BIM-enabled Sustainability Assessment of Material Supply Decisions

Abstract

Sustainability concerns and methods to improve sustainability in the supply process of construction materials have been investigated widely over the last decade. Enhancing sustainability of the supply process of construction materials is challenging and requires accounting for a variety of environmental and social impacts on the top of the traditional, mostly economic, impacts associated with a particular decision involved in the management of the supply chain. The economic, environmental and social impacts associated with various components of a typical supply chain are highly sensitive to project specific and market specific conditions. Nevertheless, literature is slim in providing a systematic trade-off between these impacts in order to support the supply decisions. This paper proposes a novel framework for sustainability assessment of construction material supply decisions by taking advantage of the information made available by customized building information models and a number of different databases required for assessment of life cycle environmental impacts. A decision making model for supply of materials is proposed by integrating the BIM-enabled life cycle assessment (LCA) into supply chain and project constraints management. The integration is achieved through the addition of a series of attributes to typical building information models. The framework is supplemented by a multi-attribute decision making module based on technique for order preference by similarity to ideal solution (TOPSIS) to account for the trade-offs between different economic and environmental impacts associated with the supply decisions. The application of the proposed method is illustrated using a case study.

Keywords: Supply Chain Management, BIM, Life Cycle Assessment, Project Constraints

Introduction

Materials play a pivotal role in sustainable lifecycle of a building (ref). They account for up to 65% of cost in a construction project (ref) and have been considered as the most significant source of carbon footprint and energy consumption during the construction stage (ref). On the other hand, two-fifth of the world materials flow belongs to buildings (ref). The choice of materials can considerably affect the life cycle sustainability of the buildings which requires achieving a balance between economic, environmental and social impacts throughout the building's life cycle (ref). The materials used in a building can affect its up-stream impacts including the embodied energy, embodied carbon and effects on depletion of natural resources (ref). Furthermore, economic, environmental and social impacts associated with the operation phase of a building are influenced by the choice of materials. This is mainly due to the direct effects of material type and quantity on the energy use, greenhouse gas emissions, freshwater use and indoor air quality during operation phase (ref). The type and quantity of materials have been also shown to affect the viability of the end-of-life strategies, such as reuse and recycling, applicable to a building and thus the end-of-life economic, environmental and social impacts of the building (ref). In addition, material supply decisions including the location of supplier and mode of transportation may considerably affect the life cycle impacts of the material and thus the building. Local sourcing has been broadly promoted by environmental and social sustainability advocates due to its contribution to minimizing the transport emissions and promoting the local business and employment (ref). Furthermore, the life cycle impacts of the building may be also affected by technology used to produce the material. For instance, it has been debated that modularization and prefabrication may lead to cost and time savings as well as reduction in the construction waste (ref). With this in mind, incorporating sustainability principles into material selection and supply chain decision process at the project outset has been recognized in previous studies and existing green building rating schemes as an effective way to promote building's life cycle sustainability (ref). However, the focus of a majority of previous studies (ref) and green building rating schemes such as the Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), Building Environmental Performance Assessment Criteria (BRG), and Building for Environmental and Economic Sustainability (BEES) has been placed mainly on a single component of sustainability; i.e. environmental impacts of the material supply process (refs). While contributing to sustainability goals, this is far from ideal in terms of reconciling the economic, social, and environmental impacts which is required to achieve a sustainable system. A material supply decision process that accounts for overlapping effects of various supply parameters including material type, location of supplier, mode of transportation on life cycle economic, and environmental and social impacts of the building is currently lacking.

A number of multi-criteria decision making methods have been proposed in the literature to rank the available material alternatives based on various criteria (ref). However, the proposed methods have a number of drawbacks. First, the scope of such methods is principally limited to selection of the material type and other important supply chain variables such as location of supply, material's prefabrication level, and transport mode are overlooked (refs). Second, previous works rely mostly on assessment of material alternatives based on qualitative criteria which are often subjective (refs). While attempts have been made to address this issue by proposing fuzzy methods for assessment of measures' significance in selection of materials, the proposed methods do not reflect the materials' properties and quantities (ref).

To address these drawbacks, this paper suggests a novel framework for assessment of material supply decisions by considering the economic, social, and environmental impacts of decisions during the life cycle of a building. The contractual requirements of material supply defined by a comprehensive list of lifecycle measures are established as evaluation criteria for a hierarchy of decisions in supply process. The framework utilizes Building Information Modelling (BIM) as a database of project-specific information required by quantitative life cycle performance measures used in decision making. The framework also contains a computational module fed by supplier data, logistic data, and a number of available databases used in environmental impact analysis. Finally, preference ranking of decision alternatives is determined using a multi-attribute decision making module based on technique for order preference by similarity to ideal solution (TOPSIS). The application of the framework is demonstrated by a case study on involving material supply decisions for fabrication of curtain wall in a building project.

Research background

The short term approach in selection of building materials considers mainly the economic factors including acquisition costs (ref) and construction costs (ref). A longer-term perspective, however, may additionally take into account the maintenance costs (ref) and disposal costs affected by the choice of the material. Furthermore, time has always been of the essence in acquisition of material and hence, is considered as an important objective in supply chain management (ref). On the other hand, material selection process should account for technical efficacy requirements including durability (ref), fire resistance (ref), and thermal and load performance; if applicable (ref). Other recently highlighted technical criteria include quality indicators, such as maintainability (ref), constructability (ref), and aesthetic (ref). With the emergence of sustainability concerns, social and environmental aspects of material selection have been highlighted in the literature. As a result, an increasing number of measures are introduced to the field. Health and safety (ref), effect on indoor air quality (IAQ) (ref), reuse and recycle potential (ref), natural resource depletion (ref), waste minimization (ref), water use reduction (ref), reduced energy use (ref), and emission reduction are instances of decision factors in this category.

Life Cycle Analysis (LCA) has been widely recommended by international and local environmental authorities as a means of monitoring and minimizing the environmental impacts associated with materials and processes (ref). In LCA, a product undergoes a thorough analysis of the environmental impacts associated with all different stages of its lifespan including manufacturing, use, maintenance, and final disposal (ref). In other words, LCA provides a roadmap for developing a systematic evaluation of a product in order to avoid shifting the environmental problems from one place to another (ref). Nevertheless, while the results of LCA help in making informed-decisions, reliability of the results highly depends on the quality of data used in the process (ref). Depending on accessibility of data and its quality, ISO 14044 specifies three approaches toward evaluating environmental impacts of a building throughout its lifecycle which are input-output, process-based, and hybrid method (ref).

The processes involved in manufacturing a product and thus the product's associated environmental impacts may vary significantly. Materials used in a building project may not be solely supplied as bulk, and hence, LCA approach taken should appropriately meet characteristics of the materials supply structure. Depending on project strategies, materials may be prefabricated (ref). Degree of prefabrication in an item, however, relies on supply chain structure of a specific material (ref). Manufacturing sector classifies supply chains into four non-overlapping groups namely Made-To-Stock (MTS), Assembled-To-Order (ATO), Made-To-Order (MTO), and Engineered-To-Order (ETO) products (Olhager, 2003; Babu, 1999). Based on this categorization, MTS materials are typically bulk or off-the-shelf items that are readily available in abundant quantities and ATOs are products made from MTS items in standard configurations. Fabrication of MTO items is based on design drawings provided by seller and the final product is ready for installation at its factory-gate status. The response to a seller's request for production of an ETO item starts from design stage where manufacturer receives conceptual specifications for fabrication of a customized item (ref). These four categories of materials can be prioritized based on the level of prefabrication as ETO, MTO, ATO, and MTS, respectively (ref). After factory fabrication, transport of these products is an important stage that can be dissimilarly influenced by factors such as weight, size, type of materials, and its supply chain structure (ref). Transportation has been acknowledged widely as a significant contributor to life cycle impact of construction materials (ref). Besides, the decision to select supply chain category for a specific type of material also depends on analysis of information made available from design stage.

