CONCEPTUAL FRAMEWORK OF DECISION SUPPORT MODEL FOR THE SELECTION OF STRUCTURAL FRAME MATERIAL TO ACHIEVE SUSTAINABILITY AND CONSTRUCTABILITY IN SINGAPORE

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ABSTRACT

The construction industry plays a significant role not only in economic growth, but also in environmental impacts. As the global recognition on sustainable development, the construction industry is now highly challenged from high material consumption, energy consumption, CO_2 *emission, and social problems. In addition, Singapore government has launched buildability appraisal system and productivity enhancement scheme to encourage construction industry improve productivity. Under the pressure of reducing environmental impacts and increasing productivity, economic goal is not the only factor that should be considered when doing decision making. There is a clear need for a link between economic performance, environmental performance and productivity performance. Sustainability philosophy and constructability philosophy are useful when establishing such a link. However, little has been done on the connection between constructability principles and sustainable development. This paper presents a holistic framework to show the factors that affect the decision making on selecting structural materials. Based on the framework, a decision support model is established using Multi-attribute value technique. The weights of* 1^{st} *level factors and* 2^{nd} *level attributes have been computed using AHP method and 1-5 likert scale method. The rating method is offered as well.*

Keywords: *Building Structural Material, Multi-Attributes Value Technique, Sustainable Construction.*

1. INTRODUCTION

Constructability is a unique and important target that should be achieved by the Singapore construction industry. Constructability is defined by Construction Industry Institute of Australia (1993) as “a system for achieving optimum integration of construction knowledge in the building process and balancing the various project and environmental constraints to achieve maximisation of project goals and building performance”. As Singapore is a city state boasting a 5 million population with a land area of about 700 square kilometres, one problem occurs in this city is the confliction between progressive tightening on supply of foreign workers and increasing demand for better quality make. Hence, it is necessary for the Singapore construction industry to adopt labour-efficient designs and construction techniques.

In recent years, as global environmental problems, such as the depletion of natural resources, environment pollution, earth warming, sea levels raising, and biodiversity endangering, attract the attention of many countries and organisations, sustainability has become an essential concept in many countries’ strategies for both economic and environmental development. For a small country like Singapore, developing in a sustainable way is not an option but a necessity. Subsequently, the Sustainable Singapore Blueprint (Inter-Ministerial Committee on Sustainable Development, 2009) was announced by the Singapore government in April 2009.

The building and construction sector, being one of the key drivers of Singapore’s economy, will be at forefront of this national effort, Sustainable Singapore. This means sustainable construction should be strongly encouraged in the building industry because half of the total of raw materials extracted from the planet is used by construction and more than half of the waste produced comes from this sector (Mourão, 2007).

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Nowadays, building and construction industry is under great pressure of reducing environmental impacts and increase productivity. Therefore, economic goal and constructible performance are no longer the only targets that should be pursued by this industry; environmental sustainability should be highly considered as well. The challenge lies in achieving the right balance between economic performance, environmental performance and constructible performance. There is a clear need to establish the connection between these three aspects. The implication and existing applications of sustainability philosophy and constructability philosophy will be useful when establishing such a link. However, little has been done on the connection between constructability principles and sustainable development.

In order to take a good starting to establish such a connection, three considerations should be noticed. Firstly, from the economic perspective, building structure accounts for 20%-25% of total construction cost (Elnimeiri and Gupta, 2008). Secondly, in the environmental aspect, according to the report by Canada Wood Council (CWC, 1997), materials of building structure (concrete and steel) have high environmental impacts such as resource consumption, green house gas emission, etc. Thirdly, for constructability performance, building structure occupies half of the total score in Buildable Design Appraisal System (BDAS) in Singapore (BCA, 2006), and half of the total score in Constructability Appraisal System (CAS) (BCA, 2011b). It is obvious that selection of frame materials in a sustainable and constructable way is a proper point to take the first step to build the link between economic sustainability, environmental sustainability, and constructability. Therefore, this paper aims to develop a framework to help decision makers select structural frame in a more sustainable and constructable way.

