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DESIGN ECONOMICS FOR DUAL CURRENCY MANAGEMENT IN CONSTRUCTION PROJECTS

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ABSTRACT

Design variables are major determinants of cost of a building and the theoretical stance of the relationship between design variables and cost is already established. However, design economics becomes more interesting when dealing with dual currency – cost and carbon. Also, the knowledge of design economics becomes significant for dual currency management as there is a growing concern to reduce embodied carbon economically. Therefore, the aim of the paper is to review the literature on design economics and deduce relationships between Capital Cost (CC) and design variables; and initial Embodied Carbon (EC) and design variables by collecting data of 10 office buildings in the UK. The relationships are explained through descriptive statistics and comparisons are made between CC and initial EC relationships with that of the design variables. Findings reveal building size, height, façade area and no. of basements are correlated with CC and initial EC of the buildings. Also, a fair linear relationship was evident between CC per Gross Internal Floor Area (GIFA) and EC per GIFA of the buildings which gives an indication that it is possible to reduce both CC and initial EC by concentrating on the outline design.

Keywords: capital cost, correlation, design economics, initial embodied carbon, office buildings.

INTRODUCTION

Design economics is a key to meet complex challenges imposed by client and external factors to ensure balance between triple bottom line – economic, environment and social performances (Robinson, Symonds, Gibson, & Llozor, 2015). While there are prepositions for design economics in terms of cost, the other side of the coin which is carbon, has gained popularity only since fairly recently. Hence, there is a lack of literature in design economics for carbon management. Also studies conducted at different parts of the world prove that the defined cost and design variables relationships deviate from some of the general propositions of capital cost and design variables relationships which demonstrate that the theoretical propositions are context specific (Picken & Ilozor, 2015). Therefore, it is important that the cost and design variables relationships are identified in a specific context by collecting data. Furthermore, dual currency management is becoming a trend in the construction industry (Ashworth & Perera, 2015) and eco clients also demand dual currency appraisal of their projects (i.e. cost and carbon appraisal). On the other hand, low and zero operational carbon agenda created the necessity of focusing on the unregulated composition of carbon emission which is embodied carbon emissions.

Embodied Carbon (EC) includes fuel related and process related carbon emissions (Hammond & Jones, 2011). EC of a building can be quantified from raw material extraction till the end-of-life of the building or even beyond end-of-life impacts like recycling and reusing (RICS, 2014). The scope of EC measurement is defined as the system boundary of the analysis. Initial EC includes sum of the emissions from raw material extraction up to the construction of the building which is called as the 'Cradle to Gate' system boundary. Initial EC and Capital Cost (CC) can be expected to follow the same behavior due to same constituents (materials and plants) except for labour as carbon exhaled from labour is a natural process and cannot be accounted as an emission source of construction activity. Even though both CC and initial EC are expected to behave in a similar fashion, there can be exceptions due to differences in rates. For instance, timber is an expensive material while its embodied carbon content is very low. Therefore, it is important that this behavior is captured from historical data to develop context specific theories which in turn will help to achieve design economic for dual currency management of construction projects.

LITERATURE REVIEW

Capital cost and design variables relationships

Relationship between CC and design variables is presented in Table 1. Facts presented in the table are drawn from both theoretical concepts and experiments on cost models. The cost models reviewed were mainly regression models which confirm linear relationship between design variables and cost. Accordingly, plan shape (or Wall to Floor ratio), building size (or Gross Internal Floor Area (GIFA)), circulation space, grouping of buildings, storey height, total height of the building and quality factors are the key design variables to pay attention during conceptual stage design decision making.

Table 1: Capital cost and design variables relationships from literature

Design variables	Comments	Reference
Plan shape or Wall to Floor ratio	Design with the lowest ratio is economical in terms of plan shape. However, sometimes site layout dictates the plan shape where alternative design solutions will be limited.	Ashworth (2010); Collier (1984); Dell'Isola and Kirk (1981); Morton and Jaggar (1995); Robinson and Symonds (2015); Seeley (1996)
Building size or GIFA	As the building size increases project overheads tend to decrease due to economies of scale. Also discounts on bulk purchase will result in reduced cost per m^2 GIFA.	Ashworth (2010); Asiedu and Gu (1998); Bowlby and Schriver (1986); Collier (1984); Dell'Isola and Kirk (1981); Karshenas (1984); McGarrity (1988); Morton and Jaggar (1995); Phaobunjong (2002); Robinson and Symonds (2015); Seeley (1996)

