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Abstract: Previous works on estimating construction carbon emissions from energy consumption were primarily capitalizing on the quantity of construction materials, equipment and an emission inventory. It is envisaged that with the aid of Building Information Modeling (BIM) technologies that are featured by semantic-rich data and information, the present-day practice of energy and emission estimation can be well improved. Despite an ideal BIM model typically encompasses information that ranges across building design, construction and operation details, a rationale around how to leverage semantic-rich BIM to address building energy consumption and carbon emission topics is still unclear. Under this backdrop, this study is centered on formulating a semantic-rich building energy consumption ontological model that is capable of accurately calibrating the energy consumption and emissions of a building. The formulated model will consider various factors that can affect the calibration and estimation such as materials, fabrication, logistics, processing, and the like.

Keywords: Construction Phase, Ontology, Emission Estimation

1. INTRODUCTION

Buildings provide great contributions to environmental emission throughout their life cycles (Hong et al., 2015; Chau et al., 2012). In previous studies, efforts were primarily put on the use phase, because it produces 80-90% of the total emissions in the life cycle of buildings (Jonsson et al., 1998; Wu et al., 2012). In recent years, research interest has gradually shifted to other phases such as the construction phase. The reasons of this change are mainly from two aspects: 1) the advancement of applying energy-efficient materials and designs lead to the decrease of energy consumption at the use phase (Li et al., 2010; Sandanayake et al., 2016a); 2) the realization of the short-term intensive emission may cause more damage to the environment and society rather than the long-term mild one (Guggemos, 2005; Tam et al., 2002; Yan et al., 2010).

To reduce emissions in the construction phase, accurate and efficient estimation must be implemented primarily. Although there are plenty of different emission estimation methods available from different studies, Life Cycle Assessment (LCA) is the most widely adopted technique by researchers to measure and compare environmental impacts of a certain product or process (Finkbeiner et al., 2006). LCA usually has three analysis approaches, Input/Output (I/O) based, Process-based, and Hybrid based. To analyze construction phase emissions, the process-based approach is easier to compute and define the assumptions, limitations and objectives (Sandanayake, 2016). However, this approach requires the input data with high quality and accuracy which is difficult to be assured (Hendrickson et al., 1997), and a huge amount of data input is extremely time-consuming.

Along with the development of information technology in the Architecture, Engineering and Construction (AEC) industry, Building Information Modeling (BIM) has been widely used by different participants. BIM has successfully helped to achieved efforts saving in many different scenarios in the AEC industry. Information stored in BIM could facilitate the construction emission estimation, however, information from BIM is not enough for the estimation. Combination of information from other sources such as construction plan, emission inventory is highly required. In the previous study, different methods were raised to satisfy the needs of connecting data from different resources to fulfill automation in many tasks (Pauwels et al., 2017). Based on various studies, semantic web technology is deemed as a promising technique to link information across domains (Berners et al., 2001). As ontologies are the core of a semantic web, combining information from different sources relies on the quality of constructing the domain ontology (Giri, 2011).

This study aims to develop a construction emission domain ontology which contains the knowledge of both construction process and air emission. Connecting it with the building product ontology, known as the BIM model, will enable more automatic and accurate estimation of the construction phase emission. This paper is structured as follows: In Section 2, the research methodology for developing the proposed ontology is elaborated. After that, the construction emission estimation methods and parameters involved are discovered in Section 3. Following the discovery, the general architecture of the semantic model is designed in Section 4. The taxonomical structure and attributes of a construction plan are explored in Section 5. At last, Section 6 summarises the contributions and suggestions for the future work.

2. RESEARCH METHODOLOGY

The key purpose of applying semantic web technology in this study is to link data across domains. In this case, reusing the existing ontology from other domain if available becomes the most natural and efficient choice. According to the popular ontology developing method (Noy & McGuinness, 2000), there are seven steps as follows: 1) determining the domain and scope of the ontology; 2) considering reuse of existing ontologies; 3) enumerating important terms; 4) defining the classes and the class hierarchy; 5) defining the properties of classes; 6) defining the values for the properties; 7) creating class instances. Because this study is about an application-level ontology development, it is more reasonable to firstly identify instances that have the relation with emission calculation from construction activities rather than determine concepts/classes at first. Hence, the developing process of this study follows the bottom-up procedures including the following four steps.