2. THE DEVELOPMENT OF THE FRAMEWORK - DSSSSM

2.1. PREVIOUS STUDIES ON ECONOMIC, ENVIRONMENTAL SUSTAINABILITY AND CONSTRUCTABILITY

In building investment, traditional cost-accounting methods are widely used as the core indicators for investment decision as well as alternative making. However, as it becomes increasingly more important to consider environmental sustainability and constructability, decision makers will need to pay more attention to these two dimensions when seeking to attain profit goals. Life Cycle Cost (LCC) methodology is proved as a good solution to evaluate the real economic performance when considering environment issues (Aye *et al.*, 2000; British Standard Institute, 2008; Kaenzig and Wüstenhagen, 2010; Smith and Jaggar, 2007). In this study, the cost categories of LCC defined by British Standard Institute (2008) was adopted. The BSI LCC system is composed by 6 categories: construction costs, maintenance costs, operation costs, occupancy costs, end of life costs, and non-construction costs. In these categories, operation costs and occupancy costs are mainly affected by the materials and size of envelop elements, usages of buildings, and air-condition systems etc. Structural materials have little effect on operation costs and occupancy costs. Therefore, operation costs and occupancy costs are not evaluated in this study.

To investigate the environmental impacts, the authors have reviewed the Building Research Establishment (BRE) Environmental Assessment Method (BRE, 2011), Leadership in Energy and Environmental Design (USGBC, 2011) and Singapore Green Mark (BCA, 2011a) systems. It was found that these systems have provided the following indicators to assess the environmental performance associated with structural materials: percentage of reuse materials (reuse rate), percentage of recycle materials (recycle rate), waste, CO_2 emission, water consumption, noise and etc.

BDAS and CAS, encouraged by Singapore Building and Construction Authority (BCA) to improve buildability and constructability, are mainly focus on labour saving improvement (BCA, 2011b). However, other than labour saving, there are several aspects are implied in constructability concept, such as resource accessibility (Trigunarsyah, 2007), construction quality and safety (Ugwu *et al.*, 2004).

In order to develop an integrated model for material selection, considerable works have been done. For example, Castro-Lacouture *et al.*(2008) and Paya-Zaforteza *et al.* (2009) developed their models for selection of structural material by integrating the environmental and cost goals where constructability criteria were absent. Elnimeiri and Gupta (2008) and Giudice *et al.* (2005) developed their models for selection of structural materials by integrating the environmental and constructability requirements where economic factors were not considered. Sirisalee *et al.* (2004) developed their model for selection of structural material by integrating the cost and constructability goal where environmental factors were excluded. Despite the growing awareness of the importance of pursuing both sustainability and constructability in building and construction industry, there is still no model which synthetically assesses economic sustainability, environmental sustainability and constructability performance for structural material selection between RC and steel. In this paper, a synthetically conceptual framework is given below.

2.2. CONCEPTUAL FRAMEWORK

Based on the literature review, it can be hypothesised that building structural material selection is determined by the synergies of the economic sustainability performance, the environmental sustainability performance, and the constructability performance. The conceptual framework is shown in Figure 1, which indicates how these factors function in the decision system.

