the database for construction may be neglected; only waste generated during the construction phase is considered (Ortiz-Rodríguez et al., 2010). Wastage shall be allowed when the estimated quantities are obtained from the BQ or drawing. Wastage is deemed to be about 5%, through the mishandling of materials, vulnerability of materials and unusable residuals due to poor installation (Rossi, Marique, Glaumann, & Reiter, 2012). Apart from that, the operation phase requires data on operation energy and building maintenance. Energy in a building is consumed mainly by electricity and natural gas. Energy simulation software can estimate it. Energy consumption depends on lighting and electric appliances, as well as the Heating, Ventilation and Cooling (HVAC) System. The maintenance database shall also include activities such as painting, changing of windows and also replacement of roof coverings (Ortiz-Rodríguez et al., 2010). Replacement intervals were referred to the National Association of Home Builders (NAHB) due to data limitations in Malaysia (Iyer-Raniga & Wong, 2012). Lastly, the end-of-life (EOL) phase involves recycling building materials, which in fact reduces the embodied energy (Blengini & Di Carlo, 2010). In Malaysia, aluminium and steel are recycled. Hence, only these two offer raw materials to reduce environmental impacts. It is better for this phase to include the valuation of energy consumption by machinery during demolition, and also average transportation distances from the site to landfill or a recycling centre.

During the impact assessment, the potential environment impacts of a product are evaluated using outputs from the inventory. Selection of the impact assessment method, and the categories of impacts, shall accord with the goal and scope definition (Goedkoop, de Schryver, Oele, Durksz, & De Roest, 2010). It definition comprises impact assessment including classification, and characterisation, normalisation, and weighting. First; the classification of impacts. The impact categories are represented by a number of groups which consist of the inputs and outputs from the product's life cycle. However, a universally accepted official list of environment impacts, to be referred and evaluated, is lacking (Ortiz-Rodríguez et al., 2010). The characterisation of impacts involves evaluating the relative strength of unwanted emissions, and measuring its contributions toward the environmental impact. It can be compared with different materials which contribute the same environmental impacts. The normalisation of impacts is used where emissions consist of different units and cannot be compared, so the impact categories are compared instead. The weighting provides a single score of a product's environmental profile (ISO14040:2006). Finally, in the interpretation stage, the results of impact assessment are analysed for sensitivity and robustness to inputs (Ortiz-Rodríguez et al., 2010). The conclusion is then made in meeting the LCA targets and objectives.

Building Information Modelling (BIM)

BIM utilizes 3D models with additional intelligence. BIM has become a platform to improve the capacity of project teams, to monitor and coordinate design and construction works, and to manage building operations. It plays a major role in enhancing the environmental impacts assessment, energy and life cycle of a product (Yung & Wang, 2014). BIM has created a knowledge resource for building information which can be shared among construction players. It also acts as a platform for decision-making over the entire life cycle of a project. BIM relates to five dimensions as follows:

3D Geographical information
4D Work schedule information
5D Cost information
6D Lifecycle information
7D Facilities management-related information

BIM-Enabled LCA

BIM-enabled LCA focuses on the carbon footprint of construction material. BIM can solve problems regarding the automation of the assessment on building sustainability or 6D BIM. During early design stages BIM can produce quantities, such as the total area or volume of a building. These quantities are necessary for the cost estimation. Moreover, it is easier to extract every building element from a 3D model that is comprehensive. It serves as a basis for more accurate cost estimates (Raphael & Priyanka, 2014).

BIM is able to deal efficiently with design changes by coordinating them. As well, it maintains its consistency when changes occur. A change in one drawing by an architect will be updated and represented in all other drawings. This allow QS to identify and easily detect the changes made, and to update quantities automatically (Raphael & Priyanka, 2014).

In the work of Yung & Wang (2014), Step 1 requires incorporating 3D models and 4D schedule information, by scripting between planning activities and their unique object ID.

The 4D assessment should also include the method statement (method of construction) and derive the preliminary items. Subsequently, the calculation of the quantities must be conducted in Step 2. Figure 2 shows the calculation of the carbon footprint of material. Next, it deals with social and environmental impacts. After deriving the quantities of building elements in Step 2, it is possible to produce the environmental impacts embodied in construction materials. Figure 3 summarizes these steps.

Methodology

This study started with the identification of LCA methodology based on ISO14040:2006, and analysis of 6D BIM. Secondary data derived from Google Scholar and a university database were also reviewed. The resources included electronic books, journal articles, and conference proceedings. The search keywords include carbon footprint calculation, LCA, BIM, and 6D analysis.

Later, mapping integrated LCA using BIM workflow. That resulted in the development of a preliminary BIM-enabled LCA framework. Mapping relates every idea to other ideas through note-taking. It is known as a graphic representation of the matter and framework details. Mapping is a key strategy for describing concepts, ideas or arguments from a literature review. It is the established approach for externalizing knowledge and thinking processes.

