EVALUATING THE WHOLE-LIFE COST IMPLICATION OF REVOCABILITY AND DISRUPTION IN OFFICE RETROFIT BUILDING PROJECTS

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Retrofit buildings are becoming popular in the United Kingdom as well as many parts of the advanced economies. Existing whole-life costing models have however, not proven to be robust enough to deal with building retrofit scenarios. Recent research has made a case for the existence of revocability and disruption in building retrofit investments. This paper evaluates the whole-life cost implication of revocability and disruption in office retrofit building projects. The potential implication of revocability and disruption are evaluated based on probability and fuzzy logic principles respectively. Two case study projects are selected to appraise the economic potentials of revocability and disruption. It was found that the average cost of revocability relative to the initial capital cost can be up to 119% over a 60-year life. It was also found that the average cost of disruption relative to the initial capital cost can be up to 12%. Future studies will utilise sensitivity analysis in assessing the relative preference of building retrofit configurations in office building projects. The external validity of this work is moderate, as the intention is to establish analytical generalisation rather than statistical generalisation for office retrofit building projects.

Keywords: disruption, office buildings, retrofit, revocability, whole-life costing

INTRODUCTION

The retrofitting of buildings provides a sustainable opportunity to reduce primary energy-use (Holness, 2010), extend the life-expectancy (Menassa and Baer, 2014), reduce maintenance and operating costs, as well as improve thermal comfort of occupants (Ma *et al.*, 2012). Despite the social and environmental benefits of retrofitting, the economic costs of retrofit buildings are not exactly straight-forward (*Gleeson et al.,* 2011). At the heart of retrofitting is the strategic task of improving energy, waste and water efficiency in buildings (Dixon *et al.,* 2014). Energy-efficiency however, tend to be the more pressing issue, especially due to fluctuating energy prices, falling oil prices, and growing interests in renewables.

In recent times, whole-life appraisal has been more widely embraced in order to better integrate building design and out-turn costs (Flanagan and Jewell, 2005, Robinson and Symonds, 2015). A whole-life scenario provides a holistic and sustainable outlook to appraising the economic implications of built facilities (Caplehorn, 2012), and hence

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allows for a broader spectrum of variables to be examined. There are however, some difficulties in evaluating the whole-life cost estimates of building retrofits, and these pertain mostly to defining the nature and type of economic uncertainties associated with such building typology (Menassa, 2011). Some crucial uncertainties in costing of building retrofits relates to the savings estimations, energy-use measurements, weather-forecasts, changes in energy-consumption patterns, and system performance degradation. Other primary variables of uncertainties in whole-life cost estimations across a building's lifecycle include cash flow data, building-life period, investor's commitment, component service-life, and future decisions (Ellingham and Fawcett, 2006). High levels of uncertainties generally tend to diminish the accuracy of cost forecasts, and there is therefore a need for increased robustness in the representation and processing of uncertainties in the whole-life costing methodology.

Given the complex and intricate issues in whole-life cost modelling of office retrofit projects, identifying and evaluating the drivers of uncertainties provides an avenue for enhancing the integrity of whole-life costing models, and ultimately providing better decision-support for stakeholders. A common concern on the performance of existing whole-life cost models relates to the difficulty in predicting future costs. Ferry *et al.,* (1999) reckons that the estimation of future costs in built facilities, is often a product of guess work, and will be dependent on a mix of personal preferences and policy standards. In order to address these conceptual limitations in whole-life costing, it will be useful to appraise the implicit assumptions in existing models. This procedure holds potential in enhancing robustness in the whole-life costing methodology. It is also considered appropriate to focus on distinct strands of whole-life costing – future costs and initial costs. The drivers of uncertainties in the future costs and initial costs, will be discussed under the concepts of revocability and disruption respectively:

Revocability

Economic revocability connotes the potential for variability in the future cost projections in a building over its estimated life. Physical revocability implies that a certain level of efficiency or inefficiency is locked into a building. The term 'revocability' is attributable to Verbruggen *et al.,* (2011). However, other works have made implicit reference to the concept of revocability in a number of ways. For instance, the Communities and Local Government (CLG, 2011) referred to revocability as "lock-in" syndrome in buildings. Modelling revocability in whole-life cost scenarios comes across as a challenging task. One approach to enhancing the capacity for physical revocability is by designing for flexibility and adaptability in buildings. Economic revocability, which is the focus in this work, pertains mostly to future cost prospects in buildings. Ellingham and Fawcett (2006) suggested an approach to evaluating economic revocability in buildings by representing cash flows over building's life using the Negative Binomial Probability distribution. Kishk *et al.,* (2004) found that the choice of probability distribution function used in describing uncertainties associated with the input variables in whole-life costing, has no significant impact on the simulated output. It is however admissible that the use of probability distribution in representing cash flow distribution is a promising and established approach in the whole-life costing of buildings. Revocability, being an inherent driver of uncertainties in future costs will be appraised in this work.

Disruption

Disruption relates to the diminished building use, or un-usability, over a period of implementing a retrofit initiative. The cost of disruption is a useful consideration prior to deciding on a retrofit intervention. Investments initiatives in retrofit scenarios tend to involve some levels of disruption to the normal operation of building occupants (Gleeson *et al.,* 2011). Depending on the scale of disruption, this could significantly alter the business case of the entire retrofit project. Verbruggen (2013) implied that, a robust scenario analysis will be vital in appraising the effects of disruption. Gleeson *et al.,* (2011) conducted a disruption analysis on retrofit interventions, and provided a 3-scale assessment of Low, Medium and High level of disruption for various retrofit interventions. Gleeson *et al.,* (2011) estimated the number of days of disruption for individual installation of retrofit technologies in a typical house building project, and suggested the time of disruption could range between 2 – 12 days. For package retrofit installations, it is expected that project management considerations will impact on the effects of disruption in retrofit projects. Given that the effects of disruption are more readily defined in qualitative terms, the fuzzy logic approach will provide a systematic mechanism to evaluate and assess the effects of disruption in retrofit building projects.

Bearing in mind, the growing interest in retrofit initiatives, it will be necessary to assess the long-term implications of revocability and disruption in buildings, with a view to evaluating their potential costs over the entire life of the building. Menassa (2011) posits that a financial appraisal framework for retrofit initiatives does not yet exist. It is therefore essential that whole-life cost modelling be re-oriented to provide a viable means for appraising retrofit building scenarios. This study evaluates the whole-life cost implications of revocability and disruption in office retrofit building projects based on two case studies, using probability and fuzzy sets principles.

Whole-life costing

The application of whole-life costing in the UK began in the late 1950's. Goh and Sun, (2016) buttressed that whole-life costing allows the comparison of values which transcends problems of different lives, or different balances between capital and future costs. According to Ashworth and Perara (2013), whole-life costing serves as an aid to long-term, rational and realistic decision outcomes in building investment appraisals. The evidence from the built environment literature however, raises doubts on the ability of existing whole-life cost models to robustly appraise building projects. The distinct categories of existing whole-life costing models are the Standard whole-life costing, and the New-Generation whole-life costing models. The principles of these models, have been identified and discussed in Tokede *et al.,* (2013). The principal concerns regarding these existing whole-life costing approaches relate to the reliability of cost data (Ellingham and Fawcett, 2006), insufficient consideration of uncertainties (Caplehorn, 2012), and lack of robustness in model framework (Kirkham*,* 2014).

A suggested improvements to the whole-life costing framework is the embodiment of whole-life cost decisions in an options framework (Menassa, 2011). *Figure 1* below captures the potential options embedded in buildings over their entire lives. In *Figure 1*, simple options tend to have little or no initial cost, and hence future costs, are not dramatically altered from the base-case scenario. Examples of simple options, if exercised, include options to abandon, contract, expand, and 'do-nothing'. Compound options, on the other hand, if exercised, tend to involve more significant initial costs, and often have a more significant effect on the default future cost projections. Retrofit options are arguably popular among compound-option types available, and thus have huge potentials in improving building performance and long-term cost savings.