Assessment of life cycle economic, environmental and social impacts of materials requires the availability of design data and project information. The role of design context in providing reliable and quantifiable data about required materials is crucial. The available BIM tools are versatile platforms that share knowledge and information about a facility throughout its lifecycle (ref). Two areas of BIM studies that have highly achieved recognition of scholars are capabilities of BIM for lifecycle study of a facility and its potential for integration with other tools. Ding et al. (2015) highlight the motivation, the capabilities of available BIM tools, and the technical defects of BIM as statistically significant factors affecting adoption of BIM by architects in a building's life cycle study. Applications of BIM in assessing the impacts of the operation stage of a building has been identified as a challenging task requiring substantial improvements in data exchange between operation management systems and BIM software (refs). Integration of BIM with other tools and technologies has been suggested as a solution to address these deficiencies (ref). One way to ease integration is to develop add-in applications or add-in attributes in BIM which share a diverse range of lifecycle data among different applications (ref).

The BIM-assisted assessment may provide valuable input into material supply decisions in terms of effect of supply decisions on various sustainability performance measures. If a material alternative or supply decision dominates all other alternatives in all different criteria, decision making is straightforward. However, this is rarely the case and a number of non-dominated alternatives tend to usually exist where the relative performance of different alternatives may vary considerably against different criteria. In addition, depending on project and owner preferences, different criteria may have different degrees of importance which should be accounted for in a realistic material supply decision process. This necessitates the availability of a multi-attribute decision making method capable of ranking the alternatives based on their aggregated performance against different criteria. A number of reliable multi-attribute decision making methods such as TOPSIS and Analytical Hierarchy Process (AHP) are available and have been used widely in practice and academia in different fields such as bidding, material selection, structural analysis, and conflict resolution (refs). TOPSIS establishes principles of geometry in finding the best alternative which has the shortest distance from the ideal solution and the longest gap with the worst solution (ref). AHP bases its process on pairwise comparison of criteria and alternative to find the solution that best contributes to an overall goal (ref). Robustness of a combination of AHP and

TOPSIS has been widely supported in the literature in which weights of criteria and ranks of alternatives are determined by AHP and TOPSIS, respectively (refs).

The Proposed Framework

The proposed framework consists of four main components including Criteria Database, Building Information Model (BIM), Supply Chain Management System, and Decision Support System, as shown in Figure 1. The function of Crieria Database is to specify the selection criteria for assessment of the supply decisions and the importance weight associated with each criterion based on the owner and organizational preferences. Supply Chain Management system consists of a set of databases that provide historical data on materials supply and logistics performances. BIM module of the framework is used as a platform where data related to material alternatives and their associated supply chain are modelled and orginzied. The information collected from criteria database, BIM and supply chain management system is then fed into decision support system and utilized as input paramters to calculate the performance measures representing the life cycle imapcts of the alternatives. Finally, the decision support system applies TOPSIS to rank the available supply decision alternatives based on the performace measures calculated and the relative importance of the selection criteria.

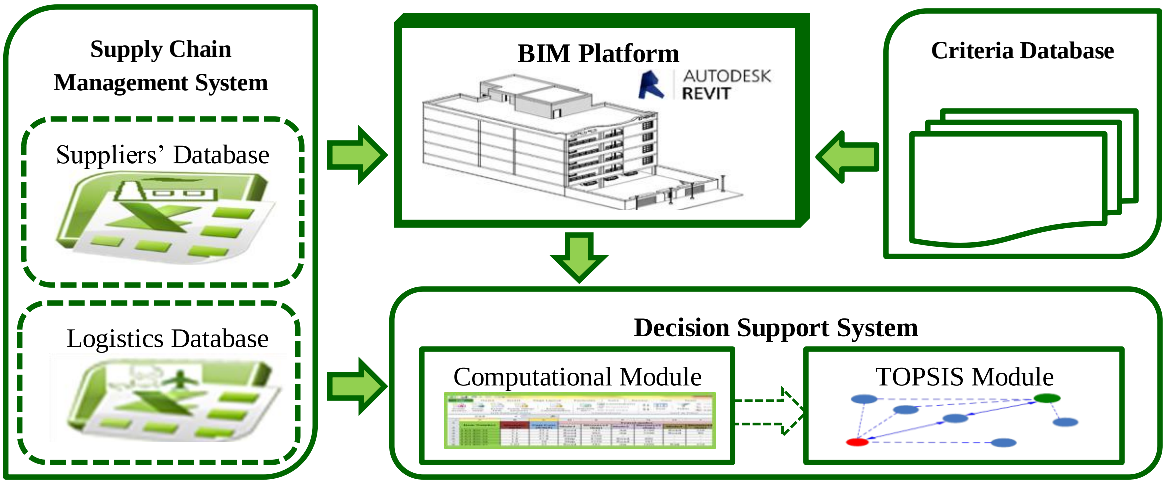


Figure 1. Components of the proposed framework for sustainability assessment of material supply decisions

The steps undertaken by the proposed framework to rank feasible supply decisions based on their economic, environmental and social impacts are shown in Figure 2. A detailed description of each step is provided in the following sections:

Selection of Assessment Criteria and Importance Weights

The Criteria Database provides decision support system with a list of selected criteria for assessment of the supply decisions as well as their corresponding importance weights. The applicable assessment criteria for a project should be selected based on the project type and its contractual and legal requirements. The assessment criteria may be generally divided into i) basic criteria defined according to the direct objectives of the project including cost, time and quality as stated in the project contracts, ii) legal criteria reflecting the legal limitations and requirements imposed by the relevant authorities and iii) sustainability criteria which evaluate mainly the socio-economic and environmental impacts of the project. For computing purposes, each criterion needs to be broken down into its constituting measures which best define the contractual requirements.

In addition, the relative importance of different criteria may vary depending on the preferences of project participants as well as strategic importance of accounting for a particular economic, environmental or social impact at the time of the assessment. Criteria Database uses a combinatorial method to calculate importance weights. First, the overall significance of each criterion is determined at executive level using a pairwise comparison approach adopted from AHP as an effective tool for comparative analysis (ref). In this approach, the opinions of project executives about comparative importance of each pair of criteria is collected using a 1-to-5 Likert scale where 1 represents equal importance and 5 represents the highest difference between significances of the two criteria being compared. Pair wise comparison of all criteria leads to a pairwise comparison matrix that is then used to calculate the criteria's priority matrix and priority vector. To ensure the consistency of the obtained priority weights, a consistency test is performed through calculating Consistency Index (CI) and Consistency Rate (CR). A CR of less than 0.1 confirms the consistency; otherwise the pairwise comparison needs to be readjusted. Further details on computations and consistency tests are given in (ref).

Apart from criteria such as cost and time in which their sub-elements are all measurable in the same units, other criteria such as quality and environmental and social sustainability may be defined using a wide range of different factors measurable in non-identical units. This requires an additional suitability assessment to select the most appropriate measures for the selected quality and environmental and social sustainability criteria. This is achieved by performing an opinion survey where experts, usually senior managers and project members with influence over material supply decisions, are asked to evaluate the suitability of each measures using a 1-to-5 scale where 1 is "least suitable" and 5 is "most suitable". The summary of opinions on suitability of measures is then computed through:

$$RI_f = \frac{\sum_{Respondents} w}{V \times N}$$

where RI_f is relative suitability of measure "f" in its corresponding criterion, "w" is scale assigned to the measure by each respondent, V is the highest scale (5 in this study), and N is number of respondents. Further, the local weight of a measure (LW_f) within its corresponding criterion is calculated through normalizing its relative suitability index (RI_f):

$$LW_f = \frac{RI_f}{\sum_f RI_f}$$

To calculate the global weight of a measure (GW_f) for use in TOPSIS, the priority weight of its corresponding criterion acquired from AHP pairwise comparison (Cr_i) is incorporated by:

$$GW_f = Cr_i \times LW_f$$

For cost and time, there exists no local weight and hence, their global weight equals the weight obtained from AHP analysis:

$$GW_{cost} = Cr_{cost}$$

$$GW_{time} = Cr_{time}$$

Defining the Required Attributes in BIM

Upon identification of assessment criteria and measures for quantifying the performance of different supply decisions against such criteria, building information model is updated to include a series of attributes required for calculation of performance measures. These attributes may belong to one of the three following families:

- An attribute that directly defines a measure and its magnitude. Such attributes are generally used to store the relevant product specifications as supplied by the vendors such as design life in years, fire resistance in minutes, etc.
- An attribute that is utilized in a combinatorial strategy for scaling a specific measure. This type of attribute may include an intangible and/or tangible aspect of a product. While a tangible aspect is predominantly based on vendor's data, an intangible property can be assessed by either vendor or other participants of a project. Product thickness in mm and its conductivity coefficient in W/m.K are examples for two tangible aspects of a product used to evaluate its thermal performance. Aesthetic is, however, an intangible aspect which may be measured by linguistic terminologies and required to be converted into numeric values.
- An attribute that is required as an input parameter in estimating the impact of a process such as emissions associated with construction of an element. Examples of this include type and duration of construction equipment used in installation, and freight characteristics.

Defining the Hierarchy of Supply Decisions

A number of decisions need to be made over course of supplying construction materials for a building project. The proposed framework accommodates a hierarchy of supply decisions which consists of four levels:

- Level 1: type of material; which lists the types of the technically feasible alternative materials for construction of a building element. Diversity of alternatives depends on the type of building element. In cases, such as load bearing elements, where the change of the material may lead to substantial changes in basic geometrical properties, BIM has to be updated to demonstrate such changes. The changes in the properties and specifications of a particular element including the changes to the added attributes discussed previously are applied automatically to respective elements in BIM after selection of a particular material type from the material library.

- Level 2: local/international supply; which lists likely local and international suppliers for the project. In addition to technical differences, source of supply may influence time, cost, and logistics variables.
- Level 3: supply chain structure; which demonstrate the prefabrication level.
- Level 4: transport mode; which is particularly important when materials are supplied internationally. This decision mainly affects the project through cost, time, and environmental consequences of the mode choice.

Life Cycle Impact Analysis

A systematic computational process is performed by decision support system using the input data extracted from BIM and various economic and environmental databases such as cost and carbon inventories and contractor's time performance database in order to assign a numeric value to performance measures for each decision alternative. The process starts by creating a list of supply decision alternatives formed from combination of possible decisions including material type and properties, level of prefabrication, location of supplier, and mode of transportation as sketched in different levels of decision hierarchy. A series of predefined formulations, if any required, are then used to evaluate the performance of each decision with regards to all the applicable assessment criteria. . Arrays of the identical measurement units, such as cost or emissions, are summed up over the whole lifecycle and a corresponding total value is reported, where applicable.

The methodology for identifying and quantifying the performance measures for a number of proposed economic, environmental and social criteria are described in the following:

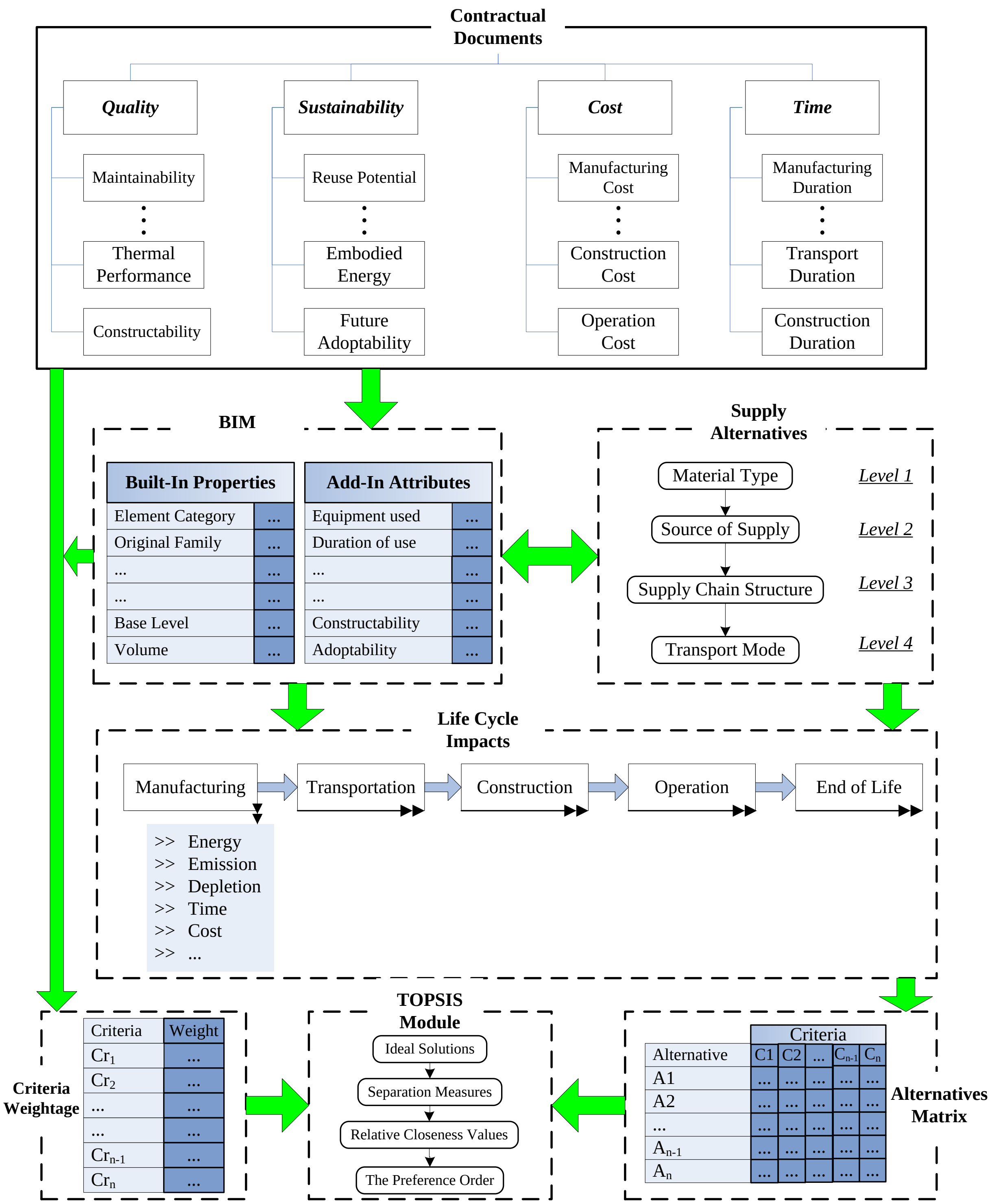


Figure 2. Steps undertaken by the proposed framework to rank supply decision alternatives according to their life cycle economic, environmental and social impacts