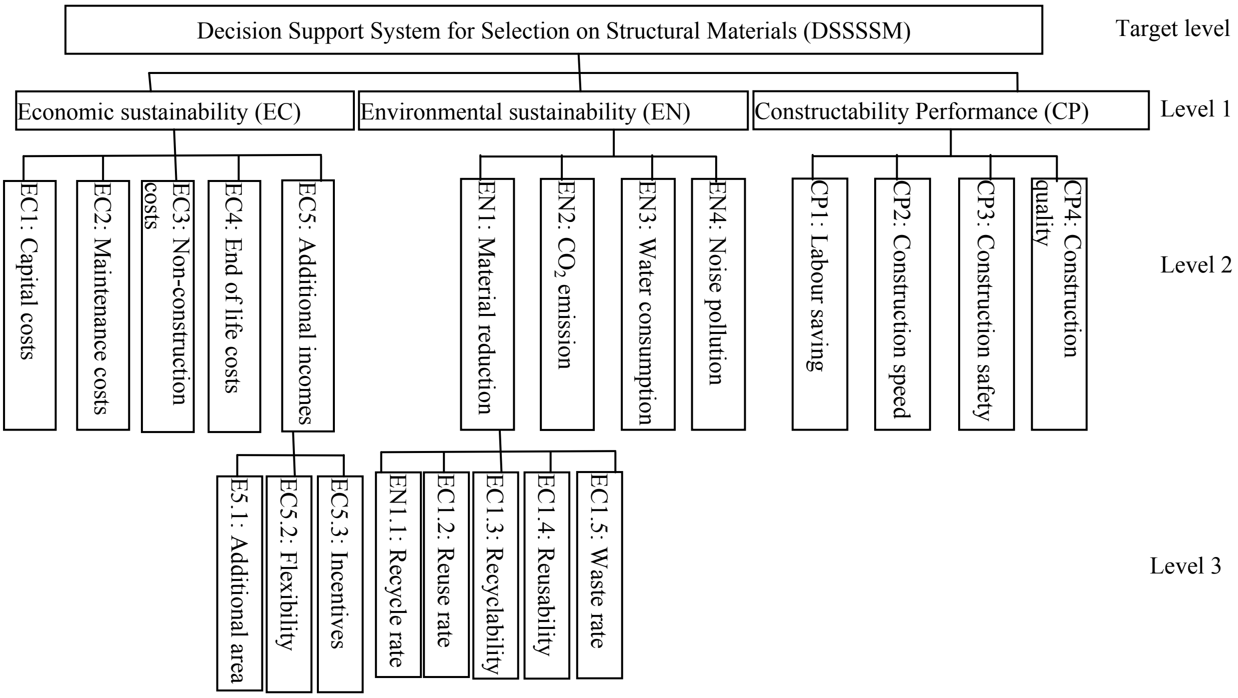

Figure1: DSSSSM Conceptual Framework

In this conceptual framework, 5 attributes indicate economic sustainability applied for structural material: capital costs (including costs of substructure, costs of superstructure, contingency costs, preliminary costs, and design costs), maintenance costs (including fire protection costs and corrosion protection costs), non-construction costs (including financial costs and taxes), end of life costs (including disposal costs and demolition cost), and additional income (including benefit from addition using area, benefit from flexibility of internal space, and possible incentive from BCA productivity enhancement scheme). 4 attributes indicate environmental sustainability applied for structural material: material reduction (including material recycle rate, material reuse rate, material recyclability, material reusability, and the material waste rate), CO$_2$ emission, water consumption and noise during construction. Another 4 attributes indicate constructability performance applied for structural material: labour saving, construction speed, construction safety, and construction quality.

3. RESEARCH METHODOLOGY

3.1. RESEARCH PROCESS

The research process is shown in Figure 2. Following the identification of research problems (step 1), literature review (step 2) was conducted to form the conceptual framework (step 3) of this study, as well as the questionnaire (step 4). After refining the questionnaire (step 6) from pilot studies (step 5), data collection (step 7) was conducted. Following statistical analysis, those data were used to develop the decision support system for the selection of structural materials (step8) using multi-attributes value technique (MAVT). The establishment of the DSSSSM is composed by two elements, weighting of all factors and attributes (section 4.1) and rating of attributes (section 4.2) Validation of the model (step 9) is currently conducted before making the conclusions and recommendations (step 10). This paper mainly reports the model construction, which including step 3, step 7 and step 8.