To validate the framework, this research conducted expert interviews. This gained in-depth and technical information on the proposed BIM-enabled LCA framework. The proposed framework is new. Hence the expert interviews offer a suitable exploratory method that allows fast access to unfamiliar fields (Bogner, Littig & Menz, 2009). In the beginning of interviews, experts were presented with the preliminary BIM-enabled LCA framework, and the discussion focused on the accurate workflow, practicality and applicability of the framework (Appendix A). Snowball sampling identified the respondents due to inadequacy of targeted population – they were BIM Managers or QS knowledgeable in either BIM or LCA, or both. Five respondents were involved. They were labelled numerically for easy identification. Table 1 shows their profile. All of their detailed particulars are concealed, to comply with the university code of research ethics and in conformation with the respondents' request.

A thematic analysis reviews the qualitative data, by identifying patterns in the data. Patterns are pinpointed through familiarization of data, coding, development of themes and revision. It is the fundamental stage of interpretation. This analysis follows Braun & Clarke (2006):

- Understanding and becoming familiar with the collected data;
- Generating codes;

- Exploring for themes;
- Evaluating the themes;
- Specifying and name themes; and
- Reporting the analysis.

Result and Discussion

BIM Workflow

The respondents evaluated the workflow of BIM data acquisition for each BIM dimension in the framework which is 3D, 4D, 5D, 6D, and 7D. Four respondents commented on the aspect of 3D BIM. Respondent 2 (R002) expressed that the Technical Material Sheet (TMS) is required to be inserted into the 3D BIM model, and that not only geographical information needs to be inputted. On the other hand, R001, R003 and R004 highlighted that the design information should be incorporated into the 3D BIM model, and not only gathering information from construction, operation and maintenance, but also space information. R004 as well commented that planning and procurement information should be incorporated into the 3D BIM model. In addition, R001 commented on both 4D and 5D BIM. As to 4D BIM, R001 mentioned that work performance needs to be inserted into it. Apart from that, R001 mentioned that after retrieving information from design, a drawing can be produced which is then incorporated into 5D BIM for development cost information.

Figure 2. Method of Carbon Footprint of Material Calculation (Papakosta & Sturgis, 2017)