2.1 Defining the purpose and the scope of the building construction emission ontology

The purpose of developing the building construction emission ontology is not only formalizing the knowledge of construction emissions, but also supporting the integration of the knowledge with building information models to simulate the generation of emission from construction activities. The data required in the simulation only covers parts of the whole knowledge base of construction and emission domain. Therefore, on the one hand, the ontology to be developed in this study is an application-oriented ontology within a sub-domain. On the other hand, it's essential to investigate the existing ontologies from different domains to identify what classes are already defined, and how they can be utilized to formulate the emission estimation method. Due to the length limit of the paper, only air emission is chosen as the object of this research.

2.2 Analyzing building construction emission mechanisms

Previous studies reveal that the LCA process-based method is the most accurate one to estimate the construction emission provided the data quality can be guaranteed. Because the purpose of developing the ontology is to satisfy the needs of simulating the construction emission automatically through integrating emission knowledge and building information models, it is essential to clarify the principle behind the LCA equations and the origin of each individual factor. Carefully analyzing mechanisms can provide a profound understanding how and to what aspects the construction activities may affect the emissions. Moreover, intermediate processes to determine the equation factors from the existing ontological classes are required, and it is also required that certain new classes be formalized through the analysis.

2.3 Matching in existing ontologies

As discussed previously, reusing existing ontologies or parts of them is one of the principles behind the semantic web technology, that is sharing knowledge across different domains. Thus, acquiring data from existing ontology and linking them with factors from the LCA equations is rational. Setting-up connections among those classes and factors may help form the structure of the ontology and discover omissions of the classes and properties.

2.4 Developing building construction emission ontology

A building information model can certainly be information-rich, it is, however, limited by furnishing equivalently-adequate data related to construction activities (EI-Diraby, 2012). For instance, although BIM format Industry Foundation Classes (IFC) (buildingSMART, 2016) contains a class named Pset_EnvironmentalImpactIndicators, this class does not provide information about the emission volume and its relation to the construction activities. the architecture of the proposed building construction emission ontology needs to consider the interactions among building components, construction activities and different emission substances. In this study, the ontology is modeled and edited using one of the most popular open-source tools named Protégé.

3. ANALYSING THE CONSTRUCTION EMISSION MECHANISMS FOR BUILDING

3.1 Existing process-based emission estimation methods

Within process-based LCA methods, principles behind all equations are very similar in general. Air emission is generated from different sources, and the amount of the air emission depends on the quantity of different source and emission factors, while those factors reflect the features of different construction activities and the features of different machine. Thus, the emission could be calculated through Equation (1) theoretically.

$$E_i = Q_j \times EF_{ij} \tag{1}$$

Where, E_i is the amount for emission type i, Q_j is the quantity of related source j, and EF_{ij} is the emission factor for emission type i from source j.

For different types of emission, this equation can be further developed based on the features of emission, types of machine and the accessibility of related data. In previous work (Sandanayake, M., 2016b), a criterion for the selection of emission estimation methods and standards was set up in the Australian context. Furthermore, the in-depth direct and in-direct emission mathematical models were developed. These models can depict the activity level generation mechanism of different types of air emission.

(1) Estimation of Green House Gas (GHG) emissions from material transportation

$$E_{(GHG)T} = \frac{EF_j \times e_j \times d \times w}{1000} \tag{2}$$

Where, e_j is the energy consumption of the vehicle in GJ/ton-km, d is the one-way distance denoted by km and w is the total weight of the vehicle in tons. The emission factor EF_j can be retrieved from the National Greenhouse Accounts Factors (NGAF) (2018) depending on the fuel type.

(2) Estimation of GHG emissions from equipment

$$E_{(GHG)eq} = \frac{EC_j \times EF_j \times f_e \times LF \times T}{1000} \tag{3}$$

Where $E_{(GHG)eq}$ is the GHG emissions from construction equipment in kg, EC_j is the energy content factor of fuel type j (gigajoules per kilolitre or per cubic metre) used for equipment, f_e is the fuel consumption of the equipment at full-load capacity, T is the hours of use of the equipment for the activity considered, and LF is the load factor, which is the fraction of available power during the operation of equipment.