Planning efficiency or proportion of circulation space	Lower non-usable space will save energy cost. However, it is subject to planning requirements and the function of the building.	Ashworth (2010); Morton and Jaggar (1995); Phaobunjong (2002); Robinson and Symonds (2015); Seeley (1996)
Building layout/grouping of buildings	Advantage from common elements reduces cost per m^2 GIFA.	Ashworth (2010); Robinson and Symonds (2015); Seeley (1996)
Storey height	Higher the storey height higher the cost per m^2 GIFA.	Ashworth (2010); Dell'Isola and Kirk (1981); Morton and Jaggar (1995); Seeley (1996)
Total height or No. of floors	Relationship with total height and cost is slightly complex. Different studies at different locations report different results. Generally, cost per m^2 GIFA expected to increase with building height.	Ashworth (2010); Bowlby and Schriver (1986); Dell'Isola and Kirk (1981); Karshenas (1984); McGarrity (1988); Morton and Jaggar (1995); Phaobunjong (2002); Picken and Ilozor (2015); Robinson and Symonds (2015); Sawalhi (2012); Seeley (1996)
Quality factors	Quality of finishes and services affect the cost. Higher the quality higher the cost.	Dell'Isola and Kirk (1981); Robinson and Symonds (2015); Sawalhi (2012)

Initial embodied carbon and design variables relationships

Literature on EC and design variable relationship is not rich like the literature on capital cost and design variable relationships. In fact, there is a lack of literature in this area. However, a study conducted by Luo, Yang, and Liu (2015) with 78 office buildings in China found that EC per GIFA has a strong positive correlation (0.883) with number of storeys of the buildings. Nevertheless, relationship with other design variables are not reported by Luo et al. (2015).

In addition to that data of 31 office buildings were obtained from WRAP Embodied Carbon Database (WRAP and UK Green Building Council, 2014) and the relationship between available design variables are presented in Table 2. Results reveal that there is significant linear relationship between EC and GIFA; and EC and number of floors of the buildings (as, sig < 0.05). However, correlation between EC and GIFA (or size of the building) is stronger than the correlation between EC and number of floors.

Table 2: Embodied carbon and design variable relationship from WRAP database

		GIFA	No. of Floors	No. of basements
Embodied	Correlation	.859**	.433*	-.033
Carbon	Sig. (2-tailed)	.000	.015	.860

Capital cost and embodied carbon relationships

CC and EC relationship is also rarely explored in construction management literature. Sansom and Pope (2012) reported case studies of different types of buildings including: distribution warehouse, supermarket, secondary school, office and mixed-use building. Initial EC to CC ratio were calculated for all case study buildings which are presented in Figure 1.

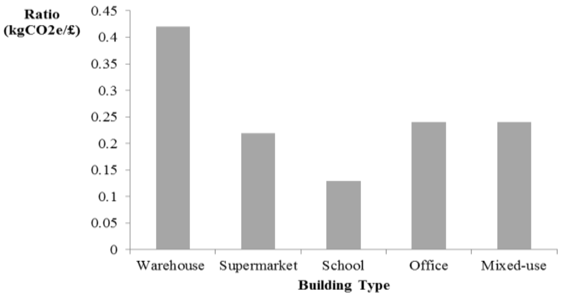

Figure 1: Embodied carbon to capital cost ratio of different types of buildings

Office and mixed-use building (high-rise) had the same ratio of 0.24; supermarket (low-rise) had a ratio of 0.22 close to office and mixed-use; secondary school (medium-rise) had the lowest ratio of 0.13 and warehouse (low-rise) with the highest ratio of 0.42 as a result of the lowest cost among all. However, when the EC to CC ratio of structure (Frame and Upper Floors) was analysed, warehouse building had the lowest ratio (0.49) whereas office building had the highest ratio (0.69). While these ratios can be used to estimate EC during early stages of design, the explanatory power of the outcome is limited.