Cost

Cost is predominantly considered in almost all construction processes. Nonetheless, the maturity of a cost-based decision making process can be improved by adopting a life-cycle perspective in the analysis, where the effects of costs reduction or increase in one or more life cycle phases on the costs associated with the other phases and thus the total life cycle costs is taken into consideration. The cost items associated with any element of a building include ordering costs, supply costs, transport costs, construction costs, operation costs, and demolition costs. The costs associated with each of these stages, except demolition, can be estimated using available cost databases and the quantity take-offs from BIM. The demolition, however, is generally reported in databases as a lump sum cost for the entire building of a given size and thus in this study, is considered to remain independent of the selected material type. Therefore, demolition costs are excluded from the calculations. In addition, while ordering, supply, transport, storage, and construction cost items are stated in their present worth, the magnitudes given for operation costs are either in their annual value or a future cost for different alternatives with dissimilar design life. In order to compare alternatives on the same par, hence, all the cost items given for each alternative are converted to their equivalent Annualized Present Value (APV). The present worth of costs associated with ordering, supply, transport, storage, and construction stages (P_s) are related to their equivalent APV_s by:

$$APV_s = \frac{P_s i(1+i)^n}{(1+i)^n - 1}$$

where i and n are interest rate and design life of the alternative, respectively. Operation costs of an alternative may consist of periodic maintenance, usually stated as a future value (F_m), annual cost of cleaning (APV_h), and saving on annual cost of energy (APV_e). Consequently, maintenance cost (F_m) is annualized as follows:

$$APV_m = \frac{F_m i}{(1+i)^n - 1}$$

Therefore, the total annualized cost associated with each alternative (AC_A) is the summation of annualized present values of different cost items:

$$AC_A = APV_m + APV_n + APV_e + \sum_{s=stages} APV_s$$

The saving on cost of operating energy is valued with reference to a base case building with a specific type of material in the contractor database. Therefore, a negative or a positive value, depending mainly on thermal performance of an alternative, is assigned to this item. The cost items are computed based on cost per each measurement unit of the building element for different alternatives. As LCA requires comparisons to be based on "equivalent use" (ref), "equivalent use" of different types of building elements need to be identified before computations. By considering its predominant use as unit of measurement for a majority of the building elements, "one square meter area" is used in the proposed framework as default measurement unit for all the elements, unless otherwise is required.

Time

Time is a key performance indicator in a majority of construction contracts. Depending on criticality of scheduled activities, as determined by precedence relationships between activities, the time required to construct any element of a building may influence overall duration of a project. To calculate the total time required to complete installation of a building element, the framework assumes a finish-to-start relationship between material supply stages. Therefore, the total time required to complete an element (T_A) is simply summation of durations associated with each stage from its start of supply until the end of its construction phase and is computed as follows:

$T_A=T_o+T_s+T_t+T_c$

where T_o is time required to order, T_s is manufacturing (supply) time, T_t is transport time, and T_c is duration of construction. The boundary of time considered in the evaluation process is limited to the end of construction stage, as there is no further significant time-consuming step that can influence the decision making process. The historical records available on each stage of project can be used to estimate relevant durations through regression analyses. Table 1 lists the independent variables used to estimate the duration of each stage.

Table 1. Independent variables and databases used in estimation of supply times of materials

Dependent variable	**Independent variables**	**Database used**
Order time (T_o)	Material type, supply chain structure	Contractor
Manufacturing time (T_s)	Material type, supply chain structure, supplier capacity	Contractor/ Supply partner
Transport time (T_t)	Material type, weight, size, distance, mode of transport	Contractor/ Logistics partner
Construction time (T_c)	Material type, supply chain structure, crew size, construction equipment	Contractor

While estimation of order time and construction time solely rely on contractor's databases, manufacturing and transport times are computed based on contractor data and its partners' estimates. In addition to decision variables such as material type, supply chain structure, and mode of transport that are considered as independent variables in the estimations, there are some hidden factors that influence times. For instance, supplier's capacity is a factor that needs to be taken into account in estimating the duration of manufacturing/supply (ref). On the other hand, weight, size, and distance are three factors that influence transport durations (ref). Crew size and construction equipment are two important factors that control construction time (ref). In this study, such hidden factors are taken into account as "parameters" governing the decision variables rather than "decision variables" themselves.

Quality

The measures defining quality of a material alternative are summarized in Table 2. As can be seen, the quality determinants include design life, load performance, thermal performance, fire resistance, aesthetics, air infiltration, water penetration, constructability, and maintainability. The quality measures applicable to a particular project may be identified from contractual obligations defining the technical requirements of the building elements or from the relevant literature. The quality measures may have a element-specific or generic feature. For instance when selecting the material for the curtain wall of a building, air infiltration and water penetration particularly specify the quality of the wall in terms of resistance against air and water which are measured in l/s.m2 (litres of air per second passes from each square meter of a curtain wall-"Standard Number") and in minutes (number of minutes to resist against rain or water fall-"standard Number"), respectively. Design life, thermal and load performance, constructability, and maintainability, on the other hand, are examples of generic quality features. Such generic features require a new scale definition and assessment method for each type of building element. Table 2 also summarizes the factors affecting the performance measures and the corresponding measurement unit of each factor. As required by TOPSIS, in cases where a quality measure is defined by two or more factors or in non-numeric (linguistic) terms, an aggregate numeric performance measure should be calculated using the assessment strategy proposed in Table 2.

Table 2. The proposed measures for quality as well as environmental and social sustainability of a material alongside their proposed assessment methodology

Criteria	Measure	Contributing Factor(s)	Measurement unit	Assessment strategy applied
Quality	Design Life	-	Years	-
	Load performance	Wind load resistance	kPa	Combinatorial scale definition based on two factors
		Thermal movement	Inches/10ft @ 80ºF	
	Thermal Performance	Conductivity	W/m.K	(Conductivity*thickness/1000)
		Thickness	mm	
	Fire resistance	-	Minutes	-
	Aesthetic	-	Likert scale (1 to 5)	1=Extremely eye-catching 2=Very eye-catching 3= Moderately eye-catching 4=Slightly eye-catching 5=Ordinary
	Air infiltration	-	L/s.m^2	-
	Water penetration	-	Minutes	-
	Constructability	-	Likert scale (1 to 5)	1=Very hard to construct 2=Hard to construct 3=Fair to construct 4=Easy to construct 5=Very easy to construct
	Maintainability	-	Likert scale (1 to 5)	1=Nearly no component of the alternative is maintainable 2=A few components of the element are maintainable 3=Half of the components are maintainable 4=Many components of the alternative are maintainable 5=Almost all components of the alternative are maintainable
Environmental and social sustainability	Embodied energy	Cradle to Gate	MJ/m^2	-
		Transportation	MJ/m^2	-
		Construction	MJ/m^2	-
	Embodied carbon	Cradle to Gate	kgCO2-e/m^2	-
		Transportation	kgCO2-e/m^2	-
		Construction	kgCO2-e/m^2	-
	Raw material depletion*	Raw material abundance	Likert scale (1 to 5)	1= Scarce 2= Shortage 3= Poorly spread over the globe 4= Adequately available over the globe

				5= Abundant
		Recycled material used	Percentage (%)	-
		Renewability	Likert scale (1 to 5)	1=Non-renewable 2=Centuries to be renewed 3=A century to be renewed 4=Decades to be renewed 5=A decade to be renewed
	Reuse/Recycle/Down cycle potential	-	Percentage (%)	-
	Future adoptability	-	Percentage (%)	-
	Acoustic performance	-	dB of sound reduction	-
	Light transmission	-	Percentage (%)	-
	Effect on indoor air quality (IAQ)	Summer temperature Winter temperature Humidity Air circulation	Likert scale (1 to 5)	1=No effect 2=Poor 3=Moderate 4=Strong 5=Very strong
	Waste in construction	-	Percentage (%)	-
	Water use in operation	-	L/m^2.year	-
	Safety grade	-	Standard definition (A*, A, B)	A*=1 A=2 B=3

