DEVELOPING WHOLE-LIFE COST MODELS FOR RETROFIT OPTIONS IN OFFICE BUILDINGS

Olubukola O. Tokede B.Sc. (Hons), M.Sc.

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School of Engineering and the Built Environment,
Edinburgh Napier University,
Scotland, UK.

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Abstract

Office retrofit building projects have become a subject of increased attention among building researchers in the United Kingdom, and in many economically advanced nations. Existing whole-life costing models have however, not proven to be robust enough to deal with these retrofit building scenarios. There is a growing body of evidence that conceptual modifications in the mechanics of whole-life cost modelling, could facilitate improvements in the long-term cost assessment of buildings.

Recent research has made a case for the existence of revocability and disruption, in the appraisal of retrofit building investments. Revocability, connotes the potential for variability, in the future cost projections of a building over its estimated life. Disruption relates to the diminished building use, or unusability, over a period of implementing a retrofit initiative. Existing whole-life cost models have however, not recognised the implications of revocability and disruption in their framework. This study conducts an investigation into the whole-life costing of office retrofit building projects, and develops a Fuzzy New-Generation Whole-life Costing approach. Two office retrofit building projects are adopted, to appraise the identified issues in the whole-life costing framework. A number of building configuration permutations (BCPs) constituting different retrofit options, are developed in both projects. The potential implication of revocability and disruption, are evaluated based on probability and fuzzy logic principles respectively. Sensitivity analysis is applied to discount rate assumptions over the estimated lives, of the projects considered. The Spearman's rank correlation coefficient is used in analysing the ranking results of selected projects. This provided an assessment of the relative preference of BCPs in the projects.

Results from the case studies show 1) disruption issues account for up to 12% of initial capital costs; 2) revocability accounts for up to 35% of initial capital cost, over a 20-year life; up to 119%, over a 60-year life; 3) up to 2% underestimation in the whole-life cost, over a 20-year life; and up to 45% underestimation, over a 60-year period, in the SPACE project; 4) up to 9% underestimation in the whole-life cost, over a 20-year life; and up to 53% underestimation, over a 60-year life, in the MS project.

Declaration

This thesis is submitted to Edinburgh Napier University, in accordance, with the partial requirement for the Doctor of Philosophy. The work described in this thesis was completed under the supervision of Professor Naren Gupta, and Professor Sam Wamuziri. In accordance with Edinburgh Napier University's regulations, governing the conferment of the degree of Doctor of Philosophy, the candidate submits the thesis as original, unless otherwise referenced within the text.

Olubukola O.Tokede

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Abbreviations

AFUE -	Annual Fuel Utilisation Efficiency
AHU	Air Handling Unit
AMI -	Automated Metering Infrastructure
ASHP -	Air-Source Heat Pumps
AFC -	Alkaline Fuel Cell
BCIS -	Building Cost Information Service
BCP –	Building Configuration Permutations
BCR -	Benefit / Cost Ratio
BIM -	Building Information Modelling
BIPV -	Building Integrated Photovoltaic
BMS -	Building Management Systems
BRE -	Building Research Establishment
BREEAM -	Building Research Establishment Environmental Assessment Methodology
CAV -	Constant Air Volume
CBECS -	Commercial Building Energy Consumption Survey
CCHP -	Combined Cooling, Heating and Power
CFL -	Compact Fluorescent Lamps (T5)
CIFPA –	Chartered Institute of Public Finance and Accountancy
CHP -	Combined Heat and Power
COP -	Coefficient-Of-Performance
CPC -	Compound Parabolic Collectors
CVRMSE -	Coefficient of Variation of the Root Mean Square
D.P. -	Decimal Points
DCF –	Discounted Cash Flow
ECM -	Energy Conservation Measures
EEH -	Energy Efficiency Hub
EER -	Energy Efficiency Ratio
EF -	EnergyFusion$^{\mathrm{TM}}$
EIA -	Energy Information Agency
EPSRC –	Engineering and Physical Sciences Research Council
ESCO -	Energy Service Companies

ETC -	Evacuated Tube Collectors
EU-EBPD -	European Union’s Energy Performance of Buildings Directives
FCU -	Fan Coil Units
FL -	Fuzzy Logic
FL-NWLC -	Fuzzy-Lower New-Generation Whole-life Costing
FM-NWLC -	Fuzzy-Mean New-Generation Whole-life Costing
FU-NWLC -	Fuzzy-Upper New-Generation Whole-life Costing
FPC -	Flat Plate Collectors
GSHP -	Ground-Source Heat Pumps
GPIC -	Greater Philadelphia Innovation Cluster
H_A -	Alternative Hypothesis
H_0 -	Null Hypothesis
HVAC -	Heating, Ventilation, Air-Conditioning
HMSO -	Her Majesty’s Stationary Office
IEA -	International Energy Agency
IES<VE> -	Integrated Environmental Solutions Virtual Environment
IFRS -	International Financial Reporting Standards
IRR -	Internal Rate of Return
LED -	Light Emitting Diode
LCEMs -	Low Cost Energy Measures
LPHW -	Low Pressure Hot Water
LTHW -	Low Temperature Hot Water
MCFC -	Molten Carbonate Fuel Cell
MS -	Medium-sized
NILM -	Non-Intrusive Load Monitoring
NLA -	Net Lettable Area
NMBE -	Normalised Mean Bias Error
NPV -	Net Present Value
NWLC -	New-Generation Whole-life Costing
PAFC -	Phosphoric Acid Fuel Cell
PCM -	Phase Change Materials
PDF -	Probability Distribution Function
PEMFC -	Proton Exchange Membrane Fuel Cell
PPP -	Public-Private Partnership

PV - Photovoltaics
RICS – Royal Institute of Chartered Surveyors
RO - Real-Options
ROI - Return-On-Investment
SOFC - Solid Oxide Fuel Cell
SHWS - Solar Hot Water Systems
TES - Thermal Energy Storage
TFL - Tube Fluorescent Lamps (T8)
TRV - Thermostatic Radiator Valves
TS - ThermalShield$^{\mathrm{TM}}$
UNEP - United Nations Environment Programme
US-DOE - United States – Department of Energy
VAV - Variable Air Volume
VIP - Vacuum Insulation Panel
VVT - Variable, Volume and Temperature
WLC - Standard Whole-life Costing

Chapter 1 General Introduction

1.1 Background

1.1.1 Office Retrofit Buildings

Office retrofit building projects are beginning to receive increased attention in the Built Environment literature. Current trends suggest an increasing potential in the coming decades (Dixon *et al.,* 2014b). It has been suggested that a substantial proportion of the UK's existing building stock are aged, and underperforming (Kelly, 2009, Gleeson *et al.,* 2011, Ma *et al.,* 2012), and as such the imperative for retrofitting is urgent (Heo *et al.,* 2012). Foley (2012) reckoned that many buildings constructed in the last century, are characterised by energy-inefficiency, as energy prices were relatively inexpensive, and concerns for global climate was rather non-existent. Holness (2010) surmised that the greatest opportunity for minimising the energy consumed in the Built sector, is in the retrofitting of existing building stocks.

According to Mansfield (2009), approximately 75% of the building stock in the UK was in existence, before the 1980's. Similar statistics are prevalent across Europe, the United States, and in many parts of the developed world. A recent study in Finland estimated the average energy savings from retrofit buildings, as 12%, (Christersson *et al.*, 2015). Numerous studies however, suggest that annual energy-savings from retrofit initiatives could be up to 50% (Ma *et al.*, 2012, Mills *et al.,* 2004, Holness, 2010). Apart from reduction in the energy consumed by buildings, other benefits of retrofitting buildings include extending the lifespan of buildings (Menassa & Baer, 2014); reduced maintenance cost, and improved liveability of buildings (Ma *et al.,* 2012).

Existing buildings possess some peculiarities as a result of unknown operation, performance, as well as degradation of components. Hence, assessing energy performance levels of buildings could prove a challenging task. Over the long-run, energy performance measurements in buildings, are also highly prone to irregularities and uncertainties (Heo *et al.,* 2012). Other peculiar challenges in retrofit building projects include, the financial justification within allocated budgets (Menassa, 2011), as well as disruption to the normal lifestyle of building inhabitants during installation. Another conceivable reason for the technical difficulties posed by building retrofits is due to faults. Faults in existing buildings could account for up to 11% of energy consumption in commercial buildings (Ma *et al.,* 2012). Also, poor constructability (Gupta *et al.,* 2015), poor usage, and poor maintenance culture could negatively impact on the functional performances of existing buildings.

Furthermore, in the UK, some existing buildings have attained the status of being ‘Listed’ and hence acquired legislative restrictions, in the alterations that can be made to them. Planning consents for such buildings could take up to two years, and in some cases disapproved, as a result of the need to maintain the heritage outlook of the building. Currently, there are over 500,000 listed buildings in the UK, and it is quite reasonable to expect a large proportion of these buildings to be in need of retrofitting.

Among commercial building types, offices seem to offer the highest potential for minimizing energy consumption, and carbon emissions (Wade *et al.,* 2003a). The possible reasons for these are, - the range of technical solutions are not too diverse, since technologies in offices are quite homogenous; and action from a small group of large stakeholders, could significantly drive the retrofit agenda (Wade *et al.,* 2003b). Also, offices are usually governed by formal policies. Hence, staff-behaviour can be monitored and directed, to further enhance energy-savings. It is also noteworthy that organisations owning offices are more likely to be desirous of attaining positive corporate image that could be engendered, by the retrofit agenda. Additional features of office buildings that make them a unique focus are, its generic nature of construction process, potential occupier base and flexibility, as well as large unit sizes of professional ownership (Christersson *et al.,* 2015).

1.1.2 Investment Appraisal Techniques

Investments in office retrofit buildings require comprehensive evaluation, in order to ascertain economic viability. The predominant approaches in financial investment appraisal of building projects, are the payback period, (Pogue, 2004) and the discounted cashflow (DCF) techniques. The payback period is the most widely-used decision making tool, in building retrofit scenarios (Ma *et al.*, 2012). It is calculated as the ratio of the investment, to the annual savings in income. The payback period is however, limited in that, it is over-simplistic, and fails to capture the time-value of money, as well as the life time of the investment (Christersson *et al.,* 2015).

In recent times, discounted cash flow (DCF) techniques tend to be considered the preferred approach, over the payback period, as a result of their potential to bring improved realism into the science of project valuation (Duffy *et al*., 2015). The discounted cash flow techniques consist of four steps: forecast the expected cashflows; ascertain the required rate of return; discount the cashflows relative to the present value; (Geltner *et al.*, 2014) and lastly, summing the equivalent present value cashflows to yield an equivalent sum.

Discounted cashflow (DCF) techniques however, have their own limitations. DCF techniques tend to utilise unverified and subjective assumptions on the respective discount rate; could wrongly guess the expected cashflows; fail to consider the cross-sectional and time-series links between alternative investments; and assume investments are irreversible (Christersson *et al.,* 2015). Other limitations of DCF techniques are related to, its failure to allow for changes in the discount rates, over time, and providing a mechanism to value project decisions that may be taken at some point in the future (Greden, 2005). Another categorical limitation of DCF techniques is its failure to properly account for significant uncertainties, during the economic valuation phase (Menassa, 2011). Despite these, DCF techniques are still recognised as one of the most generic investment valuation methodology, both in literature, and, in practice (Goh & Sun, 2015, Christersson *et al.,* 2015).

Another conceptual methodology in investment valuation that has emerged in the last two decades, is the Real Options (RO) approach. The RO approach, aims to augment the procedures of investment valuation, by focusing on the value that uncertainty creates (Ellingham & Fawcett, 2006), and tend to highlight opportunities to respond to future changes. The RO theory however, has its own limitations. It assumes the value of investments depends solely on the inherent economic variables (Busby & Pitts, 1997), and fails to recognise the role of behavioural uncertainties in influencing investment valuation (Adler, 2006, Ghahremani *et al.,* 2012, Chang, 2012). Chang (2012) identified “hold-up threat” as a manifestation of behavioural uncertainties, in the RO approach of investment appraisal.

Also, the RO approach does not deal with the problem of valuing non-financial or non-quantitative costs, in projects (Adler, 2006). It can equally be argued that, RO may not be desirable, because it can minimise organisational commitments from interested investors (Ghahremani *et al.,* 2012). RO may also be unavailable, in certain situations as a result of legislative or regulatory restrictions (Busby & Pitts, 1997). To enhance the capability of the RO approach, Decision analysis and Dynamic programming are often incorporated, into the investment evaluation framework (Chang, 2012). While the Decision analysis and Dynamic programming approach has potentials to enhance the explicitness of the RO framework, they do not have the capacity to address behavioural uncertainties, and also cannot explicitly cater for non-quantitative costs and benefits, in the investment valuation of retrofit initiatives.

It will however, be helpful to undertake an appraisal of the potential costs accruable, over the entire life, prior to retrofitting existing buildings, in order to understand their economic implication. Given the scale and intensity of these retrofit imperatives, a financial Investigation of retrofit building projects, that recognises the complexities and uncertainties in existing buildings, could potentially amount to walking an economic tightrope. In view of these complex issues in the appraisal of office retrofit buildings, this work has developed, and proposed, a new model to financially appraise the whole-life cost implications of office retrofit buildings. This aligns with the primary aim of this work, which is to apply the principles of fuzzy logic in the whole-life cost modelling of office retrofit buildings.

1.2 Whole-life Costing in Buildings

The application of whole-life costing began in the UK in the late 1950's (Goh & Sun, 2015), although the principles of whole-life costing have never been properly understood. The energy-efficiency agenda have resurged interest in the whole-life costing of buildings, as a result of fluctuating energy prices, increasing environmental awareness, as well as growing political support for the sustainability drive (Caplehorn, 2012). Goh and Sun (2015) stated that whole-life costing, is the more current terminology, and is synonymous with life-cycle costing. Whole-life costing can be defined as the present-value of the total costs of an asset, over its entire life

(Kishk *et al.,* 2003). Whole-life costing, can be further described, as a modelling technique that incorporates the analysis and estimation of both capital and future costs, over the life of a built asset (Tietz, 1987, Flanagan & Jewel, 2005). The essence of whole-life costing is the comparison of values, which transcends problems of different lives, or different balances between initial and future costs (Goh & Sun, 2015). The primary aim of whole-life costing, is therefore, the identification of the most effective choice, between a number of competing alternatives (Kishk, 2005).