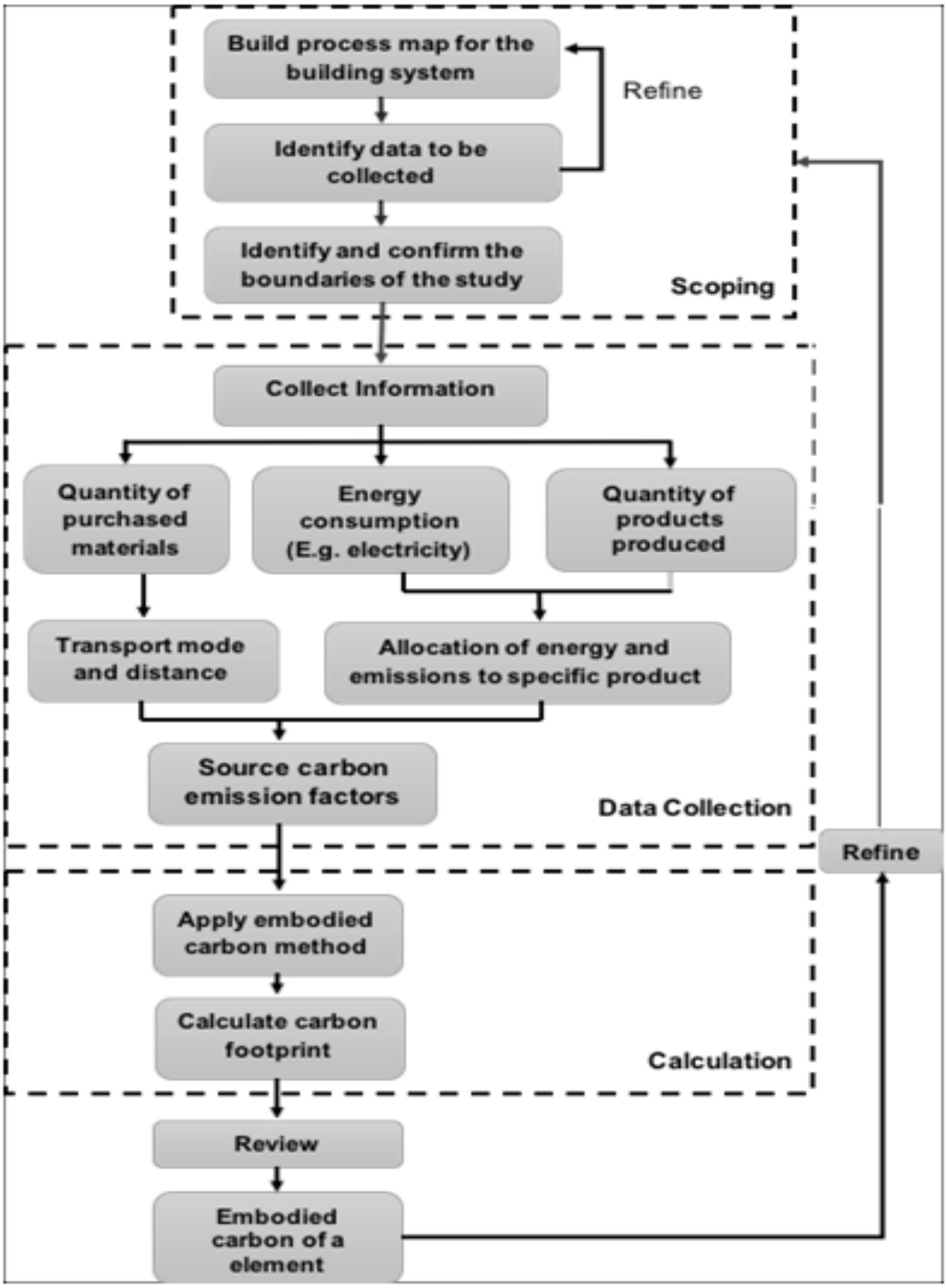


Figure 3. 6D BIM Development (Yung & Wang, 2014)

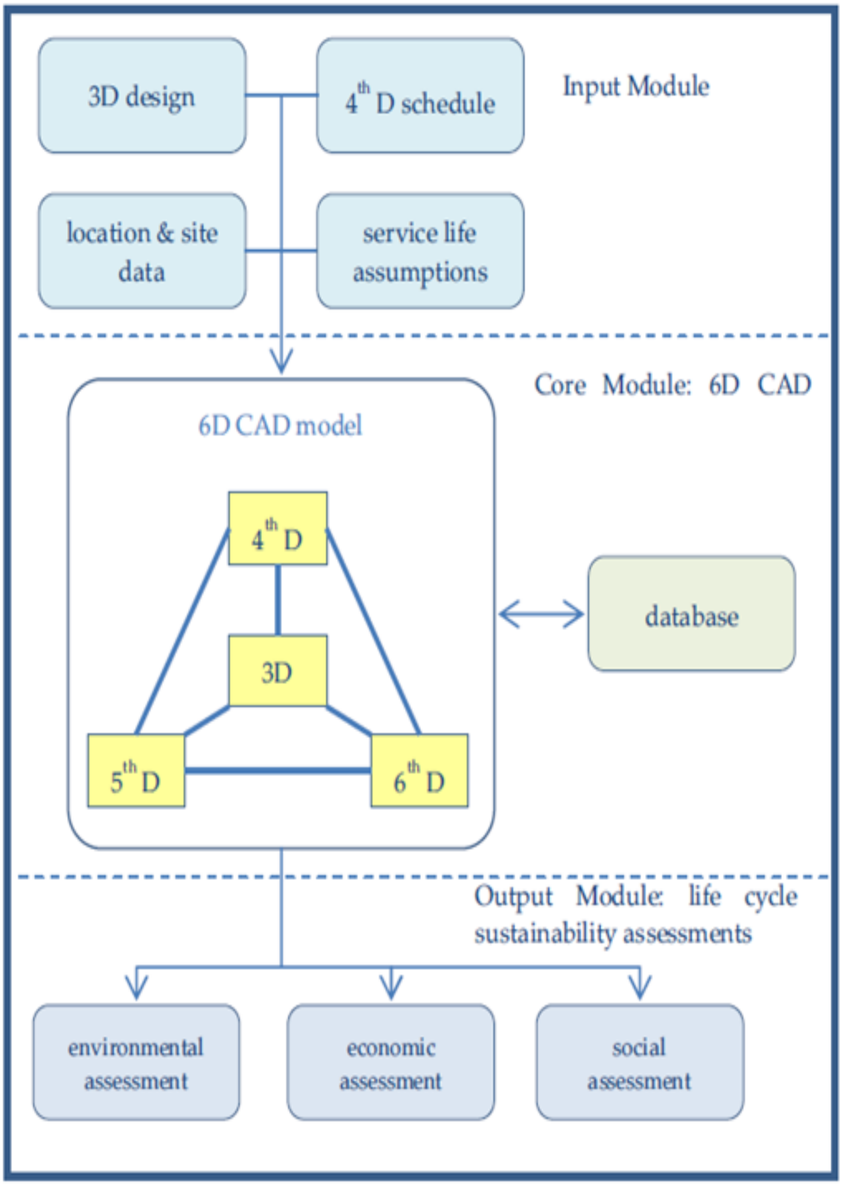


Table 1: Respondent Profiles

Code	Age	Designation	Year of Experience Industry	Year of Experience and Type of BIM Projects Involvement
R001	39	R&D Manager	12 years	5 years • Commercial
R002	46	Managing Director	25 years	10 years • Residential • Commercial • Institutional
R003	45	Head of BIM Unit	20 years	10 years • Residential • Transportation • Institutional
R004	40	Senior Quantity Surveyor	16 years	8 years • Residential • Transportation • Institutional
R005	32	Assistant Manager	10 years	5 years • Commercial

That view is supported by R003 and R004. R004 also highlighted how floor area and work programs, from planning and procurement information, can then be incorporated into 5D BIM. For the 6D BIM model, three out of five respondents pointed out that sustainability information should cover environmental, economic and social impacts. R002 mentioned environmental impacts while R001 commented on economic impacts. R003 emphasized social impacts.