Besides, Langston and Langston (2008) studied the relationship between Embodied Energy (EE) and CC at various levels of details (such as, projects, elemental groups, elements and selected items of work) with the goal of predicting EE based on CC. Langston and Langston (2008) found a strong positive correlation between embodied energy and capital cost of the buildings. However, this relationship may be as a result of a third variable producing causality between variables which was not explored. It was also identified that correlation between EE and CC drops as the level of detail increases from project level to individual work item level. This means that all work items collectively at the project level demonstrates a correlation between EC and CC rather than individually which indirectly conveys that differences in rates (cost and energy) of work items are neutralised when analysed at the project level.

There is a close association between EC and EE, however, both are distinguishable and cannot be interchangeable (Brandt, 2012; Lélé, 1991). Because, EC includes the emissions resulting from EE (fuel related emissions) as well as process related emissions as defined by Hammond and Jones (2011). Therefore, EC and CC relationship could be different to EE and CC relationship. Furthermore, the study sample of Langston and Langston (2008) includes buildings with different functions and both new build and redevelopments. A shortfall of this study is that it fails to account for differences that might be attributable to the function of the building. For instance, generally 20-30% of total emissions in buildings are associated with EC while EC of warehouses can account for up to 80% (See, RICS, 2014). This is also evident in the findings of Sansom and Pope (2012). Therefore, it is important to confine the sample to a particular type of building and type of work (i.e. new build or renovation).

THE METHOD

A comprehensive literature review was conducted to establish theoretical stance of the CC, EC and design variable relationships. Then, data were collected to verify the established theoretical relationships and deduce context specific relationships of the same. Consequently, Bills of Quantities (BQ) or detailed cost plans of 10 office buildings in the UK were collected (see table for description of the sample) and CC and EC estimates were produced using the UK Building Blackbook ensuring same base (date and location) for all estimates. Further, design variables were captured from layout drawings of the buildings. Then, a database was developed containing CC, EC and design variable data. The design variables presented in the paper includes: GIFA, total height, façade area, plan shape or Wall/Floor and number of basements. Relationship of Quality factors with EC and CC are not explored in this paper because of the on-going nature of the research.

Table 3: Summary of data

Building Code	GIFA	Storeys
B – 01	33,663	18
B – 02	11,320	8
B – 03	2,859	3
B – 04	15,120	7
B – 05	63,246	16
B – 06	21,300	13
B – 07	22,288	10
B – 08	3,289	4
B – 09	3,262	3
B –10	4,959	3

Then, statistical analysis was performed over the data to capture the relationships. Pearson's correlation was performed used to identify relationships and where bivariate analysis was performed between design variables, CC and EC (assuming linear relationship between variables). Then, the derived relationship patterns were compared with established theoretical norms and conclusions were arrived. Major imitation of the study is the sample size. As the sample size is small no definite conclusions can be drawn from the analysis, however, the analysis is presented as a preliminary investigation of the research problem identified and leads to further research. The same techniques can be applied to a larger sample and robust conclusions can be drawn.

RESEARCH FINDINGS AND DISCUSSION

Capital cost and design variables relationships

Bivariate analysis between CC and key design variables of the sample buildings is presented in Table 4. According to the analysis, GIFA, height and façade area of the building are highly correlated ($\alpha < 0.05$) with CC of the building which is in line with literature findings. Number of basements also demonstrates a moderate positive correlation. On the other hand, Wall to Floor ratio shows insignificant negative correlation.

Table 4: Bivariate analysis of capital cost and design variables

		GIFA	Total Height	Façade Area	Wall/Floor	No. of Basements
Capital Cost	Correlation	.989	.789	.962	-.436	.624
	Sig. (2-tailed)	.000	.007	.000	.208	.054

In addition to that, correlation between CC per m^2 GIFA and design variables were analysed to get insights in to the cost and design variable relationships irrespective of the GIFA as it is explicit that bigger the building higher the cost. Correlations are presented in Table 5. Results suggest that there is no significant relationship is found between design variables and the CC per m^2 GIFA of the building which is surprising while the literature suggests that taller buildings will generally have higher CC per GIFA and lower Wall to Floor ratio will result in reduced CC per GIFA. These insignificant results may be due to a lower sample size. However, with a larger sample, results can be improved and may support literature findings.

In addition to that, McGarrity (1988) argues that predicting cost per GIFA based on design variables might be misleading as it ignores economies of scale as the size of the building increases. Hence, building size has a major role in predicting CC of the building.