According to Gleeson *et al.,* (2011) the economics of retrofitting suggests, a potential for the "law of diminishing returns" to set in, with regards to investments levels, and corresponding savings accruable. Hence, there is need to pay concerted attention to the cost valuation methodology, in order to facilitate robust appraisal of retrofit options. Whole-life costing is arguably, a useful and systematic approach to robustly appraise retrofit initiatives, since it covers the entire life span of a built facility.

Whole-life costing in building retrofits, is however, a highly uncertain endeavour (Menassa, 2011), and involve complex and intricate considerations (Ma *et al.*, 2012). Uncertainties on the one hand, consist of lack of information, which could emerge from cognitive or non-cognitive sources (Ayyub & Klir, 2006). Some crucial uncertainties in the costing of building retrofits relates to the savings estimation, energy-use measurements, weather-forecasts, changes in energy consumption pattern, and system performance degradation. Other generic areas of uncertainties in cost estimation across a building's lifecycle include, cash-flow data, building-life period, investor's commitment, component service-life, and future decisions (Ellingham & Fawcett, 2006). The implementation of whole-life costing will therefore, require the use of uncertainty modelling techniques (Goh & Sun, 2015). The prevalent application of uncertainty modelling techniques in existing whole-life costing models, relate to the use of discount rates, to appraise future monetary outcomes.

Uncertainties in the time-value of money alone however, do not constitute the totality of complex and intricate considerations, in the whole-life costing of building retrofits. Recent studies has presented a case for the existence of a significant degree of economic and physical revocability in buildings (Verbruggen *et al.,* 2011, Smit, 2012, Verbruggen, 2013). Revocability pertains to the potential for variability in the future costs of buildings, over its estimated life. Physically, this implies, that once built, a certain level of efficiency or inefficiency, is locked into a building, which cannot be dramatically altered, without significant costs. In economic terms, revocability connotes the difficulty associated with withdrawing resources, already committed to a course of action, for an alternative use (Verbruggen *et al.,* 2011). 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 different ways. For instance, the Communities and Local Government (CLG, 2011) referred to revocability as a “lock-in” syndrome, in buildings.

In building retrofit interventions, another important economic and social consideration, is the cost of disruption to the normal lifestyles of building occupiers (Gleeson *et al.,* 2011). Disruption relates to the diminished building use, or un-usability, over a period of implementing a retrofit initiative. In retrofitting office buildings, disruption could hinder profit-earning activities of respective organisations. The effects of disruption in retrofit scenarios, are quite compelling, as its effect could deter building owners from embracing retrofit initiatives, in the first place (Dixon *et al.,* 2008). The impact of disruption in the whole-life costing of buildings, have been admitted in much earlier publications of the Royal Institute of Chartered Surveyors (RICS 2002). However, existing cost models have not incorporated the effects of disruption, in their framework.

Supposing Revocability and Disruption are attributes worthy of being represented in the whole-life cost modelling of retrofit building projects, the analytical underpinnings of such procedures, are not straight-forward. Uncertainty modelling techniques are quite heterogeneous, and include, Probabilistic risk assessments such as Expected-Value analysis, Mean-Variance criterion, Coefficient Of Variation, Risk-Adjusted discount rate, Certainty-Equivalent technique, Monte-Carlo simulation, Decision-Analysis, and Real-Options (Ma *et al.,* 2012). Other non-probabilistic risk assessment includes Sensitivity Analysis, Fuzzy Logic, and Dempster-Shafer Evidence theory. In whole-life costing scenarios, the use of the risk-adjusted discount rate, has been the dominant approach, in evaluating cost uncertainties associated with time-value, over the life of built assets. The risk-adjusted discount rate approach to uncertainty modelling, tends to involve arbitrary selection of discount rate values, and could lead to suboptimal assessment of risk (Menassa, 2011). Ma *et al*.,(2012) and Heo *et al.,* (2012) have suggested the need for more intricate uncertainty assessment methodologies, in building appraisal scenarios, as a result of high levels of uncertainties, associated with retrofit building scenarios.

Modelling Revocability in cost models is a challenging task. Some conceptual considerations in building retrofits that tacitly relate to revocability, are adaptability and flexibility. Adaptability can be defined, as the ability to adjust, with respect to internal or external changes, in the preferences, or needs of building-users. Flexibility, on the other hand, is the attribute that allows for possibilities of change, within a limited set of alternatives (Blakstad, 2001). In investment terms however, adaptability and flexibility are more difficult to translate into economic metrics. It is even suggested that flexibility in certain buildings, could inhibit long-term adaptability (Blakstad, 2001, Fawcett, 2011). Ellingham and Fawcett (2006) suggested an approach to evaluating revocability in the New-Generation Whole-life costing model. Ellingham and Fawcett (2006) represented projected cashflows, over a building's life, using the Negative Binomial probability distribution. The underpinning of this model, is to relax rigid assumptions in the Standard Whole-life costing model, – that all decisions are made in Year 0, (initial year of construction) and are irrevocable. This procedure presents revocability as an inherent component of uncertainty, and hence formal risk modelling procedures, should be useful in evaluating revocability.

A number of academics, and industry-experts, have hinted on the need to evaluate the effects of disruption, in retrofit scenarios. Perhaps one justification for this, is that traditional whole-life costing models, were developed for new buildings, in which case the costs of disruption were rather non-existent, and hence not considered in the model framework. It is however, reasonable for organisations owning offices to be interested in the costs of disruption, since Investment costs in energy-efficiency projects in buildings, could exceed the nominal installation cost of retrofit initiatives. Office buildings could also be unable to provide its normal services to clients, during the installation of retrofit initiatives, which could affect the patrons of the organisation.

Given the absence of these considerations in current whole-life costing framework, it is important to seek for robust and better ways of financially appraising office retrofit building projects. This initiative could provide relevant stakeholders, and investors with clearer aspirational objectives, on the economic performance of such buildings. It is also important to add that the sustainability agenda has inspired interests, in the long-term consideration of building investments (Caplehorn, 2012). Whole-life cost modelling of office retrofit projects, could provide a mechanism for systematic and sustainable consideration of costs, over the entire life of a built asset (CIFPA, 2011).

The principal aim of this study is to apply the principles of fuzzy logic in the whole-life cost modelling, of office retrofit buildings. One of the objectives of this current research is to re-orient the principles of whole-life cost modelling, to better recognise specific issues in retrofit building scenarios. This approach will involve conceptual adjustments in the mechanics of whole-life cost modelling, towards improving the integrity of whole-life cost forecasts, and providing a rational and robust means for making comparison, among a set of competing retrofit options.

This current study will develop a new whole-life cost modelling approach, which incorporates previously unrecognised cost variables. This study will also examine the potential of the new modelling approach, in appraising different permutations in office retrofit building projects, and compare the results with existing whole-life cost models. It is anticipated that this new model will provide a more realistic template, for appraising office retrofit buildings and will allow for the representation of relevant qualitative variables in the whole-life costing of buildings.

1.3 Problem Statement

There have been a number of concerns on the use of whole-life costing in appraising building investments. Goh and Sun (2015) concluded that, there is a need for new concepts and methods, that will align the intentions of stakeholders and clients. Kirkham (2014) inferred that the problem in whole-life cost modelling can be summarised as the problems of data, uncertainty representation, and the lack of robustness, in existing framework. Figure 1-1 highlights the progression in whole-life cost estimation, over the entire life, based on the Standard Whole-life costing framework.

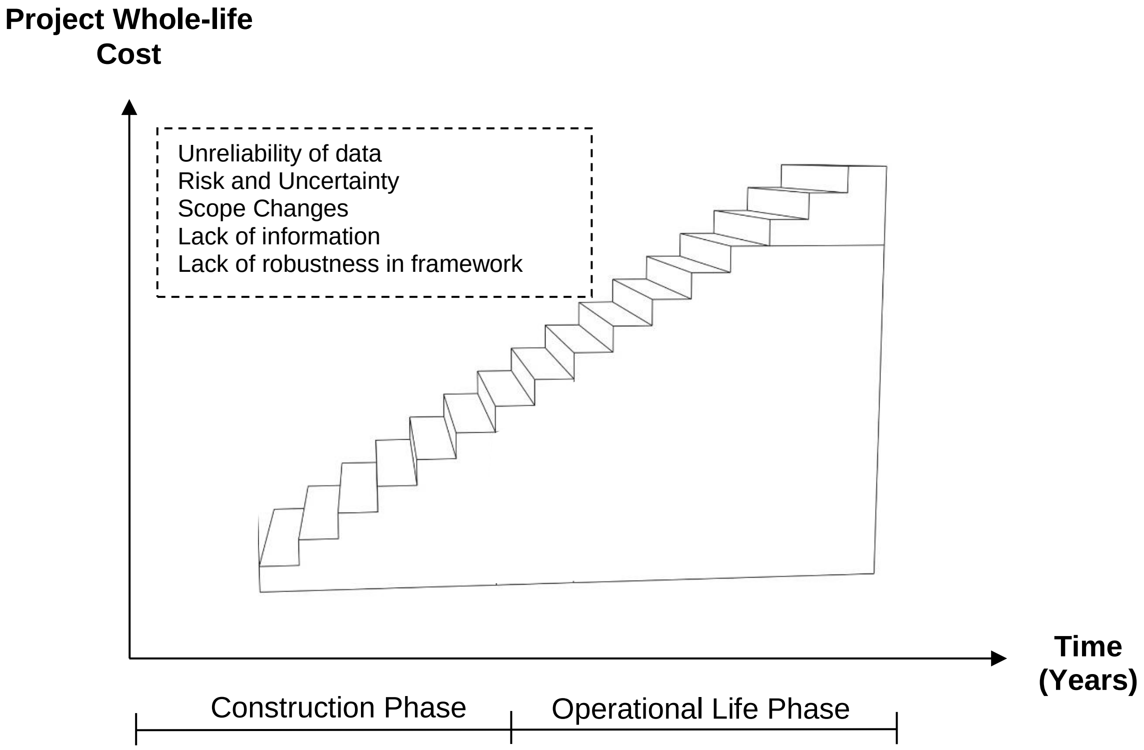


Figure 1-1 Standard Whole-life Cost Framework

In Figure 1-1, the issues of unreliability of data, risk and uncertainty, scope changes, lack of information, and lack of robustness, affecting whole-life cost variables, are not explicitly accounted, in the model framework, and as such the model is considered to be static, and in steady-state (Georgiadou *et al.,* 2012). Regarding data in whole-life costing, there is a lack of consistency in input parameters (Clift & Bourke, 1999, Cole & Sterner, 2000, El-Haram *et al.,* 2002, Goh & Sun, 2015). In current practice of whole-life cost modelling, there is a tendency for input parameters in the model framework to be inadequate, or highly diverse, which could lead to differing estimates. The lack of appropriate, relevant, and historical cost data, in whole-life costing scenarios in buildings, equally constitute an obstacle (Kishk *et al.,* 2003). Another concern with the data used in whole-life costing, is that it is based on fiscal or quantitative measures alone (Kishk, 2005, Caplehorn, 2012), and as such, the information regarding the whole-life cost implication, is not fully harnessed. Healy (2015) advised, that while quantitative information is valuable in making a case for objective modelling, it does not constitute the whole story. Furthermore, reliance on quantitative information alone could be inadequate, in explaining situations involving risk, uncertainty, intangibles, and hard-to-measure attributes.

In certain instances, uncertainties in whole-life costing scenarios could be concealed to minimize the complexity, of the model framework. This could impact on the credibility of the model. A number of publications on whole-life costing (predominantly earlier works), have argued that whole-life cost evaluations, tend to ignore uncertainties, in cost variables (Zhi, 1993, Byrne, 1997, Bordass, 2000, Coates & Kuhl, 2003, Skinne *et al.,* 2011). In more recent times, the problems with whole-life costing models, have been with the insufficiency in the representation of uncertainties (Ferry *et al.,* 1999, Kishk and Al-Hajj, 1999, Kishk *et al.*, 2004, Gluch & Baumann, 2004, Kishk, 2005, Tan *et al.,* 2010). A common and deterministic approach, used in counterbalancing uncertainties, due to time-value of money, has been through adjusting discount rate values, to cater for associated risks. There are however, a number of concerns, with the discount rate approach (Gluch & Baumann, 2004). First, the discount rate is a subjective and arbitrary value, that is likely to change, over a period of time (Greden, 2005, Jackson, 2010, Tan *et al.,* 2010, Goh & Sun, 2015, Christersson *et al.*, 2015, Ma *et al.,* 2012). Secondly, the discounting mechanism could hold bias, towards the initial capital costs (Nicolini *et al.,* 2000, Malik, 2012, Korpi & Ala-Risku, 2008). Lastly, the discounting process, assumes a single trail of reality (Gasparatos, 2010), without allowing for decisions, that could be taken at some point in the future (Christersson *et al.*, 2015, Ma *et al.,* 2012). Alternative approaches to the use of a constant risk-adjusted discount rate, are being considered, and are further discussed in Chapter 3 of this thesis.

The framework of existing whole-life costing models, are also fraught with a number of conceptual limitations Perhaps, the most obvious problem in whole-life costing, is that, it is based on a number of assumptions, which are sometimes unrealistic, and ill-informed (Cole & Sterner, 2000, Caplehorn, 2012). Some of the implicit assumptions are that, same party bears both the initial cost and future costs, and are interested in optimising the whole-life costs (Ferry *et al.,* 1999), which may not be the case. Another more strategic assumption is that, all decisions regarding future costs, are made at the outset of the project, and are irrevocable (Ellingham & Fawcett, 2006). In whole-life costing, another challenge in the methodological framework, is the inability of the model, to establish a relationship between design decisions, over the building’s life, and the information available (Kishk, 2005, Kirkham, 2005), thus providing a poor depiction of reality (Ellingham & Fawcett, 2006). Concerns have also been raised by a number of building researchers, on the input-output modelling framework, which is considered static (Koskela *et al.,* 2008, Georgiadou *et al.*, 2012, Tan *et al.,* 2010). Georgiadou *et al.,* (2012) described existing whole-life cost models, as “steady-state’, and reckoned that, they have little bearing on reality. Kodukula and Papudesu (2006) hinted that the Standard Whole-life Costing framework, in particular, only focuses on the downside of risk, and ignores opportunities for cost savings, that accrue, over the life of a built asset. Although, Kishk *et al.,* (2003), argues that the principles of whole-life costing are well developed, there is compelling evidence, that this is not the case, and there is a scope for improving on the theoretical weaknesses of existing whole-life cost modelling procedures.