Kishk *et al.,* (2003) argues that the principles of whole-life costing are well developed in theory. There is however, compelling evidence that this is not the case, and there is scope for improving on the theoretical weakness of existing whole-life cost modelling procedures, especially in emerging building typologies. It has been inferred that whole-life costing involves a complex set of decision events, actions, outcomes, with significant interdependencies (Verbruggen *et al.,* 2011, Verbruggen, 2013), and attempts to ignore uncertainties in the model framework will lead to sub-optimal models, fostering incorrect decisions (Gluch and Baumann, 2004). The pervasive lack of confidence in existing whole-life cost models has fuelled recourse to gut-feeling and experience, rather than rely on the results from objective whole-life cost analysis (Ellingham and Fawcett, 2006). Clift and Bourke (1999) reported that only about 25% of organisations conduct whole-life costing prior to sanctioning building investments.

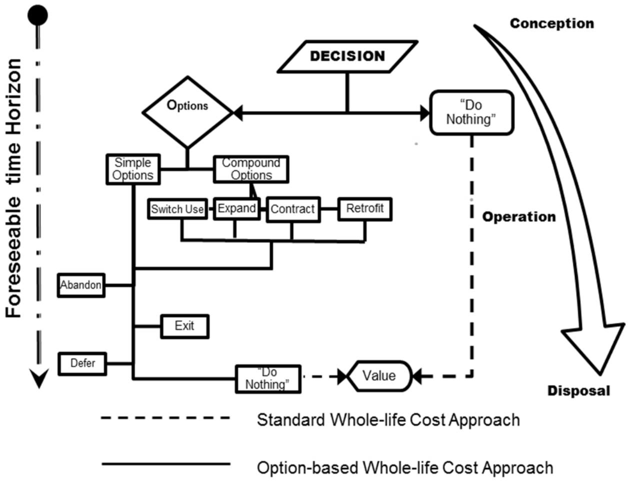


Figure 1: Mapping Whole-life Cost decisions in a Real-Options Framework

RESEARCH METHOD

This work adopts a realist perspective in investigating the issues in whole-life cost modelling. In order to address the conceptual limitations in existing whole-life costing techniques, there is a pertinent need to examine the assumptions in the modelling framework. These can be done by highlighting and identifying the phenomena that impacts on costs.Firstly, existing whole-life cost models are implicitly developed for new-build projects. The Standard Whole-life costing model does not explicitly allow for possible variations in future costs over the estimated building life. Although, the New-Generation whole-life cost model recognises the effects of revocability, it does so in a simplistic manner, presuming dichotomous values of equal proportions in succeeding years . Besides none of these models consider the economic effects of disruption. A framework is presented, that adequately considers the implications of revocability and disruption. It is anticipated that this will enhance the robustness of whole-life cost modelling in retrofit buildings. The Case study method will provide a useful approach for assessing the effects of disruption and revocability in whole-life cost modelling.

Evaluating the cost of disruption

The potential for disruption in retrofit scenarios need to be considered prior to the sanctioning a retrofit initiatve (Holness, 2010). The disruption analysis for retrofit initiatives conducted by Gleeson *et al., (*2011) provides a basis to estimate the disruption cost in retrofit buildings. The cost of disruption is an inexact measure, and requires a structured and systematic approach. Ashworth (2004) advised that some form of human judgment will be useful in the whole-life cost modelling of buildings. The Factor Chart analysis presented in *Figure 2* is proposed to evaluate the cost of disruption in office retrofit buildings.

It is conceivable that the cost of disruption will depend on the economic use of the building. Hence, it makes for logical reasoning to evaluate the respective cost of disruption over a plausible range. Fuzzy logic has great potential in assisting scenarios where numerical valuations may be inexact or vaguely represented (Zadeh, 2008). This work adopts tolerance values ($\boldsymbol{\mu}_j$) specified by Ayyub and Klir (2006), as shown in Table 1. The Low, Medium and High metrics of disruption, as previously suggested by Gleenson *et al.,* (2011) will be considered as corresponding to different levels of uncertainties in the range of disruption. In using fuzzy logic, lambda-cut sets are useful approaches in quantifying variables within a continuum.