Table 5: Bivariate analysis of capital cost per GIFA and design variables

		Total Height	Façade Area	Wall/Floor	No. of Basements
Capital Cost	Correlation	.286	.429	-.010	.146
per GIFA	Sig. (2-tailed)	.424	.216	.978	.687

Initial embodied carbon and design variables relationships

Table 6 depicts the results of bivariate analysis between EC and key design variables of the sample. Interestingly, design variables correlate with EC in a similar fashion to CC, however, the identified correlations are stronger with EC. This confirms that EC behaves much like CC, which we earlier postulated.

Table 6: Bivariate analysis of embodied carbon and design variables

		GIFA	Total Height	Façade Area	Wall Floor	No. of Basements
Embodied	Correlation	.997**	.833**	.972**	-.457	.653*
Carbon	Sig. (2-tailed)	.000	.003	.000	.184	.041

Table 7 presents the bivariate analysis between EC per GIFA and design variables. Interestingly, EC per GIFA and the identified design variables except Wall to Floor ratio demonstrate strong positive correlations unlike CC per GIFA. The study finding with regards to the relationship between height of the building and EC per GIFA is in line with the findings of Luo et al. (2015) and the correlations are very similar.

Table 7: Bivariate analysis of embodied carbon per GIFA and design variables

		Total Height	Façade Area	Wall Floor	No. of Basements
Embodied Carbon	Correlation	.827**	.814**	-.193	.701*
per GIFA	Sig. (2-tailed)	.003	.004	.593	.024

Capital cost and embodied carbon relationships

Pearson's correlation was performed between CC and EC. As can be expected from the above findings, CC and EC are linearly correlated with a strong positive correlation of 0.995 (sig = 0.000). Similarly, Langston and Langston (2008) also found a strong positive correlation between embodied energy and capital cost. However, this relationship could be a result of a third variable which is causing a strong positive correlation which was not configured by Langston and Langston (2008). The third variable is apparently GIFA of the building due to the fact that bigger buildings constitute more material which will eventually result in higher CC and EC. Therefore, the same analysis was performed again by normalising CC and EC to GIFA. Analysis suggests that there is no perfect linear correlation as with CC and EC. However, there is a significant positive correlation of 0.640 (at sig = 0.046). This showcases that both CC and EC reductions are possible at the same time through efficient building designs.

CONCLUSION

Even though cost and design variable relationships are well established, different behaviours can be observed in different parts of the world. . Similarly, EC and design variable relationship can also be assumed to be context specific. However, there is a lack of literature exploring design economic for dual currency management in construction. The analysis presented in the paper is an attempt of stimulating the research interest in this area. According to the findings, CC and EC demonstrates significant correlations with building size (or GIFA), total height and façade area, while EC had significant correlation with number of basements too. It was expected that Wall to Floor ratio will demonstrates a positive correlation with CC per m^2 GIFA and EC per m^2 GIFA while the results suggest different behaviour resulting in negative insignificant correlations. This reason for the behaviour was identified as the buildings with lower Wall to Floor ratio are the ones with higher GIFA. Hence, GIFA overriding Wall to Floor ratio. Later, when CC and EC were normalized to GIFA different behaviours were monitored as CC per m^2 GIFA did not show significant relationship with the identified design variables while EC per m^2 GIFA demonstrated significant correlations. Summary of the relationships are presented in Table 8.

Table 8: Summary of capital cost, embodied carbon, design variables relationships

Design Variables	Correlations			
	CC	**CC/GIFA**	**EC**	**EC/GIFA**
GIFA	Strong	N/A	Strong	N/A
No. of floors/Storey height	Strong	Insignificant	Strong	Strong
Façade area	Strong	Insignificant	Strong	Strong
Wall to Floor ratio	Insignificant	Insignificant	Insignificant	Insignificant
No. of basements	Moderate	Insignificant	Moderate	Moderate

Further, CC and EC are perfectly correlated while CC per m^2 GIFA and EC per m^2 GIFA are moderately correlated. If CC and EC are strongly correlated and affected by design variables in the same way then both CC and EC can be minimised at the conceptual stage as the design decisions made during early stages become irreversible and the reduction potential diminishes radically. Therefore, it is worth exploring this area with a larger sample to derive stable results as the sample size is a key limitation of the study. However, by obtaining more data sample the research intend to develop EC and CC models to simplify early design stage decision making.

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