Perhaps, given the concerns, as documented in extant literature on whole-life costing, there has been a prevalent lack of interest, in long-term cost estimation. This situation has fostered a recourse to gut-feeling and experience, rather than results from objective analysis (Ellingham & Fawcett, 2006, Adler, 2006). Gluch and Baumann (2004) claimed that whole-life cost models foster incorrect decisions. Ellingham and Fawcett (2006) also add, that the Standard whole-life costing mechanism, tends to classify whole-life cost scenarios, as a clear-cut “choose” or “lose” situation, and fail to highlight the “wait and learn” potentials, as explained in the real-options literature (Verbruggen *et al.,* 2011, Fawcett, 2011). There are therefore, plausible suggestions that existing whole-life costing models, ignore future opportunities to enhance value, in building projects. It is therefore, expected that strategic attention to critical issues in the economic appraisal of buildings, will assist the development of robust whole-life cost models, in building retrofits.

1.4 Aims and Objectives of the Study

The literature on whole-life costing, and retrofit buildings, provide a vivid account of the challenges faced, in providing economic justification, for retrofit building alternatives. Based on the literature analysis, it can be surmised that, there is a clear need for new concepts and methods of whole-life costing (Goh & Sun, 2015), in order to address the misalignment in theory and practice, of whole-life costing in office retrofit building options.

The **Aim** of this current study, is therefore, to apply the principles of fuzzy logic to the whole-life cost modelling, of office retrofit buildings. This will involve the development of a new approach to whole-life costing in office retrofit buildings.

The Specific **Objectives** of this study are as follows:

1. To appraise existing approaches to whole-life costing, for retrofit options, in office buildings.

2. To develop a Fuzzy New-Generation Whole-life costing model, for retrofit options, in office buildings.

3. To develop a mathematical algorithm that aids the implementation of the Fuzzy New-Generation Whole-life costing model.

4. To validate the developed model, using sample retrofit projects, and compare the results with existing whole-life costing techniques.

1.5 Research Design

According to Yin (2014), a research design, provides a blueprint for a research work, and addresses four main questions – what questions to study; what data are relevant; what data to collect; and how to analyse the results. The research design essentially describes a flexible set of assumptions, and considerations that connect theoretical notions and elements, to a dedicated plan of action (Jonker & Pennink, 2010).

Five components of the research design are especially important. These are the study question, study proposition, unit of analysis, data analysis technique, and method for interpreting the findings (Yin, 2014). The components, highlighted in this study, intend to establish a continuous dialogue between the theory, methodology and context. These components will therefore be examined, in subsequent paragraphs.

The **study question** herein examines

"*How retrofit decisions are influenced by Revocability and Disruption, in whole-life costing scenarios?"*

Given the complex and intricate issues in whole-life cost modelling, focusing on specific issues in the whole-life costing of office retrofit building projects, provides an avenue for enhancing the integrity of whole-life costing models, and ultimately providing better decision-support for stakeholders. Figure 1-2 highlights the considerations in the study question, in identifying and evaluating the features of Revocability and Disruption, in retrofit projects. The Cost of Disruption is presented as a component of the Construction Phase, while the Cost of Revocability is expressed as a component of the Operational Life Phase. These additional issues therefore, by implication, have potentials to increase the whole-life cost values of retrofit projects. The extent to which, these issues affect the whole-life cost estimates, are evaluated, in sample retrofit projects.

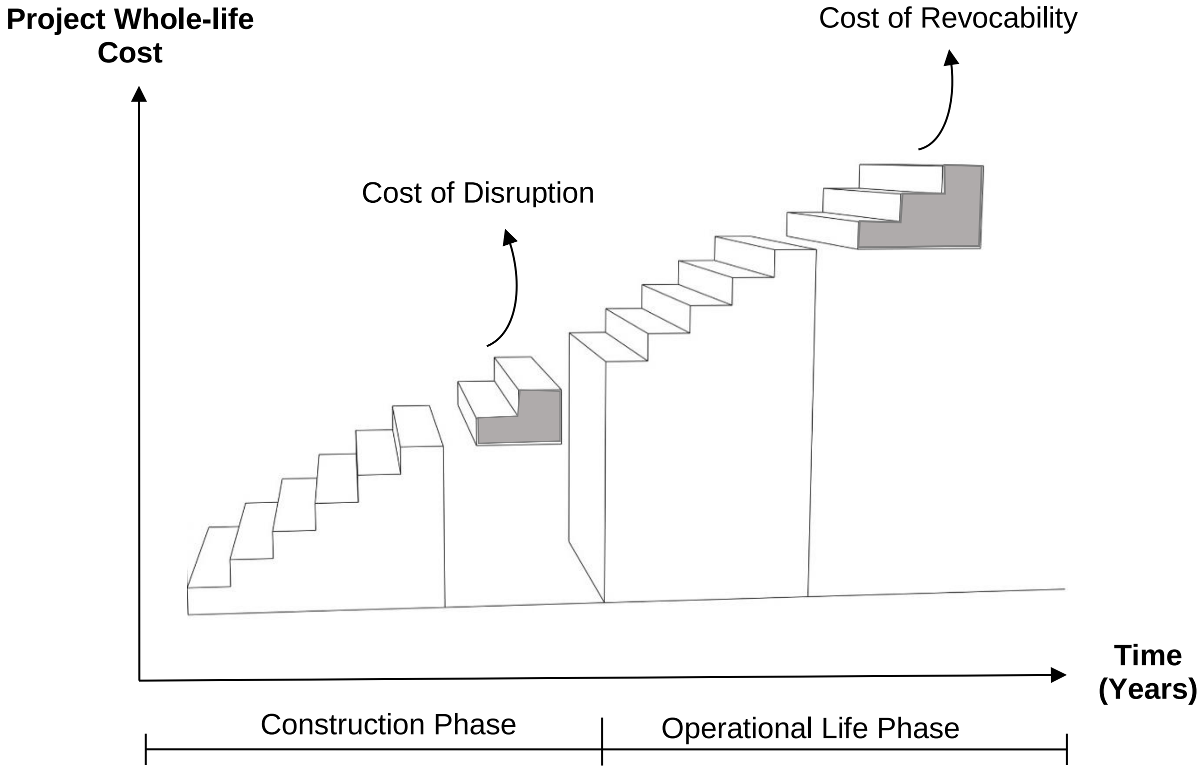


Figure 1-2   Proposed Whole-life Cost Framework for Retrofit Projects

A **study proposition** directs attention to something that should be examined, within the scope of the study (Yin, 2014). This work proposes to use fuzzy logic, to model probabilities of future cashflows, in office retrofit building projects, over its expected life. This work utilizes fuzzy logic, to evaluate the cost of disruption, in retrofit packages in office buildings. The study will also rank whole-life cost estimates, of this new model, and compare the outcomes, with existing whole-life costing models. This comparison will highlight the limitations of existing whole-life cost models, in providing sufficient guidance, in the appraisal of office retrofit building projects.

The **unit of analysis** are adopted cases of office retrofit building projects. Two cases are utilised in this study. The first case is a Grade II listed building, in the UK, called the SPACE building. First constructed, as a primary school, and currently, a multi-tenanted office building. The occupants of the SPACE building consist mostly of social enterprises, and community charities. The building consists of approximately 1,800m^2 Net Lettable Area (NLA). The second case, is a baseline retrofit office building in the US; 3-storeys tall, and is a typical masonry building (meeting the ASHRAE 90.1-1989 Code), approximately, 5,500 m^2 Net Lettable Area. The building was built, within the last twenty years. The building is made up of single-pane windows, with 20% glazing, and roof-top, packaged air-conditioning.

The **data analysis** techniques used in this study, are Scenario analysis, Sensitivity analysis, and Pattern-matching. Pattern matching is analysed, using the Spearman’s rank correlation test, to compare rankings of respective whole-life cost estimates of building permutations. This approach is used to link the data to the study proposition. The comparison implemented in different scenario has helped in strengthening the internal validity of the exercise.

Finally, attention is given to validity, reliability and generalizability of the study. Hypotheses are generated for the Spearman’s rank correlation tests, in which a P-value of lesser than, or equal to, 0.05 is used to demonstrate that observed findings are statistically significant, and therefore, provides a basis to draw conclusions.

1.6 Contributions to Knowledge

This study has developed a new approach to whole-life costing of Office retrofit buildings, called the Fuzzy New-Generation whole-life costing model, and has provided a software program, to aid its computation. The newly-developed model, outputs three estimates called Fuzzy lower, Fuzzy mean, and Fuzzy upper New-

Generation Whole-life cost values. The whole-life cost values, of two retrofit case projects, are appraised, using the declining discount rate schedule, specified by the HM-Treasury (2013). This research evaluated the cost of Revocability and Disruption in the whole-life costing of selected office retrofit buildings. This new model has provided a robust analytical framework, within which the strength of influences of identified cost variables (in this case, Revocability and Disruption), can be examined, and understood.

Based on results from the case studies, it was found that, in the SPACE project, the average cost of Revocability, relative to the initial capital cost, can be up to 33% over a 20-year life, 58% over a 40-year life, and 105% 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%, irrespective of the estimated life of the building project. Results from the SPACE project also suggest up to 2% underestimation in the whole-life cost, over a 20-year period, up to 21% underestimation, over a 40-year period, and up to 45% underestimation, over a 60-year period.

In the MS project, the average cost of revocability, relative to the initial cost, can be up to 35%, over a 20-year life; 63%, over a 40-year life; and 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 1.5%, irrespective of the estimated life of the building. Overall, in the MS project, there is potential for up to 9% underestimation in the whole-life cost, over a 20-year period, up to 30% underestimation, over a 40-year period, and up to 53% underestimation, over a 60-year period.

1.7 Remaining Thesis Structure

Chapter 2 Retrofitting in Office Buildings

This chapter examines recent trends in the retrofitting of office buildings. It commences with an overview of office building retrofits, and contextualizes its discussion on the investment potentials of office buildings. This chapter also provides an account on available energy simulation software packages, for assessing energy-efficiency in buildings.

Chapter 3 Mechanics of Whole-life costing in Buildings

This chapter examines and considers the whole-life cost of retrofit options in buildings. The chapter discusses uncertainty modelling techniques, and explains the application and principles of deterministic techniques, probability techniques and fuzzy logic. The concluding section discusses the gaps in knowledge regarding the whole-life costing of retrofit options in office buildings.

Chapter 4 Research Methodology

This chapter reports on the theoretical and practical considerations adopted to channel this research work. It commences with the research philosophy, and highlights the logical thought processes in the work. It then moves on to the core principles adopted in the course of answering the research question. The last two sections, details the data analysis techniques used, and the considerations on reliability and validation of the work.

Chapter 5 A Fuzzy New-Generation Whole-life Cost Model

This chapter embodies a major contribution of this work. It details the procedures for implementing the Fuzzy New-Generation Whole-life Cost model in retrofit building options, as well as the principal assumptions and considerations, in the model framework. The chapter highlights the parameters of the Fuzzy New-Generation whole-life cost model. It also provides a flow-chart that itemises the procedural steps to implementing the Fuzzy New-Generation Whole-life Cost model for Office retrofit buildings. The potential benefits of the Fuzzy New-Generation whole-life costing model are discussed in relation to the existing whole-life cost model.

Chapter 6 Case Study Description

This chapter provides a concise description of the case study projects – SPACE and MS Projects, used in this study. It details an account of the building projects considered, and then goes on to highlight the attributes of the building projects. The cost information relevant to the whole-life costing exercise is reported and stated.

The information obtained from the case study projects are then used to compute the whole-life cost estimates of retrofit options in the case studies.

Chapter 7 Presentation of Results

This chapter reports on the whole-life cost estimates of the case study projects under consideration. In the SPACE Project, 10 Building Configuration Permutations (BCP's) are evaluated based on the different whole-life cost models over a period of 20 years, 40 years, and 60 years. Also, the MS project having 22 BCPs, is evaluated over 20 years, 40 years and 60 years. The whole-life cost estimates are evaluated based on two different scenarios – "Discounting and Revocability only" and "Discounting, Disruption, and Revocability".

Chapter 8 Analysis and Interpretation of results

This chapter provides an analysis and interpretation on the results presented in Chapter 7. It commences with estimating the proportion of the initial cost of disruption, cost of revocability, and then conducts a sensitivity analysis on the SPACE and MS projects using discount rate values of 3%, 5%, 7% and 9%. This chapter also reports on the results of the Spearman's rank correlation test, based on the declining discount rate schedule, on the retrofit options in the SPACE and MS projects

Chapter 9 Discussion and Validation

This chapter highlights the conceptual issues that informed the studies and the methodological adjustments that potentially enhances the robustness of whole-life cost models. There is also an exposition of the results and the implications of those results, for the practice of whole-life costing in office retrofit building projects.

Chapter 10 Conclusion and Recommendation

This chapter summarizes the main findings from the studies, and discusses the implications of the findings on the practice of whole-life costing in office retrofit building projects. The chapter also provides recommendations for future research and states the limitations in the current study.

1.8 Summary

This chapter provides an introduction to the entire thesis. It provides a background and general introduction on office retrofit buildings, and makes a case for investment appraisal of office retrofit buildings, using whole-life cost modelling. It also reviews the problem statement, research methods, and the aims and objectives of the thesis. A synopsis of the contribution to knowledge is presented, and an overview of the chapter structure of the entire thesis.

Chapter 2 Retrofitting in Office Buildings

2.1 Introduction

This chapter examines recent trends in the retrofitting of office buildings. It commences with an overview of office retrofit buildings, and contextualizes its discussion on the investment potentials. The first section examines trends in the retrofitting of office buildings in the United Kingdom. It goes on to examine the key technologies available for implementing retrofit initiatives in office buildings, and discusses their potentials in achieving energy-efficiency, and improved building performance. This chapter also provides an account of available energy simulation software packages for assessing energy-use in buildings.