LCA Parameters and Workflow

In this section, the respondents evaluated the LCA process based on the QS workflow. Based on the comments by R001 and R002, the assessment parameter incorporated the green building rating system into the framework. R001 and R002 highlighted the LCA employed in the QS's practice, when evaluating the trade-offs between embodied energy and predicted operational energy consumption in the project. As well, R001 commented that the certification criteria could be identified in the goal and scope definition, to confirm the boundaries of the study. On the other hand, R002 emphasized how QS should collect information in the inventory analysis, by introducing a new documentation of the product's embodied impact into TMS, to identify the carbon emission source. R002 commented on impact assessment and interpretation by using TMS throughout the building life cycle, to review all the information. R002 further opined that TMS shall identify the tool necessary for each parameter in the LCA. He mentioned that it should be integrated with the carbon footprint calculator in the framework.

Interoperability and Software

The respondents evaluated the potential interoperability of the workflow. R001 highlighted a standard Industry Foundation Classes (IFC) format or XER File to support interoperability. Another two respondents (R002, R003) emphasized the database; an inventory is crucial to ensure the LCA covers as much materials involved in a project. The synchronization of the database must be in place to support the LCA using BIM. The proper interlinking among the various software and its inventory is crucial for further analysis and interpretation of data.

R002 and R003 emphasized the database in the proposed software. Both agreed that synchronization of the database is essential in supporting the framework for QS to calculate the carbon embodied in the material. The quantity take-off from the drawing is linked to the database or inventory, such as the carbon emission factor, to develop a 6D BIM model. It ensures the project's feasibility, low carbon emissions and a lower cost of construction. This will inhibit decision-making in the product selection. For instance, if the design data is not synchronized with the embodied carbon data, the carbon footprint calculation will be different. It depends on the quantity of material purchased and the product manufactured. Thus, the carbon embodied in material varies with quantity. In fact, data synchronization can overcome problems, by constantly updating information to a server in the 'cloud'. This enables users to see any changes directly.

Applicability towards Quantity Surveyor Practice

In this section, respondents are asked to evaluate the framework's applicability in supporting the QS' practice. R004 mentioned the information required to calculate the carbon embodied in the material. It shall consider not only the embodied impacts, to conduct LCA, but also the operational and maintenance impacts, as well as end-of-life impacts. This view is supported by R005, where the operational and maintenance stage should cover the energy used for cleaning and the product's service life. For end-of-life it covers the energy use and carbon emissions, for processing and disposal of the product. Both R004 and R005 suggested that the building components or elements be considered in the framework, in accordance with the Elemental Cost Analysis (ECA). Its elements can be the basis QS conducting the framework.

R004 and R005 agreed that, based on the parameters of the preliminary framework, the BIM-enabled LCA has a high potential for QS, as QS measure quantities and do quantity take-off. This view was well-supported by R005, where QS are involved preparing BQ. QS are also expert in identifying which building elements are crucial for assessment. Looking at the proposed framework, there is a consensus among all respondents that BIM-enabled LCA has a high potential for easing the new role into QS practice, in context of evaluating the embodied carbon and operating energy of the project. QS will then be able to advise the client in product selection for sustainable construction material, with lower costs.

All respondents also highlighted the current lack of awareness among QS about embodied carbon, environment impacts, and sustainability. This allegation, however, should be further verified by other research.