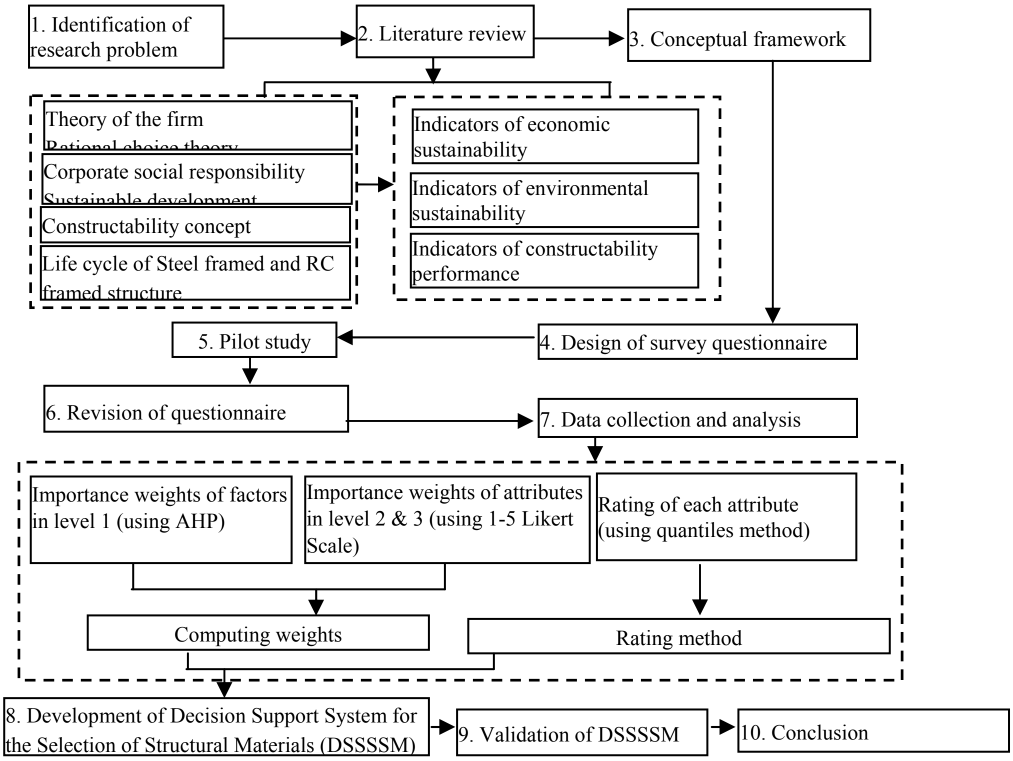

Figure 2: Research Progress

3.2. SURVEY

This research aims to investigate decision makers' perception of the impacts of those pre-addressed factors and attributes on selection of structural frame materials. Survey method is proper for achieving this aim because survey may reflect respondents' attitude and beliefs (Royse, 2008) and is efficient in collecting information from the population (Tan, 2004). The data was collected by face to face interview using a structured questionnaire. In this study, 30 Reinforced Concrete (RC) framed buildings and 9 Structural Steel (SS) buildings had been investigated. RC projects were randomly selected from those projects constructed in recent 3 years in Singapore, while SS projects were selected with wider range of 10 years due to limited numbers of SS buildings in Singapore. These projects consist of residential buildings, commercial buildings, institutions and official buildings. The information of each project was collected by interviewing a group composed by 2-3 experts who involved in that project. In order to obtain comprehensive information of each project, these experts were allocated to multi-discipline of contractors, architects and engineers.

4. MULTI-ATTRIBUTES VALUE TECHNIQUE (MAVT)

4.1. WEIGHTING

The first part of MAVT is to computing weights of criteria and attributes. Weights reflect the priority of each factor and attribute. In this study, it is shown from the decision hierarchy in Figure 2 that there are three level weights need to be determined.

The weights of the three factors (EC, EN and CP) make up the first level weighs (refer to Figure 1). The first level weights are obtained by using Saaty's Analytic Hierarchy Process (AHP) technique (Saaty, 2005). The participants were asked to compare each factor against one another based on Saaty's 1-9 point scale using pair wise comparison method to establish their relative importance. In Saaty's 1-9 point scale method, 1 means equal importance, and 9 means absolute importance. In order to minimise the possibility of bias, all participants were asked to select the number in accordance with their experienced judgments.

All of the data from the pair wise comparison were used to compute the weights of first level factors (ω_i). It was not practical to use AHP technique to obtain the weights of those attributes on level 2 and 3 due to large number. Therefore, the 1-5 Likert Scale was used to investigate the weights of those attributes in 2nd and 3rd level, where 1 means not important, 3 means neutral and 5 means very important. All of the respondents were asked to tick the extent to which each attribute contribute to the selection on structural frame material.