2.2 Office Buildings

Office buildings occupy about 18% of the total non-residential floor area in the United Kingdom (ENTRANZEE, 2012). According to Birchall *et al.,* (2014) there has been growth in the proportion of new office space relative to new residential space, which might not be unconnected to the emergence of the UK as a service-based economy, starting from the 1980’s. Dixon *et al.,* (2014b) noted that the rate of turnover of the building stock is less than 1 – 2 percent annually, compared to current renovation and refurbishment rates in the commercial property sector, that ranges between 2 – 8 percent.

It is however important to distinguish refurbishment from retrofitting. Generally, refurbishment aims to ensure buildings fulfil their initial functional design intent, while retrofitting tends to improve the existing functional performance of buildings (Thomsen *et al.,* 2009), especially in areas of energy, waste and water efficiency. Mansfield (2009) suggests that retrofitting tends to be most cost-effective, as an integral part of a refurbishment programme. Both retrofitting and refurbishment generally tend to improve the asset value of a building, and in some cases, enhance structural integrity and aesthetic outlook (Mansfield, 2009). Goh and Sun (2015) inferred that retrofit buildings possess significant operating benefits of low energy and water operation costs, as well as lower maintenance costs.

Retrofitting, a term that originated in the United States in the first half of the twentieth century, stems from a blend of words “retroactive” and “fit” (Dixon *et al.,* 2014b). Gleeson *et al.,* (2011) defined retrofitting as the refurbishment of buildings to improve their sustainability especially with regards to energy efficiency and carbon dioxide emissions. Menassa (2011) described retrofitting as a capital improvement which improves performance, and make building use more predictable over an extended period. This current study adopts the working definition of the Engineering and Physical Sciences Research Council (EPSRC) Retrofit 2050, in which retrofitting is described as the *directed alteration of the fabric, form, or systems of buildings, in order to improve energy, water and waste efficiencies* (Dixon *et al.,* 2014b). Table 2:1 describes the levels of alterations commonly adopted in retrofit scenarios for buildings, according to Dixon *et al.,* (2014b). Deep retrofits are likely to be more disruptive, but often achieve more savings in energy, than the Light retrofit and Tenant fit-out types. Information regarding the expected levels of savings for respective retrofit types are not yet available in the current literature.

Table 2:1 Levels of Alterations in Retrofitting Buildings (Dixon et al., 2014b)

Type	**Status**	**Building Works**
Deep Retrofit	Vacant, and likely to occur at lease renewal or lease end	Can involve fabric and interior
Light Retrofit	Occupied, with work likely to be carried out during tenancy by landlord/owner	Likely to be interior works only
Tenant Fit-out	Vacant and likely to be tenant-led	Likely to be interior fit-out works

The report from Birchall *et al.,* (2014) suggested that the total floor area of the office stock in the UK is about 135.6 million square metres, which is about 7% of the area of the total residential floor space. However, based on the floor area per unit, offices are on average, about four times larger than residential units. Compared to other sectors in the UK however, office buildings along with other commercial properties – retail and industrial space, are under-researched, with regards to energy-efficiency, and other retrofit measures (Dixon *et al.,* 2014a). One reason for this might be that over half of commercial properties are rented, compared to only a third of residential space. Birchall *et al.,* (2014) advised that high level of owner-occupation will be helpful in promoting retrofit initiatives in order for cost-bearers to directly benefit from the savings obtained in reduced operational and maintenance costs, over the life of the built asset. The proportion of office buildings in the UK, amenable to retrofitting, is relatively large, compared to many other countries. According to Birchall *et al.,* (2014), the age-band of office buildings in the UK follow the trends displayed in Figure 2-1. 28% of office buildings in the UK were built in pre-1945 years. Only 4% of office buildings in the UK were constructed in post-2000 years. This implies the potentials for retrofitting in many of the existing office building is reasonably high.

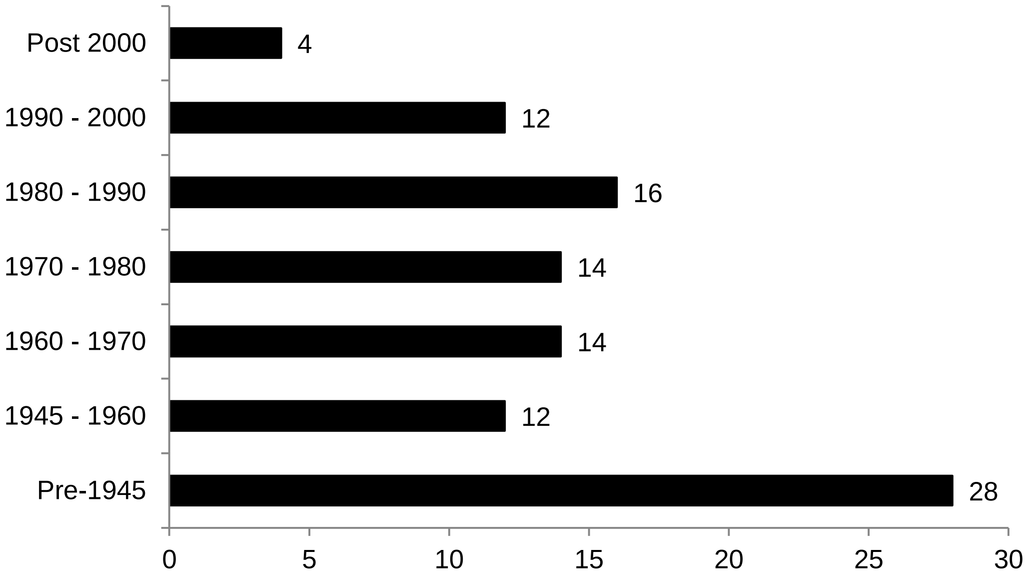


Figure 2-1 - Proportion (%) of office construction by age band in the UK

The main construction material used for office buildings in the UK, and many countries in the European Union, is concrete. During the early 1990's, Her Majesty's Stationary Office (HMSO,1988) classified the office stock into four categories, as shown in Table 2:2.

Table 2:2 Office Building Type Classification (HMSO, 1988)

	Office Type	Characteristics
1	Converted Older residential buildings, usually terraced.	These are sometimes smaller units, such as above ground-floor shops. These usually have not been refurbished, or properly insulated.
2	Large pre-1939 purpose-built office blocks.	The majority of these buildings are inefficient, having U-Values of around 2W/m^{2}K.
3	Highly-glazed office constructions (40 – 50%) of the façade is glazed typically built in the 1960's.	These are usually concrete or steel frame, with lightweight cladding or cavity walls and are energy inefficient with U-Values of between 2 – 3 W/m^{2}K.
4	Post 1970s buildings.	These types of buildings have lower U-values and lower glazing area.

2.3 Retrofit Initiatives in Office Buildings

Retrofit Initiatives are considered primarily, as energy conservation measures (ECMs) used to promote building energy-efficiency, and sustainability (Ma *et al.*, 2012). Mansfield (2009) argues that retrofit initiatives constitute the greatest weapon of the built sector, towards combating the ills of global warming. The need to retrofit buildings, particularly those constructed in pre-1960 years, has been well advanced in the literature (Foley, 2012). However, the economic and financial justification is yet to be fully addressed (Christersson*, et al.,* 2015).

In the UK, the potential cost savings achievable through retrofitting of office buildings are estimated at £1.6bn (Dixon *et al.,* 2014a). The United States – Department Of Energy (US-DOE) has set a target for achieving up to 50% improvement in the energy-performance of commercial office buildings, over a period of 10 – 50 years (Foley, 2012). Empirical studies in different parts of the world, also attest to significant energy-saving potentials, ranging between 20% and 60% (Ma *et al.,* 2012). Office buildings therefore provide a convincing context, for the adoption of retrofit solutions (Wade *et al.,* 2003b).

The retrofit agenda in buildings is not restricted to energy-efficiency alone, but also explores opportunities for achieving water and waste efficiency (Dixon *et al.*, 2008, Dixon *et al.,* 2014b). It is however, noteworthy that energy-efficiency, seems the more pressing imperative for building owners (Gleeson *et al.,* 2011, Heo *et al.,* 2012, Menassa & Baer, 2014). Energy-efficiency, has been defined as a state of using less energy, while fulfilling the energy requirement of building-users (Wang *et al.*, 2012). IEA (2015) described energy-efficiency, as a way of managing and restraining growth in energy consumption. Kelly (2009) proposed a four-action agenda for building retrofit works. These include re-engineering the building fabric; improving the efficiency of appliances used in buildings; de-carbonizing the sources of energy, and changes in personal behaviour. Foley (2012) inferred that, buildings developed in the first half of the twentieth century were mostly low energy-efficient, as energy was relatively inexpensive, and concerns for global climate were minimal.

Energy efficiency is mainly achieved through eliminating unnecessary or sub-optimal energy-use in buildings. Energy-use in buildings could be quite complex, and simplifying the building-energy consumption process could fail to recognise the dynamic interaction between buildings and occupants. Granade *et al.,* (2009) reported on “take-back effect”, – a situation where occupants, increase energy consumption levels, as more energy-efficient measures are deployed in buildings. Xu *et al.,* (2014) described such increase in energy-use by building occupiers, as a ‘rebound effect’.

Building energy performance is however, complex, and mainly determined by six main factors namely Climate, Building Envelop, Building services and energy systems, Building operation and maintenance, Occupants’ activities and behaviour, and Indoor environmental quality (Wang *et al.,* 2012). In assessing energy performance of buildings, three procedures are used in practice, namely Calculation-based methods, Measurement-based methods, and Hybrid methods. Figure 2-2 describes energy quantification methods for buildings (Wang *et al.,* 2012).

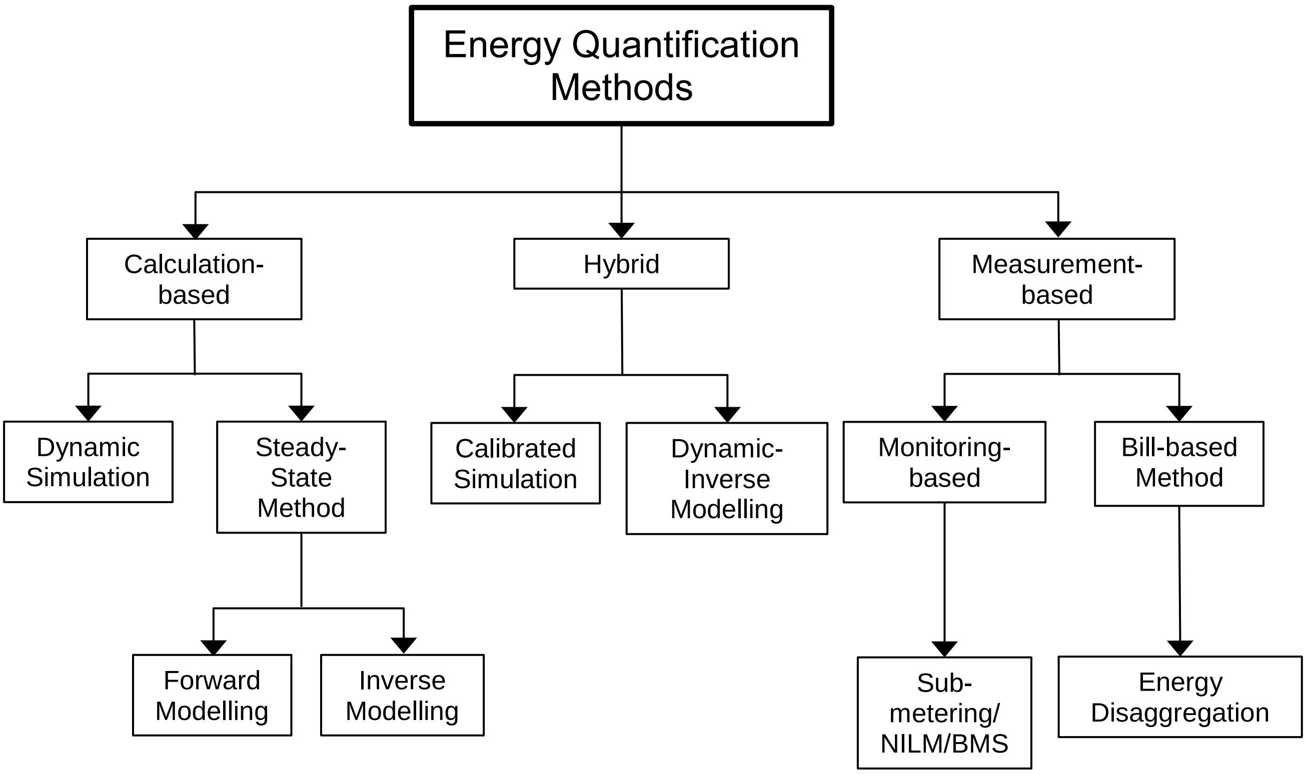


Figure 2-2 Energy quantification methods for buildings (Wang et al., 2012)

Calculation-based methods enhance the development of simplified models, which can be analysed using Steady-State methods, or Dynamic simulation. Steady-State methods can be further developed through Forward-modelling or Inverse-modelling. Calculation-based models, developed based on Forward-modelling techniques, are termed Deterministic models. While those developed based on Inverse-modelling are termed regression models. The premise of using Steady-State methods is based on simple building energy relationships (Duffy *et al.,* 2015). Accordingly, Steady-state methods have the advantages of high computational speed, and their modelling procedures are easy to follow. The disadvantage of Steady-state methods is their tendency to ignore crucial dynamic characteristics of building systems (Georgiadou *et al.,* 2012), and could therefore provide sub-optimal models.

Dynamic simulation methods are capable of capturing more dynamic attributes in buildings, such as thermal dynamic envelope and system dynamics. Most dynamic methods adopt Forward-modelling, to create thermodynamic building models, using fundamental engineering principles (Clarke, 2001).

Using Dynamic simulation requires inputs to be first collected, and then, fed into a simulation engine (Wang *et al.,* 2012). Typical inputs for a dynamic simulation exercise include four groups of parameters – Weather conditions, Building descriptions, System description, and Component description (Clarke, 2001). Weather conditions generally include dry and wet bulb temperature of outdoor air, solar radiation, and wind speed. Building description data mainly include location, design and construction data, thermal zones, internal heat gain, infiltration, and usage profiles. System description includes system types and sizes, control schedules, as well as outdoor air requirements. Component description includes HVAC components, equipment types and sizes, performance characteristics, load assignments and auxiliary equipment.