The Development of a BIM-Enabled LCA Framework

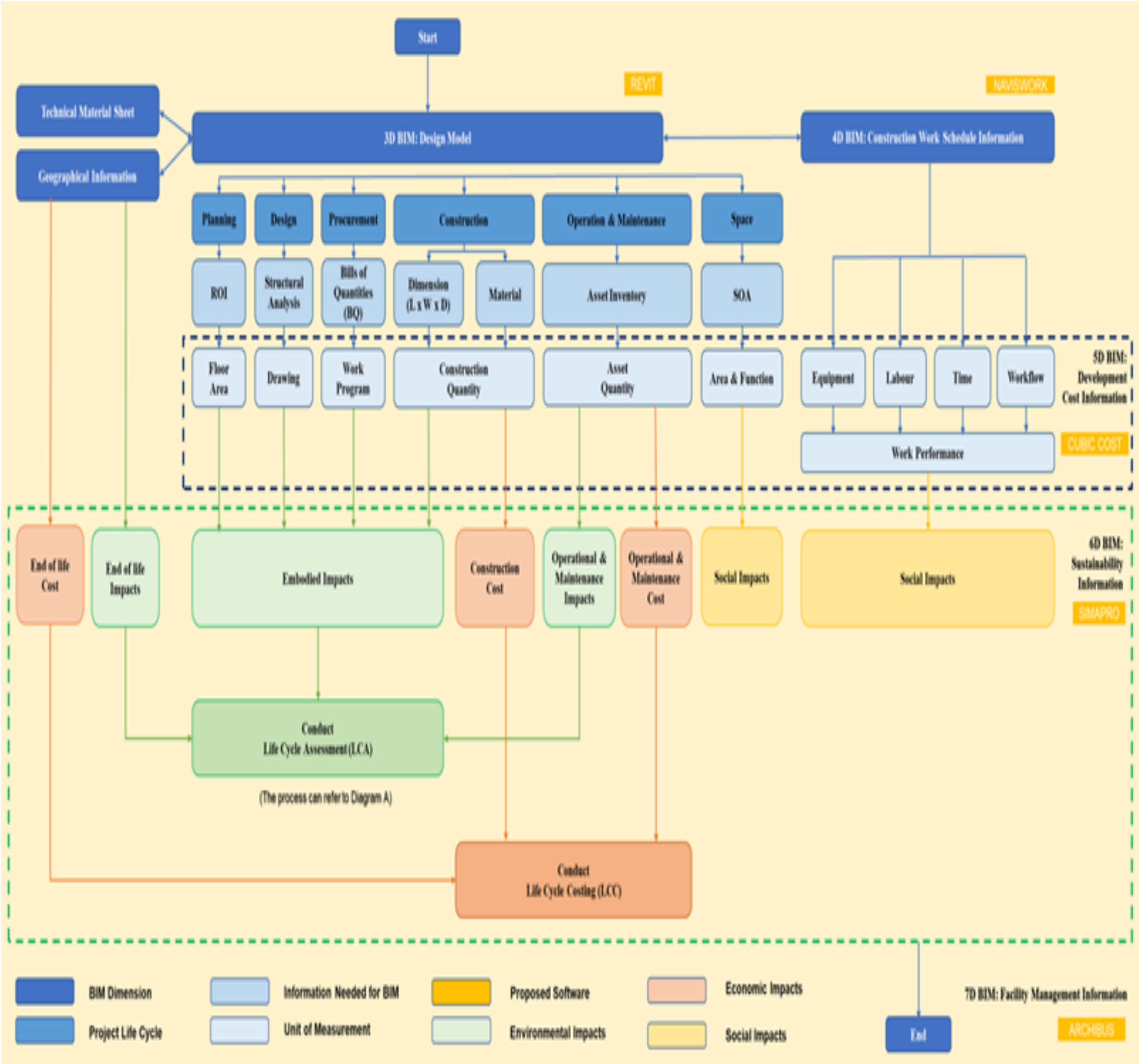
The respondents also evaluated the framework graphical presentation. Table 2 shows the framework elements amended by the respondents, while the other presentation elements were retained as there was no feedback.

Table 2: Amendments to the Proposed Preliminary Framework

Framework Element	**Preliminary Framework**	**Finalized Framework**
BIM Workflow	3D BIM: Construction, Operation & Maintenance, Space Information 4D BIM: Equipment, Labour, Time and Workflow Information 5D BIM: Construction and Asset Quantity Information 6D BIM: Environmental Impact Information 7D BIM: Facilities Management information	3D BIM: Technical Material Sheet (TMS), Planning, Design, Procurement, Construction, Operation & Maintenance, Space Information 4D BIM: Group them under Work Performance 5D BIM: Floor area, drawing, work program, construction and asset quantity. 6D BIM: Environmental, Economic and Social Impact 7D BIM: Facilities Management information
LCA Parameters	Goal & scope definition, inventory analysis, impact assessment and interpretation.	Incorporate with green rating assessment system certification criteria and carbon footprint calculator.
Proposed Software	3D: Revit 4D: Primavera 5D: Cubic cost 6D: SimaPro	3D: Revit 4D: Navisworks 5D: Cubic cost 6D: SimaPro 7D: Archibus
Carbon calculation	Embodied impact	Embodied impact, operation and maintenance impact and end-of-life impact