(3) Estimation of non-GHG emissions from material transportation

$$E_{(NG)T,k} = \frac{A_k \times EF_{(NG)k}}{1000} \tag{4}$$

Where k is the non-GHG considered, A_k is the vehicle activity in km and $EF_{(NG)k}$ is the exhaust emission factor for non-GHG k in kg/km, which can be obtained from the Australian National Inventory Report (NIR) (2011).

$$A_k = \frac{f \times e_j \times d \times w}{EC_j} \tag{5}$$

Where f corresponds to the fuel capacity of the vehicle in km/L, e_j is the energy consumption of the vehicle in GJ/ton-km, d is the distance denoted by km, w is the weight of the loaded vehicle in tons and EC_j is the energy content factor of fuel type j in GJ/kl.

(4) Estimation of non-GHG emissions from equipment

$$E_{(NG)eq,k} = EF_k \times P \times T \times LF \tag{6}$$

Where EF_k is the non-GHG emission factor for the emission substance k for equipment eq considered in kg/(kW-hr) and P is the rated power output of the equipment considered in kW, T is the usage hours and LF is the load factor, which is the fraction of available power during the operation of equipment.

(5) Embodied emissions from materials

$$E_m = \sum Q_{BOQ} \times (1 + \mu) \times e_m \tag{7}$$

Where Q_{BOQ} is the quantity of a type of materials indicated in the bill of quantity (BOQ) of a construction activity, μ is the waste factor for the material m and e_m is the emission factor for material m in $kgCO_2$-eq/kg.

(6) Estimation of emissions from electric equipment

$$E_{elec} = \frac{P \times \eta \times h \times e_{elec}}{1000} \tag{8}$$

Where p is the power of equipment in kW, ηis the efficiency of the equipment determined by the feature of equipment, h is the usage hours for activities considered, e_{elec} is the emission factors of purchased electricity in $kgCO_2$-e/kWh.

(7) Estimation of emissions from construction waste

$$E_W = W_i \times Q_i \tag{9}$$

Where W_i is the waste factor for the type of waste material, and Qi is the amount of material delivered to the site for the specific activity.

3.2 Mechanisms analysis

Although some variables from the above-listed in-depth models may imply inter-correlations with the existing ontological classes, still are there some classes need to be formalized to underpin variables value assignment. In Table 1, each variable is assigned with depending objects, which describe the mechanisms about how the value of that variable is determined. Furthermore, data sources are categorized into two clusters, namely, direct and indirect ones. A direct source means variables could find data directly from possible sources, while those sources could be a building information model, an air emission report or a machine inventory. An indirect source can only provide basic information for variables calculation. Take the variable d in the GHG estimation from transportation as an example, it requires the location information of both the project and vendors for computing purposes. To accurately determine the information for a specific variable, it is typically required to apply metadata to constitute the filter rule parameters.

There are some variables, for example, LF and T in Equation (3), that their values are mainly determined from company norms or other previous studies' empirical data. These data barely reflect the status or features of the project to be evaluated, in the meanwhile, only a little part of the construction plan information is involved in the value calculation. Therefore, special attention on classes defining and relations setting up will need to be paid to incorporating these types of information into the newly designed ontology.

4. THE STRUCTURE DESIGN OF CONSTRUCTION EMISSION ONTOLOGY

The intention of this study is to develop a model to formalize the construction emission knowledge. Because an existing ontology named ifcOWL has already included concepts and relationships of construction products and processes, they can be linked to the new construction emission ontology. Besides the building product model, there are another two sub-models that need to be developed, which form the construction emission ontology.

In my method, the construction sub-model and emission sub-model inherited from part of the construction process ontology (EI-Gohary & EI-Diraby, 2010) and AIR_POLLUTION_Onto (Oprea, 2009). Figure 1 demonstrates the developed ontology.