Dynamic Simulation tools, are perhaps the most powerful methods available, in providing abundant, and detailed energy performance outputs, for buildings (Wang *et al.,* 2012). The applicability of dynamic simulation tools in existing buildings could however, be problematic. This is because, simulation packages tend to generate uncertainties, as they are based on peculiar assumptions (Heo *et al.,* 2012, Kensek *et al.,* 2013). In existing buildings, these assumptions may be inappropriate, and unsuitable, as previous studies have found that discrepancies between monitored data and simulated data could be up to 30% (Güçyeter & Günaydın, 2012). The core part of most simulation programs, is the simulation engine, which describes the details of mathematical simulation algorithm. A simulation engine generally involves three major steps, – thermal loads calculation, system simulation and central plant analysis.

Simulation tools are also applicable for modelling the thermodynamic properties of buildings, and energy performance of retrofit building projects (Ma *et al.,* 2012, Güçyeter & Günaydın, 2012). These tools predict the energy consumption of a building, over a specified period (Heo *et al.*, 2012). A number of commercial energy simulation packages have been developed, and are used in practice. These includes BLAST, BSim, DeST, DOE-2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, EnergyPlus, eQuest, ESP-r, IDA ICE, IES <VE>, HAP, HEED, PowerDomus, SUNREL, TAS, TRACE, TRNSYS (Crawley *et al.,* 2013). A few of the more commonly used ones, will be discussed.

DOE-2 is a powerful simulation tool, useful for all types of building envelops (Wang *et al.,* 2012). DOE-2 assumes heat transfer, air convection, and solar gains. The energy values derived are independent, and approximated as a linear process. EnergyPlus is another popular energy simulation package, produced by the United States Department of Energy (US-DOE). EnergyPlus works on a thermal balance method, which considers elements in the model as independent surfaces (Kensek *et al.,* 2013, Wang *et al.,* 2012), and is widely used in both research and industry (Heo *et al.,* 2012). The IES<VE>, an acronym for the Integrated Environmental Solutions Virtual Environment, is arguably the most versatile suite of tools, used for building energy simulation. The EnergyPlus package is perhaps next in line, to the IES<VE> package, in terms of versatility. A comprehensive comparison on a number of simulation tools, applicable in practice, have been carried out by Crawley *et al.,*(2013). TAS is a response-factor based dynamic simulation tool, with a 3-dimensional design interface (Güçyeter & Günaydın, 2012). Another popular simulation package, is TRNSYS (Transient System) simulation program, based on modular structure, with dynamic models of single building components (Alanne & Klobut, 2003). TRNSYS utilises the concept of “component” in assembling a simulation model. TRNSYS provides a versatile calculation platform to call, modify, define and assemble components in buildings. It is particularly excellent in simulating HVAC performance (Wang *et al.,* 2012). Kensek *et al*., (2013) argues that the choice of software, should not significantly change the predicted energy consumption levels in buildings. There are suggestions that, a number of Building Information Modelling (BIM) tools can also be used in predicting energy consumption levels in existing buildings (Ma *et al.,* 2012). Foley (2012) however, argues that BIM tools are not as sophisticated as model-based design tools, such as HYSYS, ASPEN or CHEMCAD, used in chemical processing plants, and there is scope for enhancing the energy-simulation capabilities of current BIM tools.

Measurement-based methods involve the collation of data through two main approaches, – Bill-based methods and Monitoring-based methods. Bill-based methods involve the collation of energy consumption data, through energy bills. Energy bills allow for the collection of high-quality measurement data, and are sometimes considered, the most cost-effective method to quantify and justify energy-use in existing buildings. However, the financial statements from Energy bill companies could prove insufficient for energy performance assessment, because this type of data is aggregated across end-users, and high-level parents. In order to better appraise building retrofit solutions, it will be necessary to disaggregate energy bills, in order to apportion the respective energy consumption into end-use of main systems and equipment, with an acceptable level of accuracy.

Monitoring-based approaches involve the use of sophisticated metering systems, or platforms to obtain more accurate and detailed energy information on the energy consumption of end-users. Established methods for monitoring energy data include End-use Sub-metering, Non-Intrusive Load Monitoring (NILM), and Building Management Systems (BMS) method. End-use sub-metering is mainly used to provide detailed energy data for research or validation purposes, and is usually considered an expensive procedure for energy data retrieval. The implementation of sub-metering in existing buildings, might be difficult and expensive, due to possible complications from previous maintenance and repairs (Wang *et al.,* 2012). Non-Intrusive Load Monitoring (NILM) is a pattern-recognition method consisting of two modes, – sampling mode and disaggregation mode. In sampling mode, the operating characteristic, and usage pattern, of each end-use, are determined based on data collected over a period of several days, using at least one current sensor per appliance. In the disaggregation mode, only the main electric entrance is monitored. The electric signal is generally analysed using pattern recognition, to disaggregate monitored energy-use, into end-uses. This approach is useful in commercial buildings, but the application is likely to be more difficult when there is large complexity and diversity of facilities (Wang *et al.,* 2012). NILM is generally useful for accumulating detailed energy-use data, with less cost, but this approach has many challenges when used for complex buildings. Building Management System (BMS) are generally sufficient in obtaining a clear picture of the energy-use of typical HVAC systems. Previous case studies have demonstrated that, BMS can be a powerful platform for energy performance monitoring (Moura *et al.,* 2013).

Hybrid quantification methods often combine aspects of calculation-based and measurement-based approaches, in deducing the energy performance levels in buildings. Wang *et al.,* (2012) hinted that many hybrid quantification techniques tend to use “calculation” and “measurement”, as stand-alone “parallel” approaches, rather than as components of an integrated system. Two types of hybrid methods are the calibrated simulation approach, and the dynamic inverse modelling approach. Majority of efforts in hybrid methods, are on the calculation analysis, while the measurement techniques serve as supplements, and tend to focus on minimising calculation discrepancies, and identification of relevant model parameters. Hybrid methods are however, advantageous in providing flexibility in the quantification of energy-use in buildings.

In summary, there is a need for retrofit projects to be implemented without detracting the building experience of owners, and occupiers, of buildings (Wade *et al,* 2003a). Retrofitting seeks to optimise the capacity of existing infrastructure (Menassa, 2014), and where possible, retain the built environment form, thus preserving a sense of identity, and collective memory (Mansfield, 2009). Retrofit initiatives achieve a balance between the possible savings from energy-use in buildings, and the opportunities for alternative energy generation. Retrofit initiatives can be classified into supply-side management and demand-side management retrofit Initiatives.

2.3.1 Supply-side Initiatives

Supply-side management retrofit initiatives are primarily concerned with the use of alternative energy sources to provide electricity, and thermal energy for buildings. In retrofit projects, upgrading energy-conversion plants, or replacing inefficient energy-conversion plants, could significantly assist, in satisfying the energy-needs of buildings in a more environmentally-friendly, cost-efficient, and sustainable manner (Foley, 2012). Alternative energy sources in the supply-side management initiative of retrofits include the use of renewable sources, such as, Solar Photovoltaics (PV), Wind, Biomass, Fuel Cells, Geothermal, and Combined Heat and Power (CHP) systems (Ma *et al.,* 2012). The principles of these renewables sources of energy are discussed.

2.3.1.1 Solar Photovoltaics (PV)

Solar Photovoltaic (PV) technologies are one of the frontline innovations being embraced in the retrofitting of office buildings in the UK. Gleeson *et al.*,(2011) reckons that solar PVs are the dominant form of renewables, in the domestic building sector. It is however, unclear if this is also the case with commercial office buildings. Solar PVs, are also one of the hosts of micro-generation technologies, which provide power to meet energy-needs onsite.

PVs directly convert light into electricity. Electricity is generated when photons of lights are absorbed by a semi-conductor (Ali, 2008). Different materials yielding varying efficiency standards are used in the solar PV configuration. Amorphous silicon PVs, often attains 4 – 6 percent efficiency levels, while Crystalline PVs, could achieve up to 15 – 20 percent efficiency levels (Boardman *et al.,* 2005). Besides the material properties, PV outputs also depend on the installation and orientation. If the roof area of PV panels required exceeds 40 percent of the ground floor area, design to maximise solar orientation is increasingly likely to be required (ZCH, 2009). In the UK, PVs are best orientated towards the south, although it is claimed that yields are at least 95% of the optimum value, when aligned between the South-East and South-West (Boardman, 2007).

One notable disadvantage of the PV technology, is its requirement for a large amount of electricity for its production, whose source is often, fossil-fuel based (Ali, 2008). Other obstacles in Solar PV schemes include, difficulty in connecting it to the National Grid; getting a qualified installer in certain places, as well as identifying a suitable orientation (Caird *et al.,* 2008). Gleeson *et al.,(2011)* advised that in hot countries, PVs offer greater emission reductions due to abundant solar radiation. Mempouo *et al.,* (2010) reported on building integrated photovoltaic (BIPV) systems, where modules are integrated into the roof or façade of a building. This system could make window surfaces serve as solar panels. BIPV systems demonstrate promising potentials, in the retrofitting of office buildings.

McManus *et al.,* (2010) inferred that a payback period of 3 – 26 years should be expected in PV technology schemes. This range may not be considered favourable, and the upper limit transcends the working life of typical PV systems. Kim *et al.,* (2011) reported that the life-expectancy of PV systems is around 20 years. The suitability of the PV technology, in whole-life cost scenarios will therefore require closer examination, in order to justify its applicability, and performance, in retrofit buildings.

2.3.1.2 Wind Energy

Wind is another renewable energy source that can be tapped at higher altitudes (Ali, 2008). The potentials of using wind turbines (micro, medium or large scale) in the retrofitting of office buildings, are however, not very convincing (CLG, 2010). This is because wind constitutes unpredictable and significant disturbances in urban areas (Boardman *et al.,* 2005). There are however, suggestions that buildings in small-scale rural developments could be unable to utilize micro-wind technology, while market town developments will be more suitably served through, medium- or large-scale wind turbines (CLG, 2008).

Ali (2008) notes that wind turbines along with other moving mechanical components tend to actuate vibration, in slender structures, thus threatening the structural stability of buildings. Another crucial disadvantage of wind turbines, is the noise caused by the rotating features of wind turbines (Akbar *et al.,* 2011). Wind is however, an abundant and economical energy source in certain locations, and given the right conditions, could supply significant amount of energy, at minimal environmental cost.

2.3.1.3 Biomass

Biomass is the World's fourth largest energy source, contributing approximately 14% of the global energy need (Dong *et al.,* 2009). Biomass is the sum total of all living matter on the earth, within the biosphere (Ali, 2008). Biomass can be used to generate heat, in individual settings, or as part of a community scheme (Boardman *et al.,* 2005). Biomass technology relies on a ready supply of fuel, such as woodchip, pellets or logs. The use of biomass is an effective means of achieving carbon-efficient levels, in commercial office buildings. However, it seems best-suited for rural areas.

Another obstacle in biomass-heated boilers, is that, they tend to require additional covered space for fuel storage (Akbar *et al.,* 2011). Studies suggest, that biomass systems holds potentials for complying with the 6kg/CO_2/m^2 per year of regulated carbon emissions limit specified by the UK Government (ZCH, 2011). It should however, be noted that biomass is a finite resource for which there are other competing demands. Consequently, the availability and price of biomass, are rather uncertain.

Besides the economic arguments on the suitability of biomass systems, as an alternative source of energy, health concerns have also been raised, should biomass be deployed on a large scale. Xing *et al.,* (2011) reported that biomass systems tend to increase nitrous oxides and particulate matter emissions, in the environment. This situation is of concern to researchers and practitioners. The cost of a biomass boiler can vary significantly depending on the specification. Wood-stoves biomass systems are not very common in operation due to difficulties in controlling their outputs. The extra dirt and labour as well as installation logistics involved in biomass systems, could deter their usage in office retrofit building scenarios. (Caird *et al.,* 2008).

2.3.1.4 Fuel Cells

According to Boardman *et al.,* (2005), Fuel Cells offer significant saving potential, among a host of renewable technologies. Fuel cells are electromagnetic devices that generate electricity, heat and water, by combining hydrogen and oxygen (Ali, 2008).

Fuel Cells are a clean, quiet, and efficient means of electricity generation. Available varieties include Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell (PAFC), Solid Oxide Fuel Cell (SOFC), Alkaline Fuel Cell (AFC), and Molten Carbonate Fuel Cell (MCFC).

Fuel cells can also be used in conjunction with boilers in the form of wall-mounted units that provide heating, electricity and hot-water services in office buildings, and can run on natural gas or propane. The applicability of Fuel Cell in building retrofit scenarios is sparse in the literature. There are suggestions that the future prospects of Fuel Cells are promising (Williams, 2012). The application of Fuel cell technologies could become more appealing in retrofit scenarios. This development is however contingent on the Fuel Cell technology becoming more refined and cost-effective.

2.3.1.5 Geothermal Energy

Geothermal energy involves the recovery of heat, from the ground, or the air. This often requires the use of heat pumps. Geothermal energy extracted from the ground requires a ground-source heat pump (GSHP), while geothermal energy extracted from the air requires an air-source heat pump (ASHP). A small amount of electricity is often required to run a compressor in the heat pumps. However, the energy output is in the order, of four times the input (Lund *et al.*, 2004).

GSHP extract thermal energy, from the surroundings, and utilise them in meeting specific thermal needs in buildings. A ground-source heat pump however, comes in two basic configuration – the ground-coupled (closed-loop) system, and the ground water (open-loop) system (Lund *et al.,* 2004).

In a ground-coupled system, a closed-loop of pipe, either horizontal (1 to 2m deep) or vertically (50 to 100m deep), is placed in the ground, and a water-antifreeze solution is circulated through the pipes to either collect heat from the ground, or release heat to the ground. The ground water system utilises ground water, or lake water directly in the heat exchanger, and then discharges it into another well, and onto a stream or lake, or the ground. Hence, GSHPs has the added benefit of working in reverse mode during the summer, thus returning heat to the ground (Boardman, 2007, Eicker & Vorschulze, 2009).

A GSHP, operates effectively when temperature differences between the heat source and distribution is small (Boardman *et al.,* 2005), and are therefore, favourably suited to tap ubiquitous, shallow geothermal resources (Lund *et al.,* 2004). Heat pumps are generally appropriate, and effective under certain conditions:

i. There must be large surface area for the heat distribution system. Hence facilities with mature garden, or insufficient land, might not be suitable.

ii. Buildings must be properly insulated, and should be consistently occupied.