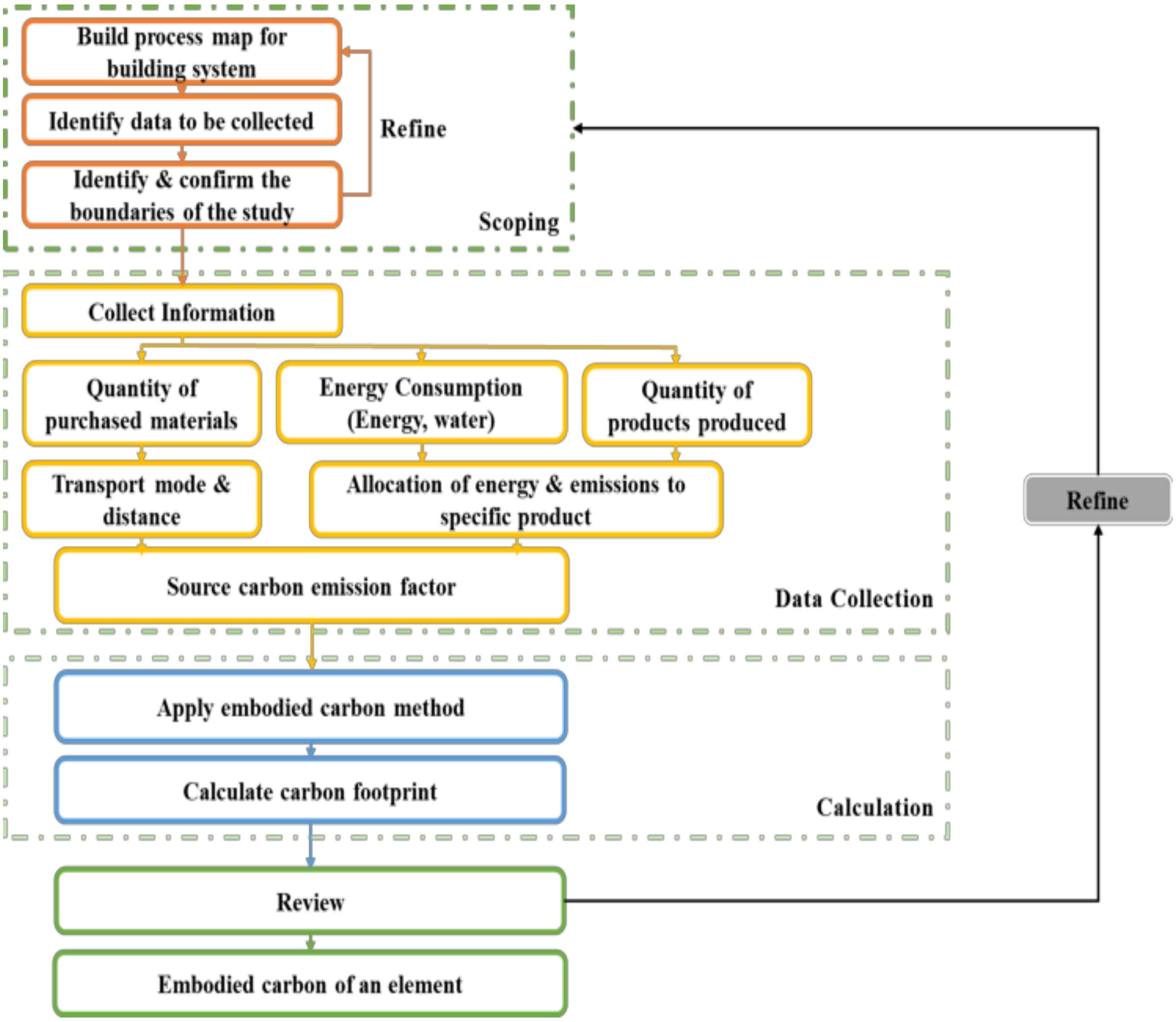
International Journal of Innovation, Creativity and Change. www.ijicc.net
Volume 10, Issue 7, 2019

Figure 4. The BIM-Enabled LCA



The finalized BIM-enabled LCA framework is as Figure 4 and Figure 5. It was developed based on ISO 14040:2006 and Royal Institution of Chartered Surveyors (RICS) professional standards and guidance as to whole life carbon assessment, for built environments, to develop an LCA framework with a proper input and understanding. The LCA framework was then mapped onto the digital construction process using BIM as a platform.

Figure 5. Diagram A (Method of Calculating Carbon Footprint)



The integration of BIM into LCA has great potential to compute carbon footprints over its project life cycle. It aids QS in determining the environmental impact of building materials when selecting them. The finalized framework is based on analysis and comprehensive discussion, as well as inputs obtained through both preliminary research and structured interviews. However, this model is yet to be validated and further research is highly recommended.

Conclusion

This study concludes that the BIM-enabled LCA framework has the capability to support BIM workflow, and that it could provide opportunity and competitive advantage for QS to further extend their role in the construction industry. With extensive information acquired from the BIM model, it will aid QS in evaluating trade-offs between embodied carbon and energy consumption in projects. The development of such information offers the autoretrieval of necessary information, such as the assemblies and specification for each building component, regarding materials purchased and products produced. It will then be used to calculate the energy use, embodied and in-use carbon of the materials. On the other hand, in terms of QS' assessment parameters, the experts highlighted that the certification criteria and rating tool could be incorporated in the framework, to enhance the QS' practice in embodied carbon calculation. It could be identified in the goal and scope definition to confirm the boundaries of the study. QS are then able to identify whether the products constructed accord with local authorities' requirements. Hence, with the development of BIM into the LCA framework, it aids QS in determining the environmental impact of building materials among different choices. Thus, fewer uncertainties occur during assessment. The client will then be more able to conveniently select more sustainable construction material with lower cost in the future, after consulting QS.

However, it is worth highlighting that, in terms of readiness, there are certain industry limitations in imposing LCA for construction projects. In calculating LCA, the Environmental Product Declaration (EPD) is crucial when quantifying the carbon footprint. Unfortunately, an EPD database does not exist in many countries such as Malaysia and other parts of Asia. That impedes the production of reliable LCA results. EPD is verified and registered documents communicate transparent and comparable information about the life cycle environmental impact of products. This is essential to advancing the adoption of LCA and BIM integration, to ensure accuracy and standardization. This proposed BIM-enabled LCA framework guide QS in assessing carbon footprint, as part of their standard cost planning service, not just for this region, but globally.