The weight for each attribute (ω_{ij}) is obtained using the Eq: 01.

$$\omega_{ij} = a_{ij}\omega_i \qquad \text{(Eq: 01)}$$

Where a_{ij} is the weight of attribute j under factor i.

$$a_{ij} = \frac{a_j}{\sum_{j=1}^{m} a_j} \qquad \text{(Eq: 02)}$$

$$a_j = \frac{1(n_1)+2(n_2)+3(n_3)+4(n_4)+5(n_5)}{n_1+n_2+n_3+n_4+n_5} \qquad \text{(Eq: 03)}$$

Where a_j is the mean importance rating of an attribute. $n_1,\ n_2,\ n_3,\ n_4,\ n_5$ are the numbers of subjects who rated the attributes as *1, 2, 3, 4, 5*. j is the attribute reference and there are m numbers of attributes under factor i.

4.2. RATING

The second part of the MAVT is to rating each attribute, which assist decision makers to allocate score to each attribute in an objective and straight forward manner. To enhance the accuracy of the performance of each attribute, exact information of particular project were asked in the questionnaire for those participants to provide (for example, the construction duration for structural works, the CONQUS score for structural construction, and etc.). Once the data having been collected, T test was conducted to test the significance.

After the statistic analysis, the performance values of each attribute were classified into 5 groups using quantiles method (Hyndman and Fan, 1996). The rating method is shown in Eq: 04. Score 10, 7.5, 5, 2.5, and 0 represent those points from located in the range of the group with the best performance (G1) to the group with the worst performance (G5).

$$r_{ij} = \begin{cases} 10, & if\ the\ performance\ value\ of\ an\ attribute\ \in\ G1 \\ 7.5, & if\ the\ performance\ value\ of\ an\ attribute\ \in\ G2 \\ 5, & if\ the\ performance\ value\ of\ an\ attribute\ \in\ G3 \\ 2.5, & if\ the\ performance\ value\ of\ an\ attribute\ \in\ G4 \\ 0, & if\ the\ performance\ value\ of\ an\ attribute\ \in\ G5 \end{cases} \qquad \text{(Eq: 04)}$$

Where r_{ij} is the rating given to the j^{th} attribute of i^{th} criteria. Due to the model is still in the validation stage, the actual rating ranges are not shown in this paper.

After rating an attribute, the score for each attribute is computed by multiplying the weight and the rating score. The additive method of aggregation was used to calculate the selection on structural material (SSM) score. The value function is given in Eq: 05:

$$SSM_k = \omega_1 \sum_{j=1}^{5} \omega_{1j} r_{1j} + \omega_2 \sum_{j=1}^{4} \omega_{2j} r_{2j} + \omega_3 \sum_{j=1}^{4} \omega_{3j} r_{3j} \qquad \text{(Eq: 05)}$$

Where SSM_k is the total score for structural material k. The option with higher SSMscore is more preferred for decision makers.

5. DATA ANALYSIS

The data collected were analysed using the Statistical Package for Social Science software (SPSS). One sample t-tests of the mean were carried out to check the entire population's response to the addressed attributes in the survey. The null hypothesis (H0) was set as: μ=μ0 and alternative hypothesis (H1) was set as: μ≠μ0, where μ was the sample mean; μ0 was the population mean. μ0 was fixed at the value of 3 according to the definition given in the rating scale 1~5. If μ is less than 3, it means the corresponding attribute is not important on the determination of selection of structural frame materials. H0 would be rejected and μ would be less than μ0 if the value of significance at 95% confidence level was less than 0.05 with negative mean difference.

Respondents were asked to tick the importance of each attribute when making decisions on selection of structural materials. Then the collected 39 sets of data were input into SPSS to conduct sample t-tests. According to the results of sig (2-tailed) value and mean difference, those attributes were regarded as not important when H0 was rejected with negative mean difference. To refine the decision support model, those non-important attributes will be removed from the model.

6. CONCLUSIONS

This study offers a new framework to assist decision makers to select building structural frame material to achieve sustainability and constructability in Singapore. It explored the factors that affect the decision making on selection of building structural materials, revealing that the determination on building structural materials is integrally affected by 3 factors: economic sustainability (EC), environmental sustainability (EN) and constructability (CP). Furthermore, these 3 factors are determined by 13 attributes (EC1~5, EN1~4, and CP1~4). A series of survey had been conducted to test the hypothetical framework.