GSHPs are relatively more costly than many alternate Heat, Ventilation and Air-Conditioning (HVAC) systems (Bloomquist, 2001). They even tend to be less cost-effective in areas without a well-established infrastructure of GSHP drillers, and installers. In the UK, the adoption of GSHPs has been rather slow, perhaps as a result of its relatively mild climate, poor insulation levels, extensive natural gas grid, and complexity of geology, within a relatively small area (Lund *et al.,* 2004). Concerns have also being raised, about the sustainability of the energy tapped from the ground.

ASHPs can be used to harness geothermal energy from the air. Xing *et al.,* (2011) argue that ASHPs are suitable options for office buildings due to ease of installation and minimal space requirement. According to Pan and Cooper (2011), there are two types of ASHPs namely, air-to-air and air-to-water systems. The air-to-air systems, provide warm air, which is then circulated to heat up buildings. The air-to-water systems, are used to heat-up water to provide sanitary hot water, and heating to the building through radiators, fan coil emitters, or an underfloor system. ASHPs are a viable renewable energy source in the retrofitting, and refurbishment of small commercial office buildings. There are however, concerns that renewable energy from air, made to deliver thermal energy, could prompt no net-gain in energy output (Lund *et al.,* 2004).

Geothermal energy however, constitute reliable energy sources, and demonstrate promising potentials in retrofit initiatives. There are however, a lot of uncertainties regarding the viability of geothermal energy sources in office retrofit building scenarios in the UK.

2.3.1.6 Combined Heat and Power (CHP) Systems

According to the European Union's, Energy Performance of Buildings Directives (EU-EPBD, 2011), CHP systems are promising renewable energy sources in buildings, where the floor areas exceed 1000m^2. CHP systems can be defined as the simultaneous generation of usable heat and power, usually electricity, in a single process (Hinnells, 2008). CHP systems can generate electricity locally, while they recover heat to satisfy heating loads in buildings. CHP systems typically produce electric power on-site, and harness “waste” thermal energy, produced in the power-generation process (Zogg *et al.,* 2005).

CHP systems generally consist of a prime mover, power generation/power conditioning system, heat recovery device, utility interface, and controls (Zogg *et al.,* 2005). The prime mover, and the power generation system, are perhaps the principal components of a CHP system. Prime mover technologies include Steam turbine, Stirling engines, and Organic Rankine Cycle Engines. The power generation system is electrically powered, and involves the burning of fuel, which can either be natural gas, biogas or diesel, to drive a generator which produces electricity and heat, in the process (Hinnells, 2008, Duffy *et al.,* 2015).

CHP tends to be an attractive choice in commercial office buildings, where thermal loads are relatively high and continuous. The potential for primary energy savings in CHP systems are as follows:

- Electricity generation at an efficiency, higher than the grid on average, will amount to reduction in energy consumption, based on electric output alone

- Electricity generation at similar, or lower efficiency than grid, but adequate utilisation of waste heat in useful capacities, such as space heating, space cooling and water heating.

Another closely related system to the CHP is the Combined Cooling, Heating and Power (CCHP) system. They work on same principle as the CHP, except that the system is extended to drive absorption chillers, for cooling applications. Absorption chillers generally use thermodynamic heat pump principles, to produce chilled water from a heat source. They can use waste heat from a CHP system, to improve overall system efficiencies and economies. The process typically involves the use of thermal compressor to replace the electrical compressor. The waste heat from the CHP system, is used to boil a solution of refrigerant/absorbent, which is then captured and used to chill water, after a series of condensation, evaporation and absorption (Hinnells, 2008).

CHP systems tend to have a considerable capital cost than separate renewable sources. The CHP technology is being improved, and there is scope for overcoming some associated technological and economic shortcomings (Dong *et al.,* 2009).

Supply-side retrofit technologies are however, still emerging, and they demonstrate significant potential in retrofitting existing office buildings. In the UK, Solar PVs are quite popular, and well-established in retrofit work (Gleeson *et al.,* 2011). Biomass and Geothermal energy sources, are considered to be more popular, in other parts of Europe than the UK (Roberts, 2008). CHP and Wind Energy sources, are widely known, but are not well-tested and monitored (Gleeson *et al.,* 2011). Also, Solar PV and Wind renewable sources tend to be intermittent (Chidambaram *et al.,* 2011). Arguably, among supply-side retrofit technologies, Fuel Cells appear to be relatively unpopular in buildings, despite its comparatively high carbon-efficiency. An explanation for the unpopularity of fuel cells, could be the inexactness in the system performance, and its relatively high upfront cost (Williams, 2012). Research into Fuel Cells are still ongoing, and developments over the next few years, could address the issues associated with this form of renewable energy.

In retrofit buildings, supply-side retrofit technologies, could be combined in order to buffer-up the energy needs of users, and overcome the intermittent supply of energy. Given the relatively high, energy requirements in commercial office buildings (Battle, 2003), it is unclear whether renewable sources alone, will be able to meet, total energy requirements in buildings. Hybrid retrofit technologies could however, significantly halt reliance on fossil-fuel based energy sources, and minimise the energy costs of organisations owing office buildings. Hybrid packages consist of a number of renewable energy sources, and different permutations of them, could be modelled using energy-simulation software packages. Prior to embarking on physical implementation of a hybrid package in a buildings, it will be helpful to develop a virtual simulation model, in order to assess the performance of the proposed building configuration permutations (BCPs), in respective retrofit scenario. In modelling hybrid retrofit packages, it is important to understand the nature of respective technologies, their compatibility with alternate sources, and their efficacy in meeting the energy needs in the respective building configuration. The projects examined in this study will showcase a number of BCPs, developed based on dynamic energy simulation packages, and will provide estimates of the estimated energy supply in respective retrofit scenario.

2.3.2 Demand-Side Initiatives

Demand-side retrofit management initiatives, consist of strategies, embraced to minimise the building's heating and cooling demand, and involve the use of energy-efficient equipment, and low energy appliances (Ma *et al.,* 2012). Minimizing the heating and cooling demand of buildings, involve procedures such as draught-proofing, insulation-enhancement, improving the performance of the building fabric, changing individual behaviours, and inclusion of more specialised equipment, that can potentially enhance the thermal envelop of existing buildings (Kelly, 2009). Demand-side management initiatives, embed both technical and behavioural aspects.

The installation of energy-efficient devices, and low-energy appliances could take the form of upgrading energy conversion plants; replacing energy end-use appliances; replacing and including energy control gadgets, as well as, improvement of management performances (Williams, 2012, Duffy *et al.,* 2015). It also involves the installation of more specialised facilities to meet building-occupants' needs, such as better harnessing the natural ventilation, more efficient heat recovery systems, as well as the use of thermal storage systems, to manage consumption loads efficiently (Roberts, 2008).

2.3.2.1 Improving the building fabric

Heat in buildings, tends to be transferred, through a combination of infiltration of the outside air - in the form of draught, or purpose-designed ventilation, and thermal conductivity. Draught-proofing is a process of minimizing, or eliminating air-exchanges, and could include draught-stripping, replacing leaky windows and doors, sealing-off air-leakage spaces around doors, closing-off unused chimneys, provision of key-hole covers and letter-box plates. Draught-proofing results in fairly small savings, but has been proven to be a low-cost and effective, energy conservation measure in building retrofit scenarios.

It is commonly acknowledged that buildings require some form of ventilation, and hence, adequate fresh air should be considered in the design (Clarke, 2001). Ventilation achieves comfort for building occupants, and helps reduce the risk of condensation in buildings. In the absence of adequate ventilation, treatment of cold-bridges could be carried out, in order to reduce heat loss, and avoid localised condensation (Burton, 2014). Treating cold bridges however, tend to be difficult in balconies, and other cantilever-like structural elements (Robert, 2008).

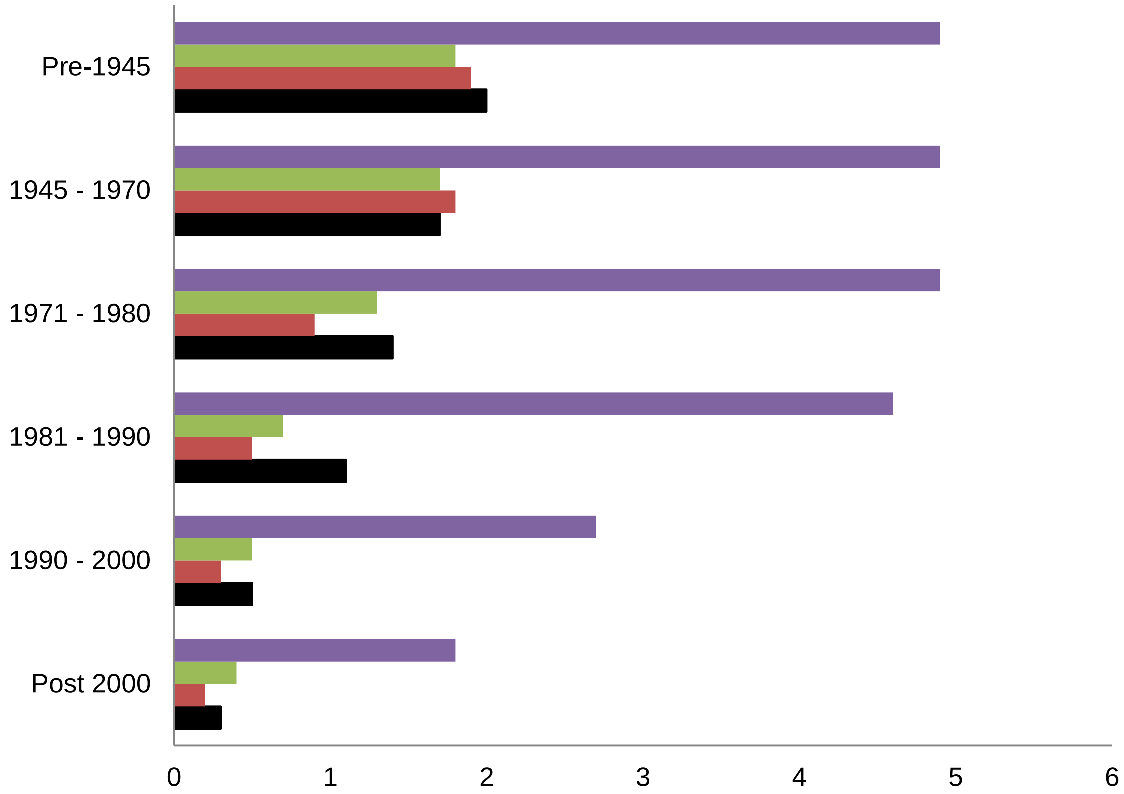
Many existing office buildings are not properly air-tight, leading to the loss of heat, through the joints of windows, doors, or roofs (Dixon *et al.,* 2014a). The air infiltration rate of a building, could also be affected by its age, which could be worsened through cracks at joints (Heo *et al.*, 2012). Proper airtightness is however, essential to minimising heat losses in buildings (Roberts, 2008).

Heo *et al.,(2012)* reported on a survey of 10 UK Office buildings, and found the airtightness data, ranged between 8.3m^3/h and 32 m^3/h per unit area at 50Pa, with the mean value being 17.9m^3/h. This heat loss quotient could be reduced through improved attention to the constructability of buildings. In existing buildings, draught-proofing could enhance air-tight conditions. Different materials used in enhancing draught-proofing in buildings, include brushes, foams, sealants, draught-excluders and tapes. One disadvantage of intense air-tightness in buildings, is the likelihood for reduction in air-change levels, leading to thicker building envelops, which over a period of time tend to be uncomfortable, leading to formation of mould and dampness, as well as odour stagnancy (Cook, 2011). The Passivhaus building is an example, where the effects of intense air-tightness, is yet to be fully addressed (Williams, 2012). The wind cowl is a technological adaptation, used to counteract such situation. The wind cowl works like a domestic chimney, and allows for passive ventilation with heat recovery, thus supplying the building with fresh air, while extracting stale air. The wind cowl is particularly beneficial, because it does not require any additional energy-use, for its operation. The principle of the wind cowl is such that natural wind currents are used to create air pressure sufficient to provide healthy fresh air through a heat exchanger (Roberts, 2008).

Other factors that affect building indoor conditions, include radiation, which affects different parts of the building, at different times of the day, and with strong seasonal variations in many climatic zones (Foley, 2012). Envelops and fenestration, foot-traffic through revolving and hinged doors, as well as natural door spaces such as keyholes could also affect the energy and mass transport exchange in office buildings. The dynamics of air flows in between building rooms, corridors, floors, roofs, and joints will also impact on the heat transfer levels in buildings. Besides, the ever-changing outdoor environment, will also lead to variations in the heat-transfer quotient. Managing the heat-quotient in office buildings, is therefore a complex endeavour. Energy conservation measures could effectively minimize energy losses. However, indoor comfortability also need to be considered, in order to enhance the experience of building occupants.

Thermal building insulation, is aimed at minimising thermal conductivity, and involves the reduction of the transfer of thermal energy, between surfaces at different temperatures, either in thermal contact, or via a range of radiative influences (Duffy *et al.,* 2015). There are different types of insulation materials available for specific elements in a building. The building fabric, is therefore, integral to managing the energy demands in office buildings. Recent research have however, found that the building fabric is not well understood (Gupta *et al.,* 2015).

In order to properly address the building heating and cooling needs in office buildings, it will be important to reduce the rate of heat transfer in buildings, to a minimum (Gleeson *et al.*, 2011). The actual rate of heat transfer, is defined by the U-value, which is the rate of heat loss per square metre, for one degree temperature difference ($W/m^2/K$). Gupta *et al.,* (2015) argues that the U-value might be inappropriate for evaluating the economics of solid wall insulation. The building fabric consists of the windows, walls, roofs and floors. Birchall *et al*., (2014) provided an estimate for the U-values of office building elements in the United Kingdom, from Pre-1945 years to Post-2000 years. It can be observed from Figure 2-3, that over the last few decades, there has been considerable improvements in the permissible U-values for the Walls, Roofs, and Floors. The specified U-values for Windows, have not changed much, compared to other building elements, in the years before 1990. Only in the last two decades, have there been considerable improvements in the permissible U-values of windows in buildings. The permissible U-values for window are however, still significantly higher than that of other building elements, and it may be needful to explore opportunities for improving the fabric performance of windows in office buildings. The report published by the United Nations Environment Programme (UNEP 2007) hinted that windows possess the least thermal insulation levels in buildings.