Sustainability

In this study, eleven measures were recognized for environmental and social sustainability assessment of supply decision alternatives. Embodied energy and carbon are two evolving factors increasingly considered in sustainability assessment and decision making in construction. The total embodied energy (E_A) and carbon (C_A) associated with each alternative can be calculated by adding up the values of cradle-to-gate (CtoG) embodied energy/carbon (associated with extraction, processing and manufacturing stages) reported in LCI databases and the energy/carbon emissions incurred in transport (t), and installation (e) stages; as shown in the following equations::

$$E_A = E_{A,CtoG} + E_{A,t} + E_{A,e}$$

$$C_A = C_{A,CtoG} + C_{A,t} + C_{A,e}$$

where E_A and C_A are the total embodied energy (MJ/m^2) and total embodied carbon (kgCO2-e/$m^2$of the materials , respectively. \\The data imported from energy and carbon emission inventories are reported usually as enery/emissions per unit weight (i.e. one kilogram) of the material. To convert the values from unit weight to unit area which is more commonly used in construction, a weight-to-area conversion factor ($ws_{j,A}$) is computed for each type of material (ref.):

$$ws_{j,A} = \rho_j v_{j,A} \qquad j \in A$$

where ρ_j is the density of material j in kg/m^3, and ν_j is volume of material j per square meter of the alternative "A", in m^3/m^2. Accordingly, the cradle-to-gate embodied energy and the carbon for an alternative is calculated as follows:

$$E_{A,CtoG} = FA_{A,E} \times \sum_j ws_{j,A} \times E_{j,CtoG} \quad \forall j \in A$$

$$C_{A,CtoG} = FA_{A,C} \times \sum_j ws_{j,A} \times C_{j,CtoG} \quad \forall j \in A$$

where $FA_{A,E}$ and $FA_{A,C}$ are the supply chain structure correction factors and $E_{j,CtoG}$ and $C_{j,CtoG}$ are respectively the cradle-to-gate embodied energy, in MJ/kg, and cradle-to-gate embodied carbon, in kgCO2-e/kg, of material j. In the present study, a material energy and carbon database (for $E_{j,CtoG}$ and $C_{j,CtoG}$)was created using the data reported in Inventory of Carbon and Energy (ICE V2.0) (ref). To account for the energy use and emissions associated with prefabrication and assembly level as indicated by ATO, MTO, and ETO supply chain structures should be incorporated into $E_{j,CtoG}$ and $C_{j,CtoG}$. However, this is challenging due to confidentiality issues with regards to disclosure of assembly procedures which may be required for LCA. To overcome this issue, supplier/manufacturer of a product may be asked to provide a correction factor that escalates the embodied energy and carbon of the material to account for prefabrication energy use and carbon emissions . When supply chain structure is MTS and no factory fabrication is involved, $FA_{A,E} = FA_{A,C} = 1$; otherwise, $FA_{A,E} \neq FA_{A,C} > 1$.

In the next step, to calculate the energy and emissions associated with transport of the construction product, an overall weight-to-area conversion factor (WS_A) should be calculated for any construction product that consists of two or more (j) material constituents: :

$$WS_A = \sum_j ws_{j,A} \quad \forall j \in A$$

The following equation can then be used to estimate the transport energy and carbon emissions:

$$E_{A,t} = WS_A \times \sum_k \frac{q_k \times e_k}{CAP_k} \quad \forall k \in t$$

where q_k is quantity of fuel consumed over mode "k" of transport during transportation stage, in litre (L), e_k is energy content of the fuel type associated with mode "k", in MJ/L, and CAP_k is gross capacity of transport system in kg. The amount of carbon emissions incurred in transport of the product may be similarly calculated using the following equation:

$$C_{A,t} = WS_A \times \sum_k \frac{q_k \times c_k}{CAP_k} \quad \forall k \in t$$

where C_k is the emission factor for fuel type k, in kg CO2-e/L.

The energy use and carbon emissions incurred during construction are mainly attributed to operation of the machinery and equipment used. Therefore, the embodied energy associated with operation of construction equipment ($E_{A,e}$) in MJ/m^2 can be calculated as follows:

$$E_{A,e} = \sum_{l} \frac{P_l \times T_l \times LF_l}{3.6 \times A} \quad \forall\, l \in e$$

where P_L is the rated power energy output of equipment lin kW, T_L is the equipment's operation time in hours, LF_L is the load factor (the fraction of power used in the operation) for equipment l, and A is the total area of the element in m^2. Accordingly, the carbon emissions incurred during construction may be calculated as follows:

$$C_{A,e} = \sum_{l \in e} \frac{CF_l \times E_{A,e_l}}{A} \quad \forall\, l \in e$$

where C_L is the equivalent CO2 emission factor, in kgCO2-e/MJ, for an equipment which depends on the type of fuel or energy used by the equipment (EPA). In the above equation, E_{A,e_l} is a derivative of equation (X) for a single equipment and is formulated as:

$$E_{A,e_l} = \frac{P_l \times T_l \times LF_l}{3.6}$$

Another energy/emission factor that should be ideally considered in life cycle impact analysis is the energy and emissions associated with transportation of, equipment and labourers to and within the construction site (ref.). In this study, however, the variations in the equipment/labourer transport needs with variations in the material type are considered to be negligible and thus are not included in the analysis.

The resources depletion rate is another factor that significantly affects the environmental impacts of the material. The higher the depletion rate of resources, the more crucial is to preserve the material. In the present study, the depletion rate index for a material is defined as a function of material's abundance rate (R_Q), renewability rate (R_W), and recycled content and is calculated using the following equation::

$$RMD_A = \frac{R_Q \times R_W \times (100 - \ \%of\ Recycled\ materials)}{100}$$

End of life sustainability of materials as well as the amount of waste generated both during the production and service life of the materials and at the end of their life are other important environmental factors to be considered in evaluating of supply decisions. With regards to end of life waste, reusability and recyclability of materials are two important characteristics affecting the life cycle impacts of the materials. Apart from reducing the end-of-life impacts of the material, reuse and recycling of materials may also considerably reduce the need for extraction of the new materials. . In this study, the local or national average representing the percentage of the material that is recycled or reused is considered as a measure of environmental sustainability of the material. Besides the end-of-life waste, a considerable amount of waste is also generated during production, also referred to pre-consumer waste, and installation of the materials (i.e construction stage). The pre-consumer waste is usually easier to contain and recycle, whereas dealing with the construction waste is sometimes difficult and costly. In this study, the total material waste, in percentage, is considered to include both pre-consumer and construction waste. The water use, in L/m^2, during the life of a material, especially for cleaning and maintenance purposes, is another environmental sustainability indicator to be considered in sustainability assessment of different material alternatives.

Design for adaptability has been proposed as another important sustainable strategy to reduce the life cycle impacts of a building through extending its service life. This is achieved through designing the building elements with adaptability features that allow flexibility in terms of future changes in the use of the building. (ref) percentage of damage in each square meter of its surrounding.

As shown in Table 2, apart from economic and environmental measures, social sustainability measures such as acoustic performance, light transmission, effect on indoor air quality, and safety should be also considered in life cycle assessment of material alternatives. Acoustic performance is measured by decibel (dB) of noise reduced through replacing the existing material with an alternative material. Light transmission is measured as the percentage of the sun light that can penetrate into the building via the element, if applicable. Furthermore, effect of a product on indoor air quality is evaluated through a numerical scale that represents combinatorial impact of an alternative on winter and summer temperature, humidity, and air circulation. The safety grade of a material alternative is expressed usually by categorizing it into a predefined risk group defined in the relevant standard. For use in decision making, however, the safety category can be simply converted to a 1-to-3 numerical scale. In the present study, a Macro in Microsoft Excel was developed to perform the computation process to estimate value of performance indicators described above. The results, i.e performance indicators, are then fed into TOPSIS module to be used in ranking of supply decision alternatives .