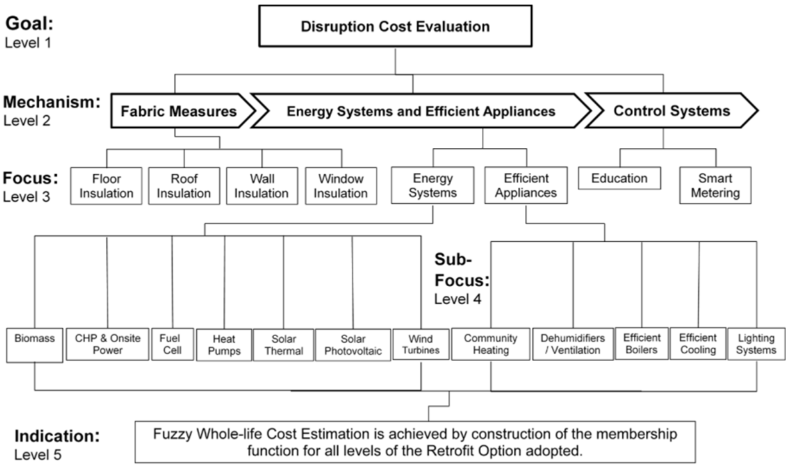


Figure 2: Factor Chart Analysis for Disruption Cost Evaluation

Lambda-cut sets are interval-valued functions that contains all the elements of the parent set, whose membership grades in the set are greater or equal to the specified values of lambda. Ammar *et al,.* (2013) stated that the lambda-cuts of 0.2, 0.5, and 0.8 provide measures analoguous to the 25%, 50% and 75% percentiles of distributions.

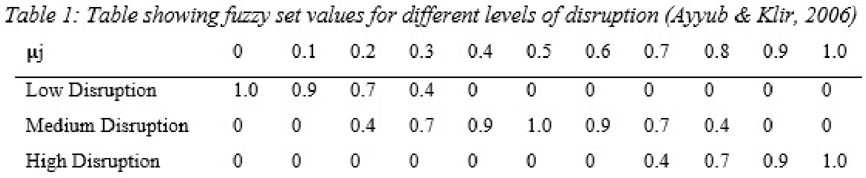


Table 1: Table showing fuzzy set values for different levels of disruption (Ayyub & Klir, 2006)

μj	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Low Disruption	1.0	0.9	0.7	0.4	0	0	0	0	0	0	0
Medium Disruption	0	0	0.4	0.7	0.9	1.0	0.9	0.7	0.4	0	0
High Disruption	0	0	0	0	0	0	0	0.4	0.7	0.9	1.0

An illustration of the procedures of evaluating the cost of disruption in “Retrofit Initiative A” is shown in fugure 3. Based on fuzzy set values in Table 1, the disruption level of Retrofit Initiative A are estimated based on the disruption measures provided by Gleeson *et al.* (2011). Using the max-min composition operator, the overall number of disrupted days can be computed into a lower, mean and upper estimate. The individual days of disruption are computed based on the average daily income-earning potential of the building.

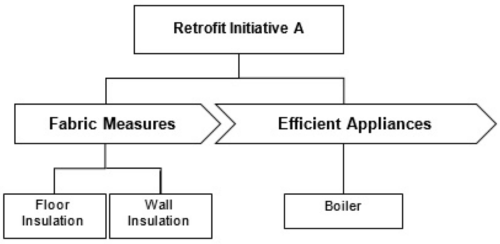


Figure 3: Illustrative Retrofit Option for evaluating the disruption cost.

$$\mu_{Floor\ Insulation} = \left[\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right] x\ 5\ day$$

$$\mu_{Wall\ Insulation} = \left[\frac{0.9}{0.1} + \frac{0.7}{0.2} +\right] x\ 2\ days$$

$$\mu_{Boiler} = \left[\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right] x\ 5\ days$$

$$\mu_{Disrupted\ days\ for\ Retrofit\ A} = \left[\frac{1.0}{5\ days} + \frac{0.9}{6.2\ days} + \frac{0.7}{7.4\ days} + \frac{0.4}{8\ days}\right]$$

$$\mu_{Disrupted\ days\ for\ Retrofit\ A} = [5\ days, 6.2\ days, 7.4\ days, 8\ days] \cdot [1.0, 0.9, 0.7, 0.4]$$

$$\mu_{Disrupted\ days\ for\ Retrofit\ A} = [(5d;\ 5.6d;\ 5.2d;\ 3.2d)]$$

For a £700 per day, building The cost of disruption for installing Retrofit A can be approximated as: Cost of Disruption = (£2,200, £3,300, £3,800)