	Post 2000	1990 - 2000	1981 - 1990	1971 - 1980	1945 - 1970	Pre-1945
🟪 Windows	1.8	2.7	4.6	4.9	4.9	4.9
🟩 Wall	0.4	0.5	0.7	1.3	1.7	1.8
🟥 Roof	0.2	0.3	0.5	0.9	1.8	1.9
■ Floor	0.3	0.5	1.1	1.4	1.7	2

Figure 2-3 U-Values for Office Buildings in the UK for Windows, Wall, Roof and Floor (Birchall, et al., 2014)

Window Insulation

The windows generally form a relevant part of the building shell, and occupy a large proportion of the thermal envelop (Huovila, 2007). Window insulation helps in conserving the thermal atmosphere, within a building. Glazing can be used in enhancing indoor thermal insulation levels, although it could also have aesthetic benefits. Glazing generally aims to, minimise heat conduction through window surfaces. Window glazing could be static or dynamic. Static window glazing involves the use of insulating paints, or increasing the thickness, and number of layers of window covers. Increased thickness of window layers are usually implemented as double glazing, and triple glazing design alternatives, in buildings. Triple glazing tend to achieve higher level of thermal insulation, with centre pane U-values of, as low as $0.6W/m^2K$. Another promising material that can be used in window insulations are aerogels (Roberts, 2008). Aerogels are particularly useful in window thermal insulation, but could also serve as super capacitors, acoustic barriers, dust capture devices, and wall decoration enhancers (Hall, 2010)

Dynamic window glazing could be implemented passively or actively, and involves material properties that respond in different ways to changes in the external environment. Passive dynamic glazing involve concepts such as photochromism and thermochromism. Active dynamic glazing, on the other hand, involves electrochromism, and dynamic façade control. Mempouo *et al.,* (2010) mentioned that chromogenic windows form the bulk of dynamic glazing, and have shown potentials in optimizing lighting and heating permissibility in buildings. Photochromism involves the use of a self-shading glass pane, reacting to light, as used in some eye-goggles (Hall, 2010). Photochromism have limited applications in office buildings, as changes tend to be automatic, and are more useful in buildings, where the occupants' view of outside is not essential (Roberts, 2008). Electrochromic glazing incorporates a coating that can be switched from clear to tinted, in order to provide good solar control performance. Thermochromic glazing consist of special layers between two glass panes, in order to modulate the physical properties of windows (Roberts, 2008). One example of an electrochromic material is polyaniline. Glazing enhancement materials tend to have significant cost implications, and this could hinder their potentials in retrofit building scenarios.

External Wall Insulation

External wall insulation is particularly useful in solid-walled buildings (Roberts, 2008). It protects the fabric of buildings; improves air-tightness; and is relatively easy to install, - leading to faster construction (Williams, 2012). External insulation can be done through Ventilated Rain Screen or Rendered Insulation System. A Ventilated Rain Screen consists of a continuous air space, open at top and bottom, to encourage airflow, and convective drying, when water gets between the cladding and the exterior wall of the building. Rendered Insulation System involves insulation being fixed mechanically, or with an adhesive to the existing walls, and a reinforced render finish is directly applied to the insulation (Roberts, 2008).

There are a variety of commercial packages used in external wall insulation. External wall Insulation however, tend to alter the outside appearance of buildings, and could be less desirable in listed, conservation and historic office buildings. Also, external wall insulation tend to be a capital-intensive process, especially in high-rise office buildings. In situations where external wall insulation is appropriate, they tend to be minimally disruptive to routine building operations.

Internal Wall Insulation

Internal wall insulation typically involves, lining the inside face of the wall with plasterboard on a frame, and filling the void with insulation (Roberts, 2008). Internal insulation, generally tend to be more cost-effective than external insulation, and does not affect the external building façade (Cook, 2011, Duffy *et al.,* 2015). Hence, internal wall insulation tend to have more desirability in listed buildings.

In heavy-weight buildings, internal wall insulation can be improved through the use of insulation materials such as mineral-wool, expanded polystyrene beads, urea formaldehyde, cellulose insulation and hydrophilic materials (Xing *et al.,* 2011). It is however, noteworthy that these fabric measures, tend to have a higher life-expectancy than many retrofit technologies (McLeod *et al.,* 2012), and are often cheaper than alternative energy renewable sources. Cook (2011) notes that hempcrete (which is made from hemp and lime mortar), woodcrete, and limecrete, are newer materials, which exhibit, excellent thermal mass performance, in a sustainable manner. Many composite materials are also emerging in the market. Richard *et al.,* (2007) highlights the advantages of composite materials over traditional construction materials.

Other material considerations for internal wall insulation include multi-foil insulation, gas-filled insulation, and vacuum insulation (Roberts, 2008). Multi-foil insulation involves the use of multi-layered reflective films, only a few micrometres thick, which are separated by wadding such as foam or sheep's wool, and are sewn together to form a thin insulating blanket (Roberts, 2008). Vacuum insulation involves the use of vacuum insulation panels (VIPs), which consist of micro-porous core structure enclosed in a thin gas-tight envelope, to which a vacuum is applied. VIPs have a thermal performance, five to ten times greater than conventional insulation materials (Roberts, 2008). However, VIPs are fragile compared with conventional materials, and edge effects are significant, requiring careful design and fabrication.

Internal insulation however, tends to be more disruptive than external insulation, and could lead to loss of floor space, and actuate thermal discontinuities in buildings (Roberts, 2008).

Roof Insulation

Roof Insulation is another approach in minimizing heat energy needs in office buildings. It involves increasing the thickness of existing insulation layers in the loft and attic spaces, and the installation of better insulation materials in roofs. Common roof types in office buildings, are ventilated pitched roofs and flat roofs. Other considerations in retrofit scenarios are green roofs.

The common use of green roofs is in the control of storm water run-off. They can also help reduce transfer of heat between the external and internal building environment. A study by Newton (2007) reported that winter temperature under membrane of green roofs was 4.7^{o}C, compared to 0.2^{o}C, in standard roofs; and summer temperature under membrane of green roofs was 17.1^{o}C, compared to 32^{o}C, in standard roofs. Green roofs however, tend to supplement conventional insulation materials. It will however, be needful to ascertain the ability of the roof to support the weight of the green infrastructure, prior to being employed in retrofit scenarios.

Installation of roof Insulation materials tend to be minimally disruptive, especially in multi-storey buildings. Roofs tend to be one of the largest surface areas through which air permeability and thermal conductivity, could be easily controlled and moderated. They also provide a large platform for the installation of solar PV panels.

Floor Insulation

Insulation of ground floors tend to be highly disruptive in building retrofits, and therefore features in major retrofit scenarios (Burton, 2014). Ground floor insulation often requires the removal of internal fittings, furniture and finishes, in buildings, which halts operational activities in the building over a period. Floor structures are often referred to as been, suspended or solid (Roberts, 2008). Suspended floors are typically very poor thermally, and are often constructed with timber joists. Solid floors are typically constructed with concrete, and bear directly on the ground, or supported by concrete beams, with infill blocks.

Timber floors are commonly used in office buildings, and ought to be checked for structural soundness, and the presence of wet or dry rot, prior to any retrofit insulation. Available retrofit materials in timber floors include foamed polyurethane, mineral wool, and cellulose (Cook, 2001; Duffy *et al.,* 2015). A structural layer of plywood deck, or chipboard, may also be added to protect insulation layers in timber floors.

Solid floors can be insulated with high-performance rigid insulation materials, above the existing concrete or screed. Laying a continuous damp-proof membrane beneath the insulation is advisable, and should be designed to overlap with any damp-proof course in the external walls. Insulation of top floors is however, a standard procedure for ventilated pitched roofs, or flat roofs, especially where there is good ventilation below the water proofing surface.

In summary, the principles for implementing demand-side retrofit management initiative is to focus first on fabric efficiency in order to achieve thermal mass – the ability of a material to store heat. Hall (2010) cautioned that while thermal mass can stabilise the temperature of occupied spaces, it cannot buffer humidity fluctuations resulting from changing atmospheric conditions. In recent times, some phase change materials (PCM), are being used in conjunction with the building fabric to achieve the addition of latent heat storage in buildings. PCMs are materials that undergo a phase-change, by re-ordering their micro-structure. This involves the storage and release of latent heat. Hall (2010) reasoned that PCMs such as paraffin waxes, fatty acids, hydrated salts are still under development, though they show potentials for night cooling. The challenge with PCMs however, is that they can only operate over a limited temperature range around the melting point (Hall, 2010).

2.3.2.2 Energy Efficient Appliances

According to Williams (2012), energy-efficiency technologies are interventions, directed at minimizing the energy-needs of buildings, and they include replacing or improving efficiency in energy end-use appliances and, replacing or incorporating energy controls

Replacing or Improving Efficiency in Energy end-use appliances

Energy end-use appliances include ventilation and cooling units, lighting gadgets, heating and hot water appliances, computing devices, and other accessories such as lifts (McKenna *et al.,* 2014). Natural ventilation in buildings is often viable, but could be restrictive, insufficient, and associated with poor air-quality. The scope for natural ventilation in office retrofit building projects, could be limited, as natural ventilation issues are best addressed at the building design stage. An alternative to natural ventilation is mechanical ventilation, which could be addressed through the use of air-conditioning and associated systems.

According to Kolokotsa *et al.,* (2011) incorporation of high energy-efficiency cooling, is vital in office building units, and can be achieved through air-conditioning equipment with high energy-efficiency ratio (EER). The CIBSE (2006) specified a comfort range of 21^{o}C to 24^{o}C, for office building units. This temperature range is appropriate with a peak summer temperature of 28^{o}C, representing no more than 1% of the annual occupied period, in non-air-conditioned spaces (CIBSE, 2006).

Currently in the UK, approximately 70% of offices have minimal or no air-conditioning systems, 24% have full air-conditioning systems, and 6% have partial air-conditioning systems (Birchall *et al.,* 2014). Cooling could be achieved through the use of air-conditioning systems and mechanical fans. Air-conditioning systems are often described by acronyms such as Variable Air Volume (VAV), Variable

Refrigerant Volume (VRV), Low Pressure Hot Water (LPHW), Low Temperature Hot Water (LTHW) systems, fan assisted VAV, Variable, Volume and Temperature (VVT) and Fan Coil Units (FCU).

Fan coil unit systems and Variable Air Volume (VAV) systems are perhaps, the more common of air-conditioning systems. Fan-coil units have high cooling capacities, and tend to be adaptable and reliable. They also have reduced space requirements compared to VAV. VAVs are however, preferable in terms of air-quality, reduced noise levels, and reduced running and maintenance cost (Battle, 2003). These systems supply warm or cool air to match cooling requirements, whilst delivering an acceptable quantity of fresh air. Air-conditioning systems also help in controlling humidity levels.

A combination of natural and mechanical ventilation could enhance comfort in office buildings. This is often termed mixed-mode ventilation, and tend to achieve better results in commercial offices, than only the natural or mechanical ventilation units (Burton, 2014). In the mixed-mode ventilation system, fan-assisted air supply could be adapted into a partition layout, and ventilation needs could be met based on the requirements of respective users. If more cool is required, a mechanical system can be added. There is scope for cooling by chilled or activated beams, in ventilation systems. Chilled beams are energy-saving technologies, that augment the air-conditioning system (Battle, 2003). Chilled beam represent an efficient alternative to cooling the air stream using mechanical ventilation techniques.

Computing devices include desktop computers, portable computers, mini computers, mainframe computers, terminals, monitors, laser printers, inkjet printers, scanners, fax machines, network server units, and copiers. There are possibilities of other specialised automated systems, used in carrying out tasks in the offices. Moreover, a host of advanced technological gadgets, and end-use appliances are becoming available in the market. The advent of 3D Printers, Laser Scanners and multi-functional devices in offices has potential impact on energy consumption levels in office buildings. In recent times, there has been significant advancement in computerised devices, and their energy-saving potentials.

Heating and hot water are often provided through the use of boilers, solar hot water systems (SHWSs) and hot water cylinders. A boiler is a closed fuel-burning container, in which water, or other fluids, are heated to generate hot water, steam or vapour, superheat steam, or any combination thereof (Duffy *et al.,* 2015). Boilers use a variety of fuel, which include fuel oil, natural gas, electricity, and wood pellets. Natural gas is often preferred in commercial office buildings, because it is readily available, burns cleanly, and is typically less-expensive than electricity or oil. Boilers generally have a relatively high life-expectancy, and the range of boilers available today have varying efficiencies, depending on the operational and maintenance regime. Condensing boilers typically operate in the 88 to 95 per cent combustion efficiency range. While non-condensing boilers typically operate in the 75 to 86 per cent combustion efficiency range. ‘Combi’ or ‘Combination’ boilers, provide heat for central heating, and hot water on demand. They consist of a higher efficiency hot water heater, and a central heating boiler combined within one compact unit. The primary benefits of Combi boilers is that they reduce space requirements in buildings, thereby eliminating the need for hot water cylinders. SHWSs convert solar radiation into thermal energy, typically using water-based liquids, as energy carriers. Two main types of SHWSs are Thermosyphon or natural circulation, and Pumped systems or Forced circulation.