Ranking the Supply Decision Alternatives using Multi-Attribute Decision Analysis

TOPSIS module is responsible for ranking the supply decision alternatives based on their performance against various criteria described above as well as the relative importance of criteria. Similar to *Life cycle impact analysis* section, this section also has a computational feature which initially starts with formation of alternatives-criteria m× n matrix in which value of each cell is represented by x_{ij}. Then, a normalized matrix of $R = (x_{ij})_{m\times n}$ is formed using following relationship:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_m x_{ij}^2}} \quad i = 1,2,\dots,m \; and \; j = 1,2,\dots,n$$

Next, the weighted normalized decision matrix is calculated by:

$$V = \left(v_{ij}\right) = (v_j \times r_{ij})_{m \times n} \ \therefore subject\ to\ (\sum_{j=1}^{n} v_j = 1)$$

Where v_j is the weight given to criteria j. Forth, the ideal solution A* and the negative ideal solution are obtained as:

$$A^* = \left\{\langle \max\left(v_{ij} | i = 1,2,\dots,m\right) | j \in J_+ \rangle, \langle \min\left(v_{ij} | i = 1,2,\dots,m\right) | j \in J_- \rangle \right\} = \left\{\alpha_j^*\right\}$$

$$A^- = \left\{\langle \min\left(v_{ij} | i = 1,2,\dots,m\right) | j \in J_+ \rangle, \langle \max\left(v_{ij} | i = 1,2,\dots,m\right) | j \in J_- \rangle \right\} = \left\{\alpha_j^-\right\}$$

where J_+ and J_- are sets of criteria with a positive and negative impact, respectively. In the next step, the distance between each alternative and the ideal solution (d_j^*) and the distance between each alternative and the negative ideal solution (d_j^-) are calculated correspondingly by:

$$d_j^* = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - \alpha_j^*\right)^2}$$

$$d_j^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - \alpha_j^-\right)^2}$$

These values are then used to calculate the similarity (closeness) to the ideal solution (S_j^*) as follows:

$$S_j^* = \frac{d_j^-}{d_j^* + d_j^-}$$

Finally, alternatives are ranked based on the value of S_j^*, where a higher value indicates a better solution (refs). This module also provides possibility of sensitivity analysis of rankings to weights and interest rate.

Case Study

The proposed framework was applied to a case study involving selection of material for construction of curtain wall in a residential building to illustrate its applications and advantages. The building considered is a six storey building, located in Melbourne, Australia, with a total floor area of 4912 m^2 designed for a service life of 50 years. The total surface area of the curtain wall is approximately 1219.4 m^2.The installation of the curtain wall is performed by a crew of eight workers working eight hours per day. An interest rate of 8% was assumed for economic assessment.

A curtain wall is a non-load bearing element of the building envelope that serves the primary function of separating the roofed and conditioned space of the building from its unconditioned surrounding (refs). The performance of a curtain wall is influenced considerably by type of its constituting materials and design (ref).\ .

Curtain walls may be fabricated according to four common supply chain structure systems including stick system, semi-unitized, unitized, and specialized custom wall system which respectively correspond to MTS, ATO, MTO, and ETO supply chain structures (ref). In stick system, the components of a curtain wall are ordered from standard items or bulk materials available (MTS) in the market. The fabrication, assembly and installation, as required, are performed on the jobsite. In semi-unitized systems, prefabricated frames and infill materials are ordered from standardized catalogues and final installation and glazing activities are performed on the construction site (ATO). In utilized system, ready-to-install panels (after glazing) for a curtain wall are ordered by providing the manufacturer with the required design information such as floor height and width and windows dimensions, while the site activity involves solely fixing the panels in place (MTO). Finally, in specialized custom walled system, the manufacturer is asked to design and produce a customized curtain wall given the overall information about building architecture (ETO) (refs).

One or a combination of a wide range of materials with different life cycle impacts may be used in curtain walls. Furthermore, depending on the type of materials used, , one or more supply chain structure may be applicable. On the other hand, a particular type of curtain wall, in terms of material type and fabrication structure, may be procurable from different manufactures. In addition, different freight options are usually available to transport the materials to the construction site. The availability of various options for the materials, supply chain structure, manufacturer and mode of transport with different overlapping effects on the life cycle impacts of the curtain wall renders the curtain wall supply decisions highly challenging. Construction of a curtain wall is usually considered as a critical activity at the very end of a project in which a finish-to-start relationship is applied to every single stage of its construction process.

Results and discussions

The feasible material supply decisions for construction of the curtain wall required by the case building are listed in Table 3. A typical curtain wall may comprise a diverse range of components with different material options. However, for simplicity purposes, the focus of present illustrative study is placed only on supply decisions with regards to main components of the wall, i.e frames material and infills material As shown in Table 3, the material alternatives considered for the frame include aluminium and steel, whereas infills material can be selected from glass, fabric veneer, brick veneer, stone veneer, and concrete. The possible supply chain structures for each alternative material is also shown in Table 3.

Table 3. Curtain wall supply decision alternatives

Alternative ID	Frame	In-fills	Supply Chain Structure				Source of Supply	Transport Mode		
			MTS	ATO	MTO	ETO		Road	Sea	Air
1	[illegible]	Glass	√				China	√	√	

2			√				China	√		√
3			√				Australia	√		
4				√			China	√	√	
5				√			China	√		√
6				√			Australia	√		
7						√	China	√	√	
8						√	Australia	√		
9		Fabric Veneer			√		China	√	√	
10					√		China	√		√
11					√		Australia	√		
12		Stone Veneer	√				China	√	√	
13			√				Australia	√		
14	Steel			√			China	√	√	
15				√			Australia	√		
16		Brick Veneer	√				Australia	√		
17				√			Australia	√		
18		Concrete		√			China	√	√	
19				√			Australia	√		
20	Concrete		√				Australia	√		

The contractor of the case project prefers to work with its long-term partners from China and Australia to supply curtain walls. The transport mode options for China include road/sea or road/air while road is the only mode of transport for local supply of components (i.e. from Australia). The available material, manufacturer and transport mode options leads to twenty feasible alternatives for the supply of curtain wall, as listed in Table 3, which were subject to life cycle analysis to identify the best supply decisions. According to the proposed methodology, the building information model of the case building was modified to include the custom attributes required for analysis of supply decisions. The model was then subject to life cycle assessment using the analyser unit developed in Microsoft Excel. A snapshot of one of the curtain wall options modelled in Revit along with its built-in properties and add-on attributes is shown in Figure 3. The modelled curtain wall belongs to alternative x and its add-on attributes include cost items, times, fabrication system, and all the required parameters used to quantify or scale quality and environmental and social sustainability measures, as described in Section Jix. Apart from added attributes, the main BIM built-in attribute required is quantity of materials in kg per overall surface area of a curtain wall in m2. Other important parameters for each element including the available transport vehicles and their capacities and fuel type, the travel distances , construction equipment required and their load factors, duration of use and storage information were collected and stored in the relevant libraries and databases.

(To be added later)

Figure 3. A sample snapshot of BIM curtain wall

Table 4 shows the pairwise comparison matrix developed for the main selection criteria based on the opinions of a team of three formed by one representative from each main party, i.e. contactor, architect, and client. As shown, the resulting priority weights vary from 0.080 (for quality) to 0.470 (for cost), highlighting the considerably higher relative importance of costs implications in supply decisions. The consistency of comparison is confirmed with a CR=0.076 (<0.1).

Table 4. Comparison of main criteria; a) pairwise comparison matrix b) priority matrix of criteria computed using AHP

a)

Criteria	Cost	Time	Quality	Sustainability
Cost	1	2	5	3
Time	1/2	1	2.5	1/3
Quality	1/5	1/2.5	1	1/3
Sustainability	1/3	3	3	1

b)

Criteria	Cost	Time	Quality	Sustainability	Priority Vector
Cost	0.492	0.312	0.435	0.643	0.470
Time	0.246	0.156	0.217	0.071	0.173
Quality	0.098	0.062	0.087	0.071	0.080
Sustainability	0.164	0.469	0.261	0.214	0.277

The suitability of measures defining the functionality of a curtain wall was assessed by fifteen experts from the case project (six from contractor, three from architect, and six from client organization). The estimated relative suitability indices for measures as well as the local weight of each measure within its own category are shown in Table 5.