Evaluating the cost of revocability

The proposed method for evaluating the cost of revocability will follow three steps involving the derivation of the fuzzy relations matrix, aggregation of the fuzzy future cashflows, and the defuzzification of fuzzy future cash flow set. These are explained:

Derive Fuzzy Relations Matrix

The Fuzzy Relations Matrix is derived based on the matrix properties of a cost framework (Ross, 2009). The Standardized numerical coefficients of the Negative Binomial Probability distribution are transformed into matrix form. The benefit of a matrix transformation is to facilitate the computation of the fuzzy-derived future cash flow, and maximise the information contained in the probability distribution. The cosine amplitude formula is perhaps the best approach for transforming the numerical coefficients of the Negative Binomial distribution into a fuzzy relation matrix.

Generate fuzzy future cash flows

The future cash flows are estimated based on the binomial cash flow framework of the New-Generation Whole-life Costing model introduced by Ellingham and Fawcett (2006). The revocability rate of 10% is used, originally intended to provide for the inflation rate in the work by Ellingham and Fawcett (2006). The revocability rate implies a proportionate increase or decrease in future cost values in succeeding years. The future cost relations matrix is a product of aggregating the fuzzy future costs and the fuzzy binomial distributions.

Defuzzify into three-point estimates

Previous work by Morrell (1993) have implied that the benefit of risk modelling is diminished, if cost estimates are presented as precise single figures. Many cost estimates however, still seek to achieve precision, at the expense of credibility (Ross, 2009). It was previously implied by Gluch and Baumann (2004) that the current practice of whole-life cost modelling, which provides a single estimate, for such diverse range of data allows for vulnerability in generating erroneous results. The defuzzification operator is a useful approach to providing a non-crisp value that represents the degree of satisfaction of the aggregated fuzzy number.

CASE STUDY PROJECTS

According to Gleeson *et al.*(2011), the case-study approach has been the most common method used in examining retrofit initiatives. Two retrofit projects have been selected to appraise the effects of revocability and disruption in the whole-life cost framework. The first project (Building A) is a Grade II listed one-storey building in the UK. It was first constructed as a primary school in the 1930's and has recently being converted into a multi-tenant office building complex. The building comprises approximately 1,800m^2 of gross internal floor area. The second project (Building B) is an office retrofit building in the United States; 3-storeys tall, and is a typical masonry building unit with approximately 5,500m^2 of gross internal floor area. These buildings provide a useful context for assessing the whole-life costs of retrofit projects.

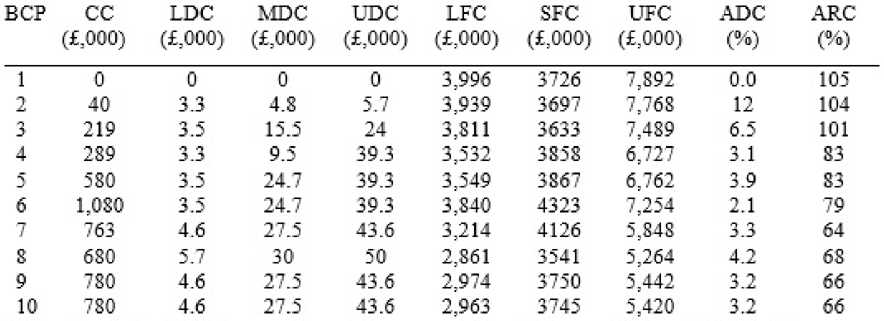
The data on the selected retrofit projects were obtained from documents and reports on the projects, and these were supplemented with interviews with the project teams. The energy cost is perhaps the most variable element of the future costs. Savings in energy costs also tend to be a key consideration in sanctioniong retrofit projects in buildings. In order to obtain the energy use data in the retrofit buildings, dynamic energy simulation softwares were used to assess various retrofit building configuration permutations. Wang *et al.,* (2012) reckons that simulations tools are perhaps the most powerful methods available in providing abundant and detailed energy performance outputs for buildings. The IES<VE> has been used to model building energy consumption levels in Building A, while EnergyPlus has been used to model building energy consumption levels in Building B. In addition to the energy costs, there are also other maintenance and operating costs in office buildings including repairs, insurance, cleaning and waste disposal. The annual and maintenance costs were obtained from the building managers and owners of the respective projects.