Acknowledgment

This research is supported by Knowledge Transfer Program (Grant No: MRUN2019-2B). We thank our university partner, Assistant Professor Dr Aniza Abu Bakar from the Islamic International University of Malaysia who provided insight that greatly assisted the research.

REFERENCES

Baldwin, S. (2006). Carbon footprint of electricity generation. *London: Parliamentary Office of Science and Technology*, *268*.

Bogner, A., Littig, B., & Menz, W. (2009). Introduction: Expert interviews—An introduction to a new methodological debate. In Interviewing experts (pp. 1-13). Palgrave Macmillan, London.

Blengini, G. A., & Di Carlo, T. (2010). The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energy and buildings, 42(6), 869-880.

BP Energy Economics (2019), BP Statistical Review of World Energy 2019, 68th Edition, BP:United Kingdom.

Curran, M. A. (2015). Life cycle assessment student handbook: John Wiley & Sons.

Goedkoop, M., de Schryver, A., Oele, M., Durksz, S., & De Roest, D. (2010). Introduction to LCA With SimaPro 7. Report Version 4.4.

ISO14040 (2006). Environmental Management: Life Cycle Assessment; Principles and Framework: ISO.

Iyer-Raniga, U., & Wong, J. P. C. (2012). Evaluation of whole life cycle assessment for heritage buildings in Australia. Building and Environment, 47, 138-149.

Jrade, A., & Jalaei, F. (2013, December). Integrating building information modelling with sustainability to design building projects at the conceptual stage. In Building Simulation (Vol. 6, No. 4, pp. 429-444). Springer Berlin Heidelberg.

Khasreen, M., Banfill, P. F., & Menzies, G. (2009). Life-cycle assessment and the environmental impact of buildings: a review. Sustainability, 1(3), 674-701.

Klöpffer, W. (2006). The role of SETAC in the development of LCA. The International Journal of Life Cycle Assessment, 11(1), 116-122.

Ministry of Finance (2018), Economic Outlook 2019, Ministry of Finance Malaysia, Putrajaya.

Stocker TF, Qin D, Plattner GK et al (2013) Climate change 2013: the physical science basis, Contribution of Working Group I to the Fifth Assessment Report of the

Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK

Neitzert, F., Olsen, K., & Collas, P. (1999). Canada's Greenhouse Gas Inventory: 1997 Emissions and Removals with Trends. Ottawa, ON: Environment Canada.

Nyári, J. (2011). Carbon footprint of construction products: a comparison of application of individual Environmental Product Declarations and Building Information Modeling software, Metropolia University of Applied Sciences: Finland.

Ortiz-Rodríguez, O., Castells, F., & Sonnemann, G. (2010). Life cycle assessment of two dwellings: One in Spain, a developed country, and one in Colombia, a country under development. Science of the Total Environment, 408(12), 2435-2443.

Pandey, S. (2015). Impact of Green Building Rating Systems on the Sustainability and Efficacy of Green Buildings: Case Analysis of Green Building Index, Malaysia. MIT-UTM Malaysia Sustainable Cities Program, 2014−2015, 1-25.

Papakosta, A., & Sturgis, S. (2017). RICS Professional Statement: Whole Life Carbon Assessment for the Built Environment.

Ramachandra, T. V., & Mahapatra, D. M. (2015). The Science of Carbon footprint assessment. In S. S. Kannan (Ed.), The Carbon Footprint Handbook (pp. 3-45). New York: CRC Press.

Raphael, V., & Priyanka, J. (2014). Role of building information modelling (BIM) in quantity surveying practice. International Journal of Civil Engineering and Technology, 5(12), 194-200.

Rashidi, M. N., Begum, R. A., Mokhtar, M. B., & Pereira, J. J. (2014). Physical Development Framework for Climate Change Adaptation in Malaysian Construction Industry-Current Scenario and Way to Improve. Current World Environment, 9(3), 552.

Caytas, J. (2018). The COP21 Negotiations: One Step Forward, Two Steps Back. Consilience: The Journal of Sustainable Development, 19(1), 1-16.

Rossi, B., Marique, A.-F., Glaumann, M., & Reiter, S. (2012). Life-cycle assessment of residential buildings in three different European locations, basic tool. Building and Environment, 51, 395-401.

Royal Institution of Chartered Surveyors. (2012). RICS Methodology to calculate the embodied carbon of materials – RICS QS & Construction Standards, RICS: Coventry.

Sanguinetti, P., Abdelmohsen, S., Lee, J., Lee, J., Sheward, H., & Eastman, C. (2012). General system architecture for BIM: An integrated approach for design and analysis. Advanced Engineering Informatics, 26(2), 317-333.

Shahid, S., Pour, S. H., Wang, X., Shourav, S. A., Minhans, A., & Ismail, T. b. (2017). Impacts and adaptation to climate change in Malaysian real estate. International Journal of Climate Change Strategies Management, 9(1), 87-103.