It should be noted that there are two limitations in this paper. First, although the DSSSSM model is flexible for application in other countries, this model is based on projects in Singapore. If decision makers want to use this model overseas, they have to build a new database by investigating the local projects in that country. Secondly, due to this study is still in the validating stage, the statistical results are not available for this paper right now. The further results will be reported in the near future. This study has taken the first step in addressing the link between economic sustainability, environmental sustainability, and constructability in terms of selection on building structural materials. In addition, the DSSSSM framework might be helpful for decision makers to choose a more sustainable and constructable structural frame.

7. REFERENCES

Aye, L., Bamford, N., Charters, B., and Robinson, J. (2000). Environmentally sustainable development: a life-cycle costing approach for a commercial oKce building in Melbourne, Australia. *Construction Management and Economics, 18*, 927-934.

BCA. (2006). *Buildable design appraisal system*. Singapore: Building Construction Authority.

BCA. (2011a). *BCA green mark scheme*. Retrieved from http://www.bca.gov.sg/GreenMark/green_mark_buildings.html.

BCA. (2011b). *Code of practice on buildability*. Singapore: Building Construction Authority.

BRE. (2011). *BREEAM UK 2011 version.* UK: Building Research Establishment.

BSI. (2008). *Standardized method of life cycle costing for construction procurement*. London, UK: British Standard Institute.

Castro-Lacouture, D., Sefair, J. A., Flórez, L., and Medaglia, A. L. (2008). Optimization model for the selection of materials using a LEED-based green building rating system in Colombia. *Building and Environment, 44*(6), 1162-1170.

Construction Industry Institute of Austrailia. (1993). *Constructibility Principles File.*. Adelaid: Construction Industry Institute

CWC. (1997). *Green by design:Renewable, durable, sustainable wood*. Canada: Wood Council.

Elnimeiri, M., and Gupta, P. (2008). Sustainable structure of tall buildings. *Structural Design of Tall and Special Buildings, 17*(5), 881-894.

Giudice, F., La Rosa, G., and Risitano, A. (2005). Materials selection in the life-cycle design process: A method to integrate mechanical and environmental performances in optimal choice. *Materials and Design, 26*(1), 9-20.

Hyndman, R. J., and Fan, Y. (1996). Sample quantiles in statistical packages. *The American Statistician, 50*(4), 361-165.

Inter-Ministerial Committee on Sustainable Development. (2009). *Report of the inter-ministerial committee on sustainable development*. Singapore.

Kaenzig, J., and Wüstenhagen, R. (2010). The effect of life cycle cost information on consumer investment decisions regarding eco-innovation. *Journal of Industrial Ecology, 14*(1), 121-136.

Mourão, J. P. J.B. (2007). Sustainable housing: from consensual guildelines to broader challenges. In L. E. A. Braganca (Ed.), *Portugal SB2007. Sustainable construction, material and practices* (pp. 27-34). IOS Press.

Paya-Zaforteza, I., Yepes, V., Hospitaler, A., and González-Vidosa, F. (2009). CO2-optimization of reinforced concrete frames by simulated annealing. *Engineering Structures, 31*(7), 1501-1508.

Royse, D. (2008). *Research methods in social work.* (5th ed.). Belmount, USA: Thomson Brooks.

Saaty, T. L. (2005). *Theory and applications of the analytic network process*. Pennsylvania: RWS Publications.

Sirisalee, P., Ashby, M. F., Parks, G. T., and Clarkson, P. J. (2004). Multi-criteria material selection in engineering design. *Advanced Engineering Materials, 6*(1), 84-92.

Smith, J., and Jaggar, D. (2007). *Building cost planning for the design team*. Liverpool: Elsevier.

Tan, W. (2004). *Practical research methods* (2nd ed.). Singapore: Pearson Education South Asia.

Trigunarsyah, B. (2007). Project designers' role in improving constructability of Indonesian construction projects. *Construction Management and Economics, 25*(2), 207-215.

Ugwu, O. O., Anumba, C. J., and Thorpe, A. (2004). The development of cognitive models for constructability assessment in steel frame structures. *Advances in Engineering Software, 35*(3-4), 191-203.

USGBC. (2011). *LEED rating systems*. Retrieved from http://www.usgbc.org/DisplayPage.aspx?CMSPageID=220