Table 5. Relative suitability index and normalized weight of measures defining quality and environmental and social sustainability

Criteria	Attribute	Relative suitability index	Normalized local weight
Quality	Designed Life	0.707	0.120
	Load Performance	0.467	0.079
	Thermal Performance	0.813	0.138
	Fire Resistance	0.693	0.118
	Aesthetic Performance	0.667	0.113
	Air infiltration	0.587	0.100
	Water Penetration	0.680	0.116
	Constructability	0.680	0.116
	Maintainability	0.587	0.100
Environmental and social sustainability	Embodied Energy	0.867	0.120
	Embodied Carbon	0.880	0.122
	Acoustic Performance	0.840	0.116
	Future Adoptability	0.613	0.085
	Reuse/Recycle/Down-cycle potential	0.520	0.072
	Light Transmission	0.467	0.065
	Raw Material Depletion	0.493	0.068
	Effect on Indoor Air Quality	0.613	0.085
	Likely waste in use	0.707	0.098
	Likely water use	0.387	0.054
	Safety Grade	0.827	0.115

Upon assigning the weights to criteria and measures, the data extracted from the BIM models generated for each curtain wall option through varying the type of the wall in the original BIM were imported to the analysis platform developed in Microsoft Excel. Table 6 shows the results of the analysis performed including the closeness of the alternatives to the ideal solution and the resulting ranking of supply alternatives. As shown, the results indicate steel as a better frame material than aluminium with respect to the criteria considered. Moreover, concrete has been highlighted as the best infill material, regardless of its supply chain structure. Brick and fabric veneer appear to be the second and the third best choices for infills. However, by considering the supply structure, the locally supplied unitized (MTO) system of fabric veneer is preferred over bricklaying (MTS brick veneer) . Despite its popularity (ref), glass appeared to be the least suitable option for the curtain wall, based on the selected life cycle impact criteria, in all cases except when it is supplied locally as a stick system (MTS) or semi-unitized (ATO) system. In such cases, glass turns out to be a slightly more preferred option than semi-unitized (ATO) stone panels. This slight preference can be related to beneficial social sustainability impacts of the glass curtain wall including its impact on IAQ, light transmission, and safety. Comparing the alternatives with similar material type and supply chain structure reveals that local supply, if possible, is prioritized over international supply under original scenario of assessment. The transport mode choice in international freights depends on size and weight of consignments. In international transport of glass curtain walls, which are usually bulky and heavy consignments, marine mode is preferred over air mode considering. Fabric veneer panels are, however, categorized as light to medium weight freights; with air transport as the preferred transport mode .

Table 6. Closeness of alternatives to the ideal solution and their ranks under different scenarios

	Original Assessment		Equal Weight of all categories		Solely based on sustainability measures	
	Closeness	rank	Closeness	rank	Closeness	rank
S^*_1	0.268	12	0.409	13	0.597	18
S^*_2	0.232	16	0.392	14	0.258	19
S^*_3	0.295	11	0.464	10	0.633	15
S^*_4	0.201	17	0.332	17	0.607	16
S^*_5	0.190	18	0.365	16	0.248	20
S^*_6	0.249	13	0.438	11	0.667	10
S^*_7	0.163	20	0.243	20	0.604	17
S^*_8	0.173	19	0.288	19	0.665	11
S^*_9	0.715	8	0.659	8	0.784	2
S^*_{10}	0.773	7	0.713	6	0.713	6
S^*_{11}	0.809	5	0.763	4	0.828	1
S^*_{12}	0.338	10	0.380	15	0.645	14

S^*_{13}	0.371	9	0.493	9	0.662	13
S^*_{14}	0.239	15	0.322	18	0.662	12
S^*_{15}	0.249	14	0.418	12	0.673	8
S^*_{16}	0.805	6	0.677	6	0.688	7
S^*_{17}	0.823	4	0.783	3	0.727	3
S^*_{18}	0.838	3	0.731	5	0.714	5
S^*_{19}	0.856	2	0.812	1	0.721	4
S^*_{20}	0.891	1	0.787	2	0.668	9

The characteristics of in-situ concreting of a curtain wall using ready mix concrete, as the best alternative ranked in the original scenario of assessment, are compared with the ideal and negative ideal solutions in Table 7.

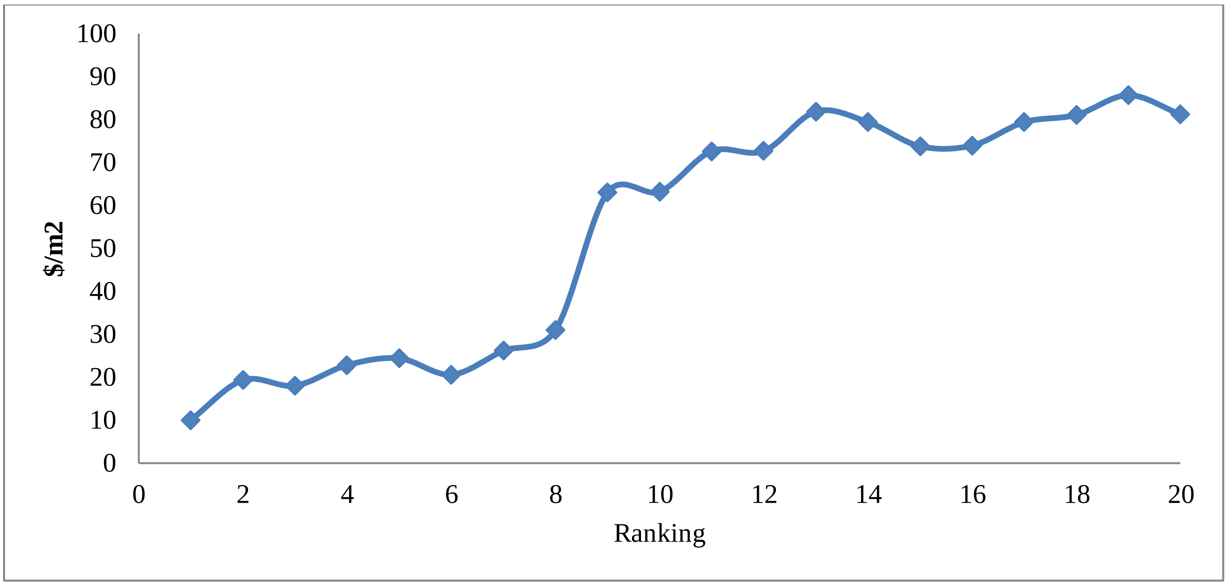
Table 7. Comparison of the selected alternative with the best and the worst solution

Criteria	Measure	Unit of measurement	In-situ concreted curtain wall	The best solution	The worst solution
Cost	Total	Annualized $/m^2$	10.075	10.075	85.716
Time	Total	Days	43.08	38.18	85.57
Quality	Design life	Years	40	40	12
	Load performance	Combinatorial	4	2	6
	Thermal performance	Combinatorial	0.0875	0.0021	0.1032
	Fire resistance	Minutes	150	150	45
	Aesthetic	Likert scale	5	1	5
	Air infiltration	L/s.m^2	0	0	2.1
	Water penetration	Minutes	60	60	17
	Constructability	Likert scale	2	4	1
	Maintainability	Likert scale	1	4	1
Environmental and Social Sustainability	Embodied energy	MJ/m^2	312.559	312.559	7858.232
	Embodied carbon	kgCO2-e/m^2	34.547	18.361	572.418
	Raw material depletion	Combinatorial	4	45	2
	Reuse/Recycle/Down cycle potential	Percentage (%)	60	65	30
	Future adoptability	Percentage (%)	15	70	15
	Acoustic performance	dB of sound reduction	58	60	39
	Light transmission	Percentage (%)	0	75	0
	Effect on indoor air quality (IAQ)	Likert scale	4	4.25	2.25
	Waste in construction	Percentage (%)	16	5	16
	Water use in operation	L/m^2.year	0.4	0.2	14
	Safety grade	Scale	2	1	3