Singh, V. (2019). Digitalization, BIM ecosystem, and the future of built environment: How widely are we exploring the different possibilities?, Engineering, Construction and Architectural Management.

United Nations. (2018). The Sustainability Development Goal Report 2018, retrieved from https://sustainabledevelopment.un.org/sdg13

Wiedmann, T., & Minx, J. (2008). A definition of ‘carbon footprint’. Ecological economics Research Trends, 1, 1-11.

Yung, P., & Wang, X. (2014). A 6D CAD model for the automatic assessment of building sustainability. International Journal of Advanced Robotic Systems, 11(8), 131.

Appendix A

Section 1: The capability of the framework

1.1 How well the BIM-Enabled LCA framework in supporting the quantity surveyors' practice?

1.2 How reliable the assessment parameter to be done by quantity surveyor employed in the framework?

1.3 How well the framework reflect the real situation in evaluating the trade-offs between embodied energy and predicted operational energy consumption in the construction projects?

1.4 How useful was the proposed software being employed in the framework?

Section 2: The applicability of the framework

2.1 How relevant the framework in evaluating the embodied carbon and operating energy in the construction project for the quantity surveyor?

2.2 How appropriate was the assessment parameter to be done by the quantity surveyor employed in the framework?

2.3 How appropriate was the framework to act as an new quantity surveyors' practices in evaluating the embodied carbon and operating energy in the construction project?

2.4 How relevant was the framework in term of flexibility?

AUTHORS PROFILE

Nurshuhada Zainon holds the Bachelor of Quantity Surveying from UM, and was awarded the Royal Education Award UM in 2005. She subsequently attained her Master of Science in Construction Economics and Management from University College London in the year 2009. She read her Doctoral degree in Construction IT Management from UM and is now persuading her research interest in Building Information Modeling (BIM) and construction economics, linking them to the knowledge of sustainable living of the Earth communities. Being a Registered Provisional Quantity Surveyor, she has extensive knowledge and experience across various industries, covering every type of building and infrastructure project, the construction processes and associated costs. Dr Nurshuhada has been active in community-based project. In research, she won the Institute of Surveyors Malaysia (ISM) 50th Anniversary Publication Best Paper Award (QS Division) in 2016. She has been working with a research partner from United Kingdom for Newton Fund Institutional Linked grant since 2014, and won Silver Award for Invention, Innovation, & Design Exposition (IIDEX 2016) for this research project.

Goh Weh Lun earned his Bachelor in Quantity Surveying from UM in 2019. He is currently a Quantity Surveyor working in Malaysian construction industry. During his degree, he has done research in Life Cycle Assessment using BIM.

Noor Suzaini Mohamed Zaid is currently teaching at the Department of Building Surveying in Faculty of Built Environment, University of Malaya. Suzaini holds a PhD degree in Planning and Urban Development from the Faculty of the Built Environment, University of New South Wales. She has teaching experience in the fields of building surveying, urban planning, and sustainable development. Her current research interest focuses on Investigating Social Psychology Factors for User Behaviour Change Towards Energy Efficiency and Conservation, zero-carbon development, climate change mitigation and adaptation in built environment. Past research project includes United Nations Environment Programme's Sustainable Building and Climate Initiative (UNEP-SBCI)'s Common Carbon Metric and Protocol tool Pilot Testing in Malaysia, SULED-BIM: Sustainability Led Design Through Building Information Modelling with University of Manchester under the 2015 UK Newton Fund, and Carbon Abatement Module for University of Malaya Eco-campus. Other projects she is involved in are within areas of housing and affordability, acoustic properties of residential buildings, and building control.

Nik Elyna Myeda is currently a researcher and senior lecturer at the Department of Building Surveying, Faculty of Built Environment. She also holds the position of postgraduate programme coordinator for Master in Asset and Facility Management). Elyna has completed her doctoral degree in Facilities Management from University College London in 2013. Prior to that, Elyna has obtained Msc in Building in 2009, a master by research programme at University of Malaya where her thesis focused on the Performance Measurement of Office Buildings Maintenance. Elyna has also completed her first degree in Building Surveying from University of Malaya in 2005. Elyna has been leading and involved in various research projects from FRGS, UMRG, Living Lab and other consultancy services related to her field. Her research areas are Facilities Management, Building Maintenance, Performance Measurement. Elyna welcomes any future research supervision and collaboration pertaining her research areas.

Nur Mardhiyah Aziz is a Senior Lecturer at the Department of Quantity Surveying, Faculty of Built Environment, University of Malaya, Kuala Lumpur. She graduated with BSc (Housing, Building and Planning) (Quantity Surveying) (Hons.) in 2003, and received MSc Facilities Management from Universiti Tekniologi MARA in 2008. She graduated with a Phd from the University of Malaya in 2013 in the area of IT Management in Construction Industry. Since her appointment at the University of Malaya, she had been teaching various subjects such as IT in construction, Integrated Project, Research Methodology and Introduction to Construction Industry. She had published books and also journal articles in various local and international journals. Her research interests were mainly IT in construction, knowledge management and project management.