RESULTS AND DISCUSSION

Table 2 and *Table 3* below presents the components of the whole-life costs of Building *A* and *B*, over a 60-year period, based on the proposed methodology. This work retains the separation of whole-life costing strands of initial costs and future costs. The inclusion of the cost of revocability – an additional variable to the future costs, and disruption – an additional variable to the initial cost, in the whole-life costing framework of building retrofit projects does not simply emphasize the prospects of underestimation, but also highlights the opportunities for savings. This approach provides a robust mathematical model that will be crucial for model validation and development.

The inputs of the whole-life components are the declining discount rate, as specified by the HM-Treasury (2013), which translates into 3.5% over a 1 to 30-year period, and 3% over a 31 – 60-year period. A revocability rate of 10% was adopted for both buildings, consistent with the work of Ellingham and Fawcett (2006). The future costs are the aggregate sum of the utilities costs and the maintenance costs. The ARC is obtained by dividing the percentage difference between the upper future cost (UFC) and lower future costs (LFC) over the life of the building, by the Standard Future Costs (SFC), obtained using the Standard whole-life costing framework. The cost values in Bulding A is reported in *Table 2.* It can be seen that the average cost of revocability can be up to 105%, over a 60-year life in Building A.

Table 2. Whole-life Cost Components of Building A, over a 60-year period

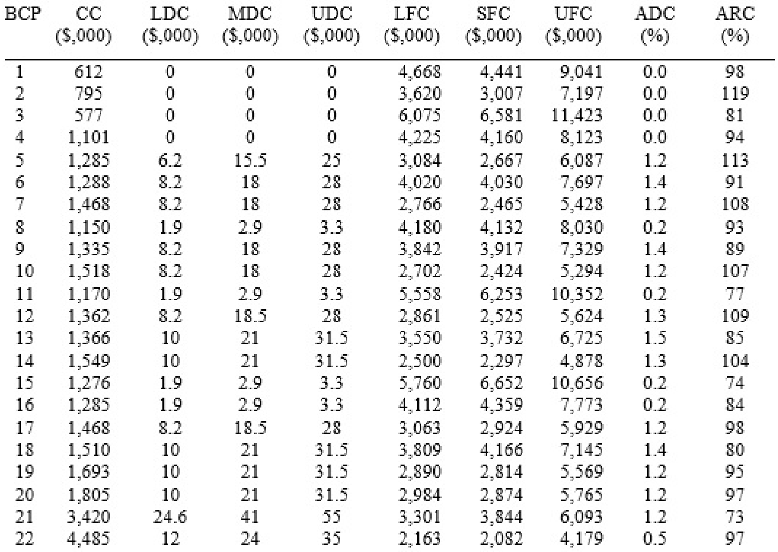


BCP	CC (£,000)	LDC (£,000)	MDC (£,000)	UDC (£,000)	LFC (£,000)	SFC (£,000)	UFC (£,000)	ADC (%)	ARC (%)
1	0	0	0	0	3,996	3726	7,892	0.0	105
2	40	3.3	4.8	5.7	3,939	3697	7,768	12	104
3	219	3.5	15.5	24	3,811	3633	7,489	6.5	101
4	289	3.3	9.5	39.3	3,532	3858	6,727	3.1	83
5	580	3.5	24.7	39.3	3,549	3867	6,762	3.9	83
6	1,080	3.5	24.7	39.3	3,840	4323	7,254	2.1	79
7	763	4.6	27.5	43.6	3,214	4126	5,848	3.3	64
8	680	5.7	30	50	2,861	3541	5,264	4.2	68
9	780	4.6	27.5	43.6	2,974	3750	5,442	3.2	66
10	780	4.6	27.5	43.6	2,963	3745	5,420	3.2	66

BCP refers to the building configuration permutation, CC – capital cost, LDC – Low Disruption Cost, MDC – Mean Disruption Cost, UDC – Upper Disruption Cost, LFC – Low Future costs, MFC –Standard Future Costs, UFC – Upper Future Costs, ADC – Average Disruption Cost, and ARC – Average Revocability Cost.