Table 1. Summary of data source of emission estimation variables

Emissions	Variables	Depending Objects	Meta Data Source	Direct Source	Indirect Source
$E_{(GHG)T}$	EF_j	Fuel type	BIM_Resource	NGAF (2018)	
	e_j	Vehicle features	BIM_VehicleModel	Vehicle Inventory	
	d	Project location		BIM_Project Information	
		vendors' location			Vendors Information
	w	Vehicle features	BIM_VehicleModel	Vehicle Inventory	
$E_{(GHG)eq}$	EC_j	Fuel type	BIM_Resource	NGAF (2018)	
	EF_j	Fuel type	BIM_Resource	NGAF (2018)	
	f_e	equipment features	BIM_EquipmentModel	Equipment Inventory	
	LF	equipment type	BIM_EquipmentModel	Vehicle Inventory	
		operation condition	BIM_Task		Company Norms or Previous Studies
	T	Planning working time		BIM_Schedule	
		idle time	BIM_Task		Company Norms or Previous Studies
$E_{(NG)T}$	$EF_{(NG)k}$	fuel type, vehicle type and age class	BIM_Resource BIM_VehicleModel	Vehicle Inventory	
	f	vehicle features	BIM_VehicleModel	Vehicle Inventory	
	e_j	vehicle features	BIM_VehicleModel	Vehicle Inventory	
	d	Project location and fabricators' location			BIM_Project Information
	w	vehicle weight	BIM_VehicleModel	Vehicle Inventory	
	EC_j	fuel type	BIM_Resource	NGAF (2018)	
$E_{(NG)eq}$	EF_k	fuel type	BIM_Resource	NGAF (2018)	
	P	equipment features	BIM_EquipmentModel	Equipment Inventory	
	T	task amount		BIM_Quantity	
		idle time	BIM_Task		Company Norms or Previous Studies
	LF	machine type and	BIM_EquipmentModel	Vehicle Inventory	
		operation condition	BIM_Task		Company Norms or Previous Studies
E_m	Q_{BOQ}	material amount		BIM_Quantity	
	μ	company's capabilities			Company Norms or Previous Studies
	e_m	material type	BIM_Material		BIM, National inventories
E_{elec}	P	equipment features	BIM_EquipmentModel	Equipment Inventory	
	η	equipment features	BIM_EquipmentModel	Equipment Inventory	
	h	task amount, schedule plan			BIM
	e_{elec}				National inventories
E_W	W_i		BIM_Material		Company Norms or Previous Studies
	Q_i	material amount			BIM

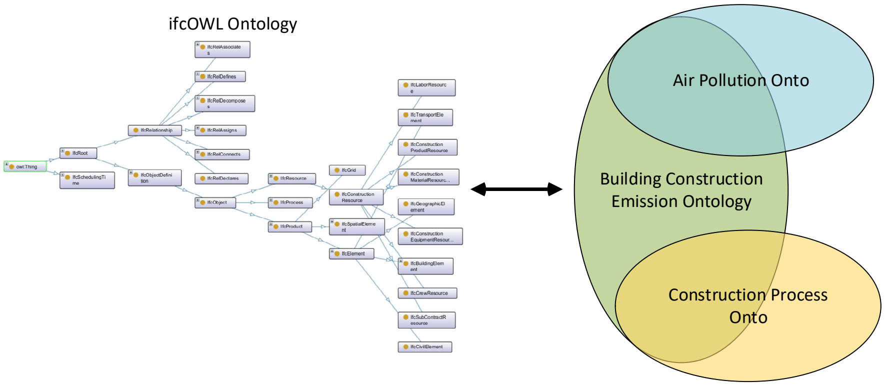

Figure 1. Ontology Structure

5. BUILDING CONSTRUCTION EMISSION SEMANTIC MODEL DEVELOPMENT

(1) Concepts of air emission

In this study, parent classes named AIR_EMISSION, EMISSION_SOURCE, EMISSION_FACTOR are adapted from the AIR_POLLUTION_Onto; meanwhile sub-classes named TRANSPORTATION, SO2, PM and CONSTRUCTION_ACTIVITY are inherited from AIR_POLLUTION_Onto. Other enriched sub-classes include EMISSION_FACTOR, RESOURCE CONSUMPTION, etc..