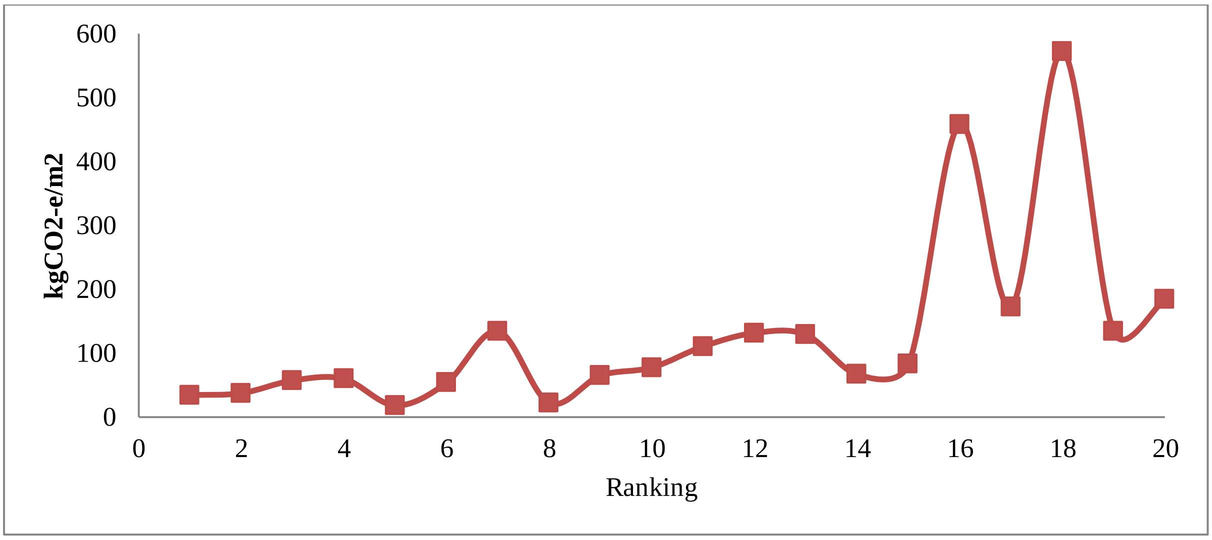
To investigate the sensitivity of the analysis to relative importance weigh of criteria, a sensitivity analysis was performed by varying the weights of different criteria. The results for two scenarios are presented in Table 6. In the first scenario, equal weights were assigned (i.e. each accounts for 25%) to each criteria whereas in the second scenario, the weights were modified so that the decision is made only based on the "environmental and social sustainability" performance of alternatives. As shown, considering equal importance for all criteria, inclines the decision making process to opt a higher level of prefabrication and a local manufacturer l. For instance, locally supplied precast concrete is promoted to the first ranking, while precast concrete supplied from China is lowered from rank 3 to rank 5. This can be attributed to the reduced importance of costs and increased importance of social and environmental criteria. In addition, as shown in Table 6, placing the focus on environmental and social impacts in the second scenario results in significantly different decisions compared to the original scenario. This can be reflected by the average change in ranking of the alternatives as computed using the following equation:

$$Average\ change\ in\ rankings = \frac{\sum|Original\ rank - New\ rank|}{Total\ number\ of\ alternatives}$$

An average change of 3.6 is observed in rankings when comparing the second scenario with the original weighting scenario. The observed trends in terms of relationships between the ranking of the alternatives in original scenario and the their associated costs and embodied carbon are presented in Figure 4. As shown, due to the relatively high importance weight given to the costs (47%), a decrease in the costs results generally in an improvement in the ranking of the alternative. The embodied carbon of the ranked alternatives, however, indicates a mixed behaviour. While a direct relationship seems to exist between reduction in embodied carbon and improved rank of the alternative in two zones (from rank1st to 4th and 9th to 13th), a fluctuating trend is observed for the last seven ranked alternatives. This difference is mainly attributable to manufacturing technology and on-site construction method behind the types of curtain walls. When a proven and ubiquitous technology is used to produce curtain wall materials and its corresponding construction method is handy and less complicated, reduction in carbon emissions could be in line with improvements in other aspects of the product, leading to an improved ranking. This notion can be exemplified in concrete or brick veneer curtain walls. On the contrary, reducing embodied carbon of alternatives that are manufactured with a diverse range of technologies and need proprietary construction equipment are dependent on heuristic methods employed by manufacturers, designers, and contractors. Glass curtain walls are an example for this category of alternatives.



a) Trend of costs



b) Trend of emissions

Figure 4. Ranked alternatives and their associations with a) trend of costs and b) trend of emissions

Due to importance of costs, the variations in the interest rate should be also considered as a potential factor affecting the outcome of the analysis. Therefore, a sensitivity analysis was conducted to investigate the effects of the interest rate on the rankings obtained.. As shown in Figure 5, doubling the interest rate resulted in an average change in rankings of only 1.2, indicating that the rankings are not significantly sensitive to errors in estimating the interest rate.

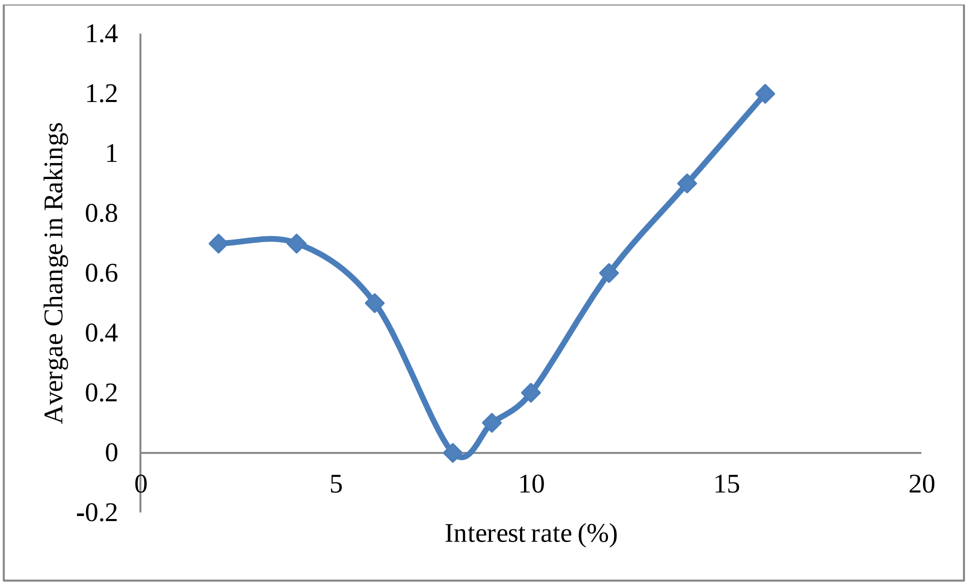


Figure 5. Sensitivity of rankings to interest rate

Conclusions

A framework for assessment of material supply decisions by considering their life cycle impacts was proposed in this paper. The framework addresses the hierarchy of decisions in the material supply process which consists of four levels including material type, source of supply, supply chain structure, and mode of transport. Following the identification of assessment criteria and appropriate measures for quantifying the performance of supply decision alternatives against these criteria, a computational approach is taken to rank the alternative decisions based on their relative life cycle performance. The computational method takes advantages of the capabilities of the state-of-the-art BIM in making available customized data on characteristics of the building elements, as required in estimating their life cycle impacts, as well as a number of available costs and environmental inventories to quantify the economic, environmental and social impacts associated with various decision alternatives. The developed framework was applied to a case study involving the supply of materials for a curtain wall in a case project where available options with regards to type of the material, supply chain structure, location of the manufacture and mode of transport were evaluated and ranked. The sensitivity of the results to the priority weights considered in the analysis and thus the attitude of decision makers with respect to relative importance of various economic, environmental and social impacts was illustrated through a sensitivity analysis. Furthermore, the sensitivity of the results of the case study to the assumed interest rate was analysed and found to be insignificant. . While providing a holistic framework for material supply decisions, there is room to improve the quality of results if sufficient information about end of cycle stage is made available. Moreover, the framework relies on general information in some measures such as construction waste. In addition, the work can be improved by automating the data exchange between BIM and different modules of the framework.

References