Also, the average disruption cost (ADC) relative to the initial cost in Building A is obtained by computing the average of LDC, MDC and UDC, and dividiing this by the initial cost. It can be seen from *Table 2,* that the ADC can be up to 12%. From *Table 3*, it is evident that the average cost of revocability (ARC) in Building B can be up to 119% over a 60-year life. While, the average cost of disruption relative to the initial cost can be up to 1.2% in Building B.

Table 3: Whole-life Cost Components of Building B, over a 60-year period



BCP	CC ($,000)	LDC ($,000)	MDC ($,000)	UDC ($,000)	LFC ($,000)	SFC ($,000)	UFC ($,000)	ADC (%)	ARC (%)
1	612	0	0	0	4,668	4,441	9,041	0.0	98
2	795	0	0	0	3,620	3,007	7,197	0.0	119
3	577	0	0	0	6,075	6,581	11,423	0.0	81
4	1,101	0	0	0	4,225	4,160	8,123	0.0	94
5	1,285	6.2	15.5	25	3,084	2,667	6,087	1.2	113
6	1,288	8.2	18	28	4,020	4,030	7,697	1.4	91
7	1,468	8.2	18	28	2,766	2,465	5,428	1.2	108
8	1,150	1.9	2.9	3.3	4,180	4,132	8,030	0.2	93
9	1,335	8.2	18	28	3,842	3,917	7,329	1.4	89
10	1,518	8.2	18	28	2,702	2,424	5,294	1.2	107
11	1,170	1.9	2.9	3.3	5,558	6,253	10,352	0.2	77
12	1,362	8.2	18.5	28	2,861	2,525	5,624	1.3	109
13	1,366	10	21	31.5	3,550	3,732	6,725	1.5	85
14	1,549	10	21	31.5	2,500	2,297	4,878	1.3	104
15	1,276	1.9	2.9	3.3	5,760	6,652	10,656	0.2	74
16	1,285	1.9	2.9	3.3	4,112	4,359	7,773	0.2	84
17	1,468	8.2	18.5	28	3,063	2,924	5,929	1.2	98
18	1,510	10	21	31.5	3,809	4,166	7,145	1.4	80
19	1,693	10	21	31.5	2,890	2,814	5,569	1.2	95
20	1,805	10	21	31.5	2,984	2,874	5,765	1.2	97
21	3,420	24.6	41	55	3,301	3,844	6,093	1.2	73
22	4,485	12	24	35	2,163	2,082	4,179	0.5	97

It is reasonable to expect the cost of disruption, on average, to be more significant in the private sector establishments, compared to the public sector. This due to the profit-drive, typical of the private sector. The organisational goals, and scale of operation of organisation owning office buildings, will also influence the magnitude, and effects of the cost of disruption, in potential office retrofit building projects.

Revocability embodies initiatives within the control of building occupiers, as well as external economic conditions. Ellingham and Fawcett (2006) espoused on the external economic condition that influences the cost of revocability, which essentially refer to inflation. However, revocability as described by Verbruggen (2013) can be exercised through internal factors such as raising building users' awareness, on the cost of energy, and potential savings, drawing attention to energy-use, clear labelling of switches and controls. Previous studies have not made concerted attempts to evaluate revocability and disruption in whole-life cost scenarios. Future studies will aim to conduct a sensitivity analysis on the whole-life cost assumptions in order to better appraise the effects of revocability and disruption over different building lives and discount rate values. Future studies will also assess the relative preference of the building configruation permutations, and compare this with results from existing models.

CONCLUSION

This work evaluates the whole-life cost implication of disruption and revocability in office retrofit buildings. It is argued that the lack of consideration of revocability and disruption in existing whole-life cost modelling suggest the potential for underestimation of the whole-life costs of office retrofit buildings. This work proposed an approach for evaluating the cost of revocability and disruption using probability and fuzzy logic principles. Two buildings – A and B, are used to appraise the effects of disruption and revocability. It was found that in Building A and Building B respectively, the average cost of revocability can be up to 105% and 119%, over a 60-year life, and the average cost of disruption relative to the initial cost can be up to 1.2% and 12%. This work is limited in focusing on just two projects, and future work should include more samples. This will provide building clients with clearer aspirational objectives on the whole-life economic performance of office retrofit building projects

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