(2) Concepts of the construction process

Parent concepts named ACTION, RESOURCE, ACTORS are based on IC-PRO-Onto (EI-Gohary & EI-Diraby, 2010) whereas PRODUCT is excluded because it is already modeled in ifcOWL. Only those specific concepts related to air emission are selected for sub-classes. Furthermore, some essential air emissions-related concepts such as CONSTRUCTION EQUIPMENT, VEHICLE, VENDOR, and so on are not found when creating the IC-PRO-Onto.

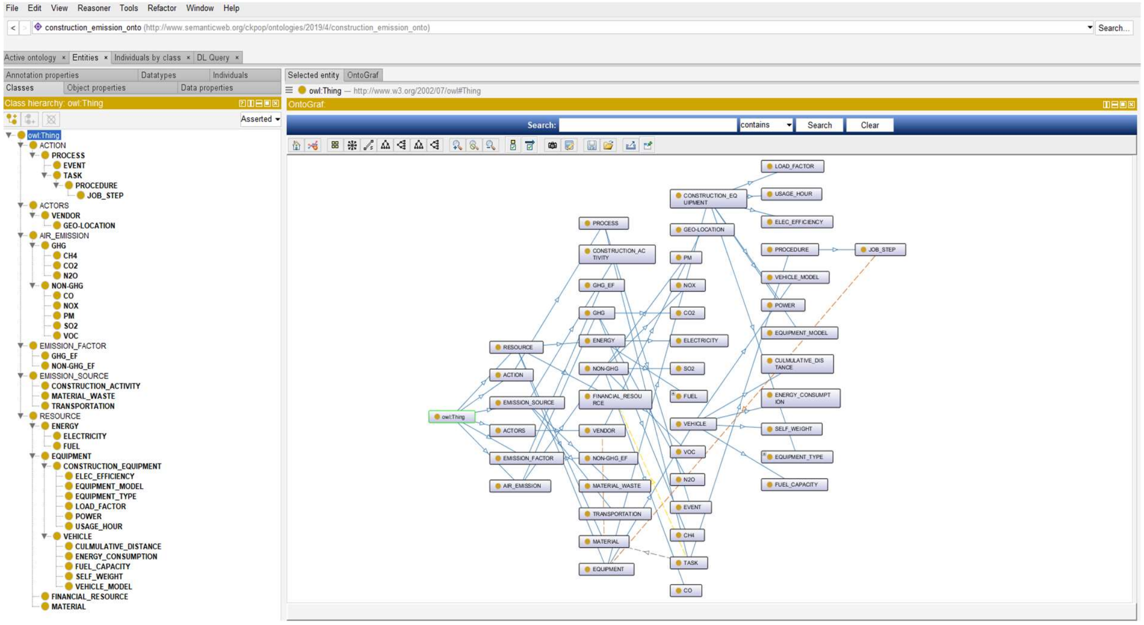

Figure 2. Taxonomy of Building Construction Emission Ontology

In the ontology, the hierarchy (a.k.a. taxonomy) of the classes represents the structure of the domain knowledge shown in Figure 2. Each axiom binds two classes or individuals with specific relations. In Protégé, Domain and Range are used to define the axiom of the subject domain in the Object properties dialogue, for instance, the property CONSUME_MATERIAL links Subject TASK and Object MATERIAL.

6. CONCLUSION AND FUTURE WORK

In this study, the methodology of semantic modeling of building construction emission knowledge has been illustrated. To formalize the knowledge of construction emission, a construction emission ontology is developed. This ontology covers part of both construction and air emission domains according to the mechanism of emission generation from construction activities. Connecting this ontology with a building information model can implement the simulation of air emissions from different construction activities and provide an understanding of building emission at the construction phase. It can also be utilized to help builders or contractors identify the whereabouts of emissions and viable optimisation solutions.

Future work will be placed around: firstly, leveraging software, interview and pilot studies to validate the ontology pertinent to syntax and semantic quality; secondly, extending the ontology to different emission types; and finally, integrating the construction emission ontology with environmental impact, cost and other related knowledge to facilitate the optimization of emission throughout the whole life cycle.

REFERENCES

Berners, T.L., Hendler, J., Lassila, O., (2001). The semantic web*, Scientific American*. 284 (5), 35–43.

buildingSMART. (2016). *IFC4 ADD2 Release.* Retrieved from buildingSMART website: http://www.buildingsmart-tech.org/specifications/ifc-releases/ifc4-add2

Chau, C.K., Hui, W.K., NG, W.Y., Powell, G. (2012). Assessment of CO2 emissions reduction in high-rise concrete office buildings using different material use options. *Resources, Conservation and Recycling*, 61, 22-34.

El-Diraby, T. E. (2012). Domain ontology for construction knowledge. *Journal of Construction Engineering and Management*, 139(7), 768-784.

El-Gohary, N. M. and T. E. El-Diraby (2010). "Domain ontology for processes in infrastructure and construction. *Journal of Construction Engineering and Management*, 136(7), 730-744.

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K. & Klüppel, H.-J. (2006). The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *The international journal of life cycle assessment*, 11, 80-85.

Guggemos, A.A. & Horvath, A. (2005). Comparison of environmental effects of steel-and concrete-framed buildings. *Journal of Infrastructure Systems*, 11, 93-101.

Giri, K. (2011). Role of ontology in semantic web. DESIDOC *Journal of Library & Information Technology*, 31(2),116-120.

Hendrckson, C. T., Horvath, A., Joshi, S., Klausner, M., Lave, L. B. & Mcmichael, F. C. (1997). Comparing two life cycle assessment approaches: a process model vs. economic input-output-based assessment. *Electronics and the Environment*, ISEE-1997., Proceedings of the 1997 IEEE International Symposium on, 1997. IEEE, 176-181.

Hong, J., Shen, G.Q., Feng, Y., Lau, W.S.-T., Mao, C. (2015). Greenhouse gas emissions during the construction phase of a building: a case study in China. *Journal of Cleaner Production*, 103, 249-259.

Jones, D.M., Bench-Capon, T.J.M., Visser, P.R.S. (1998). Methodologies for Ontology Development, *Proceedings of IT and Knowledge Conference of the 15th IFIP World Computer Congress,* Budapest, Hungary.

Jonsson, A., Bjorklund, T., Tillman, A.-M. (1998). LCA of concrete and steel building frames. *The International Journal of Life Cycle Assessment*, 3, 216-224.

Li, X., Zhu, Y., Zhang, Z. (2010). An LCA-based environmental impact assessment model for construction processes. *Building and Environment*. 45, 766-775.

Noy, N., McGuinness, D.L. (2000). Ontology Development 101: A guide to Creating your First Ontology, Stanford Medical Informatics Technical Report No. SMI-2001-0880, 2000. URL: www.smi.stanford.edu/projects/protege/publications/ontology_development/ontology101.pdf.

Oprea, M. M. (2009). AIR_POLLUTION_Onto: an ontology for air pollution analysis and control. *IFIP International Conference on Artificial Intelligence Applications and Innovations*, Springer,135-143.

Pauwels, P., Zhang, S., & Lee, Y. C. (2017). Semantic web technologies in AEC industry: A literature overview. *Automation in Construction*, 73, 145-165.

Sandanayake, M., Zhang, G., Setunge, S. (2016a). Environmental emissions at foundation construction stage of buildings e two case studies. *Building and Environment*, 95, 189-198.

Sandanayake, M. (2016b). Models and Toolkit to Estimate and Analyze the Emissions and Environmental Impacts of Building Construction.

Tam, C.M., Z.M. Deng, and S.X. Zeng. (2002). Evaluation of construction methods and performance for high rise public housing construction in Hong Kong. *Building and Environment*, 37(10), 983-991

Wu, H., Yuan, Z., Zhang, L., Bi, J. (2012). Life cycle energy consumption and CO2 emission of an office building in China. *The International Journal of Life Cycle Assessment*, 17, 105-118.

Yan, H., Shen Q.P., Fan C.H., Wang Y.W., Zhang L. (2010). Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong. Building and Environment, 45(4), 949-955.