The basic components of the SHWSs are the collectors, storage tanks, connecting pipes, auxiliary heating systems, and pumps. The collectors are however, the main component of the SHWSs, and are crucial to the overall ability to efficiently generate heating and hot water. Collectors absorb, diffuse, and direct solar radiation. They are distinguished by their motion, which can either be, stationary, single-axis and dual-axis tracking. Stationary solar collectors are permanently fixed in position, and do not track the sun. Three types of stationary solar collectors are flat-plate collectors (FPC), evacuated tube collectors (ETC), and compound parabolic collectors (CPC) (Roberts, 2008). Flat-plate collectors are easier to manufacture, and therefore, cheaper to produce, as flat-plate collectors use gas-filled glazing (Duffy *et al.,* 2015). Evacuated tubes tend to give more spread of hot water throughout the year, in proportion to the hours of sunlight exposure (Roberts, 2008). The individual units of evacuated tubes can also be rotated, in order to allow for easier alignment of the tubes to the optimum angle. Thus, solar radiation can be collected without the need for any extra support structure to tilt the whole panel. In a study by Fong *et al,* (2010), evacuated tubes achieved up to 74% primary energy savings. In some cases however, SHWSs can only be used for summer hot water needs. It often yields much little capacity in the Winter, and could be unable to fulfil central heating demands (Akbar *et al.,* 2011). SHWSs are simple, reliable, well-known and widespread. According to Boardman *et al.,* (2005), SHWSs are perhaps one of the most commercially viable renewable technologies. SHWSs are not as sensitive to partial shading as PV panels, but generation on shading tend to be reduced. Usually, an installation of around 4m^2 is needed for solar hot water to produce 200 litre tank of water. In a study by Caird *et al.,* (2008), it was found that the main drivers for installing SHWSs are environmental concern and saving money. While the main barriers to installing SHWSs, are capital cost and lack of information on reliable brands. It has also been reported that in hot countries, SHWSs offers emission reductions due to relative abundance of solar radiation (Gleeson *et al.,* 2011).

In multi-storey buildings, lifts are important utility devices to move quickly and efficiently between floors. As a rule of thumb, installations of lifts take a period of about one week per floor, plus five weeks (Nicholson, 2005). Lifts consume a lot of energy, and are statutory provisions in multi-storey office buildings in the UK. The British Standard, BS5655 provides some guidance on the Installation of Lifts. There are various lift installers in the UK. Lifts however, tend to consume a fairly large amount of energy in its operations. Many modern lifts are installed with sensors, and thus tend to save energy, when no one is using them.

In office buildings, lighting devices helps deliver visual comfort, good visibility, good colour reproduction, and glare minimisation (Duffy *et al.,* 2015). The amount of energy consumed by lighting can be reduced by installing energy-efficient light bulbs. It is however, important to supplement this, by optimising existing controls, making the most of natural lighting, observing good housekeeping practices, and reducing lighting to the minimum required standard. Lighting types includes:

- *Incandescent lamps*

  These types of light bulbs are extremely wasteful of energy, as about 90 per cent of the electricity they use, produce heat rather than light.

- *Compact or Tube Fluorescent Lamps (CFL or TFL)*

  Fluorescent lamps (T5/T8) are efficient using about 20 per cent of the power of incandescent bulbs. They are long-lasting and generate little heat.

- *Tungsten halogen lamps*

  Tungsten lamps use less than 10 to 20 percent of the energy consumed by incandescent lamps and last about twice as long. They also generate heat and should not be used near flammable materials.

- *Sodium High Pressure lamps*

  Sodium high pressure lamps produce a warm white light, and generally have a longer lifespan than metal halide lamps

- *Light Emitting Diode (LED) lamps*

  LED are semi-conductor devices that are very energy-efficient, and produce very little heat. LEDs have higher initial cost, but lower energy and maintenance cost, compared to Fluorescent lamps. LEDs typically have the longest life-expectancy, among the lamp types considered.

- *Mercury Vapour Lamps*

  Mercury vapour lamps have a long lifespan, compared to metal halides.

- *Metal Halide lamps*

  Metal halide lamps provide bright white point lights. They are more efficient than mercury vapour lamps and brighter than sodium lights.

Thermal Energy Storage (TES) Systems

A Thermal Energy Storage (TES) system is a device that can store thermal energy by cooling, heating, melting, solidifying, or vaporizing a material. TES systems are technologies that have capability to shift electrical loads from high-peak to off-peak hours (Arteconi *et al.,* 2012). They help ensure energy security, energy efficiency and environmental sustainability. TES systems can be classified into Sensible, Latent and Cold. The Cold TES is the most widespread in the market, among the available technologies. TES are also essential to overcoming the intermittent nature of some renewable technologies, such as wind and solar energy sources (Chidambaram *et al.,* 2011).

2.3.2.3 Replacing or incorporating energy Control Schemes

Energy control schemes include a host of dynamic demand devices that aim to reduce carbon dioxide emissions through switching on and off, energy supplies as appropriate, and other self-regulating processes in the operations of office buildings. Energy control systems often has a communication system between the end-user, and an external party (Arteconi *et al.,* 2012). According to Chen *et al.,* (2009) energy control devices have demonstrated potentials in minimizing energy, used in heating, cooling, and lighting. Efficient space heating and controls can save about 13% of emissions (Chen *et al.,* 2009). Thermostatic radiator valves (TRVs) are devices which allow for zoning within office buildings. In such situation, zones of limited occupation can be held at lower temperatures, and energy could be diverted to more occupied zones. TRVs however, work best with informed occupants and commensurate behavioural aptitude.

Smart metering is another approach of ensuring advanced control of energy-use in buildings. A smart meter is a device that helps to measure and communicate consumed and produced energy, (Georgievski *et al.*, 2012) with high accuracy, control and configuration functionality (Gungor *et al.,* 2012). The key features of smart meters used in Office Buildings incudes time-based pricing; providing consumption data for consumer and utility; net metering; failure and outage notification; remote command operations; load limiting for demand response purposes; power quality monitoring; energy theft detection; communication with other intelligent devices; efficiency in power consumption (Mohassel *et al.,* 2014).

Generally, smart meters comprise an electronic metering box and a communication link that aid the provision of data on energy-usage, which also serves as a basis for billing (Moura *et al.*, 2013). The smart meters are therefore, considered as a two-way automated metering infrastructure (AMI).In more recent times, smart metering devices are usually integrated within a smart-grid system, to improve on the utilities of advanced control schemes. Three mechanisms that facilitate the effectiveness of the smart-grid include rendering advice to end-users on managing energy consumption; potentials for accurate and frequent monitoring of bills; and achieving motivation regarding available incentives to end-users on energy consumption resumption (Moura *et al.,* 2013). The current challenges to the deployment of smart meters, relate to standardization, interoperability, costs, regulation and security.

In order to be effective, It is however, vital for advanced control systems on buildings to provide energy consumption visibility, integrated building operations, allow for dynamic demand response, and enhance autonomy and awareness of building occupants (Chen *et al.,* 2009). It has been suggested that cloud computing holds potentials for providing a viable model for delivering common building services, through a shared dynamic infrastructure (Georgievski *et al.,* 2012).

2.4 Investment in Retrofit Initiatives for Office Buildings

One key reason for limited investment in energy-efficiency projects in office buildings is that energy represents a small percentage of total occupancy costs (Wade *et al.,* 2003b). Christersson *et al*.,(2015) opined that energy costs, constitute just about 5 – 15 per cent, of rental income. Besides the proportion of energy costs in buildings, there are other deterrents to investing in retrofit initiatives in office buildings. These includes the high proportion of institutional ownerships in office buildings (Christersson *et al.,* 2015, Ma *et al.*, 2012, Wade *et al.,* 2003a); the fragmented nature of the supply chain of retrofit technologies (Wade *et al.,* 2003b, Kelly, 2009); the lack of access to funding for retrofit building projects (Gleeson *et al.*, 2011, Woo & Menassa, 2014); the short-term nature of leases in office buildings; uncertainties regarding actual costs and benefits accruable from investments (Gleeson *et al*., 2011, Menassa, 2011); perceived high cost of energy-efficient technologies (Dixon *et al.,* 2014b); and the lack of policy incentives to bridge the funding gap in energy-efficiency initiatives (Dixon *et al.*, 2014a, Menassa & Baer, 2014). The sentience in the building industry coupled with the lack of economic incentives, could deter the uptake of retrofit solutions. This work therefore seeks to apply the principles of fuzzy logic in the whole-life cost modelling of office retrofit buildings, in the anticipation that policy-makers and stakeholders will be better informed in pushing forward the retrofit agenda. A whole-life scenario provides a sustainable outlook to appraising the cost of retrofitting (Caplehorn, 2012), and hence, allows for a broader spectrum of variables. Woo and Menessa (2014) expressed that the benefits of retrofitting buildings transcends economic returns alone, yielding far-reaching social, health, image and environmental value for organisations. There is however, a need to objectively appraise costs, in order to better understand the demands of retrofitting in office buildings.

Studies on energy-efficiency initiatives in office building projects, have failed to provide a consensus on the cost-to-benefits levels. Santamouris and Dascalaki (2002) examined five office building retrofit projects, in four different climatic zones, and found potential for up to 56% in energy savings. Chidiac *et al.,* (2011) also studied an office building, and reported a potential savings of 20% in electricity consumption, and 32% in gas consumption. Other works by Ascione *et al*.,(2011) and Fluhrer *et al.,* (2010) reported a potential for 22% and 38% energy savings in selected office building projects respectively. All these studies attest to significant opportunities for improving energy performance in existing office buildings.

Energy-efficiency initiatives have understandably had an impact on the decision to retrofit. A few authors have advocated the need to better understand the behaviour of organisations, in relation to investment decisions in energy-efficiency retrofit projects for office buildings (Dixon *et al*., 2014a, Christersson *et al.*, 2015). Invariably, investment decisions for energy-efficiency projects are complex (Ma *et al.,* 2012). Gleeson *et al.*,(2011) surmised that the economics of retrofitting suggests a potential for diminishing returns. Hence, an optimal cost-to-benefit analysis need to be identified. Menassa (2011) concluded that a framework that facilitates the evaluation of retrofit measures, and its long-term benefits, is still non-existent.

Traditional approaches to investment appraisal in building projects are the payback period, and discounted cashflow (DCF) techniques. The payback period is the ratio of the initial investment cost to the annual savings. The payback approach is considered over-simplistic, as it fails to capture the time value of money, as well as the life time of the investment (Christersson *et al.,* 2015). Despite this limitation, there are claims of the payback period, being the most widely used decision-making rule, in energy-efficiency projects (Ma *et al.,* 2012). Foley (2012) remarked that retrofit projects should aim to achieve a 3 – 5 years payback, in order to appeal to building investors. This target however, seems over-ambitious and unrealistic, as it fails to capture the investment complexities in retrofit scenarios. Parker *et al.,*(2012) advises that simply using the pay-back period rules out many retrofit technologies, as being economically viable, and might stifle investment endeavours.

The discounted cash flow techniques include measures like the Net-Present Value (NPV), Internal Rate of Return (IRR), Return-on-Investment (ROI) and benefit/cost ration (BCR). Among twenty-five techniques of economic viability measures examined in the literature, Ma *et al.,* (2012) found that the NPV is the most widely-used. The discounted cash flow (DCF) techniques consist of four steps: forecast the expected cashflows; ascertain the required rate of return, and discount the cashflows relative to the present value (Geltner *et al.,* 2014), and lastly summing up the present value cashflows to yield an equivalent sum.

Discounted cashflow (DCF) techniques however, have their own limitations. DCF techniques tend to utilise unverified and subjective assumptions on the respective discount rates; could wrongly guess the expected cashflows; fail to consider the cross-sectional and time-series links between alternative investments, and assume investments are irreversible (Christersson *et al.,* 2015). Other limitations of DCF techniques, are its failure to allow for changes in the discount rates over time, and providing a mechanism to value project decisions, that may be taken at some point in the future (Greden, 2005, Menassa, 2011).

Another rather important limitation of DCF techniques, is the insufficient consideration of significant uncertainties during the economic valuation phase of projects. (Menassa, 2011). Despite these, DCF techniques are considered, the most popular and prevalent investment valuation methodology, both in literature and in practice (Goh & Sun, 2015, Christersson *et al.,* 2015). Kaplan (1986) argues that some of the acclaimed limitations of DCF techniques, are essentially limitations of the user, rather than the technique. For example, the selection of a single discount rate over a time horizon, rather than fluctuating rates, is a choice of the user, rather than the technique.

Using a single discount rate presumes that risk borne per period is constant, and that uncertainty is resolved continuously at a constant rate over time (Yao & Jaafari, 2003). Mun (2002) suggested using multiple discount rates in DCF procedures, in order to derive more realistic cash flow predictions. However, this could be highly complicated and could make investment calculations over the whole life of building assets difficult to follow through. It must however, be stated that the conceptual benefit behind the DCF technique, is essentially to consider the time-value of money in the derivation of cash flows. This objective may however, be realized subject to the discretion and capability of the users, just like in many other investment valuation techniques.

The real options (RO) theory has been put forward as a conceptual philosophy that holds potential to counter some of the limitations in the DCF approach (Adler, 2006, Blanco *et al.,* 2012, Yao & Jaafari, 2003, Ghahremani *et al.,* 2012). The RO theory is a conceptual idea that certain decisions can be taken in the future with better information. The RO theory is however, not a conceptual substitute to the DCF technique; rather it supplements, and fills the gap which DCF has failed to address (Kodukula & Papudesu, 2006). The RO theory therefore, has potentials to integrate traditional valuation tools into a more sophisticated and realistic framework.

Kodukula and Papudesu (2006) add that real-options approach, could prove invaluable as “tie-breakers,” where two or more competing projects have similar return-on-investments. The common approaches to implementing the real options theory are the Black-Scholes option pricing model or the Binomial model (Yao & Jaafari, 2003). Block (2007) remarked that the binomial RO approach is arguably the prevalent implementation of the RO theory framework. One of the principal assumption behind the RO approach, is that returns follow a log-normal distribution pattern (Boussabaine & Kirkham, 2008).

The binomial RO model is based on the notion, that over a single time period, the underlying asset price can move from its current price, to only two possible levels, up or down, in successive periods (Yao & Jaafari, 2003), and by a pre-specified proportion. Menassa (2011) hinted that binomial RO model, is the more general approach for dealing with American Options. Figure 2-4 depict a Four-step Binomial model of the Future Cost movement of an underlying asset. After a time period (typically one year), the asset price could move up to either R_u, in the case of the upward movement, or R_d, in the case of the downward movement. Equally, the succeeding price of R_u, can further rise through an upward movement to R_{uu}, in the next succeeding period, or undergo a downward movement to R. It should however, be noted that the assumed multipliers are d < 1, while u > 1. Furthermore, d < 1 + r < u; where r = discount rate, and R is the Present value of the future cost cashflow projections. A four-step binomial model utilised in Figure 2-4 aptly represents a four-year cashflow period. Goh and Sun (2015) implied that in whole-life cost scenarios, it is not uncommon for the number of steps in the binomial model to range from 20 to 60 iterations, depending on the expected life of the built asset.

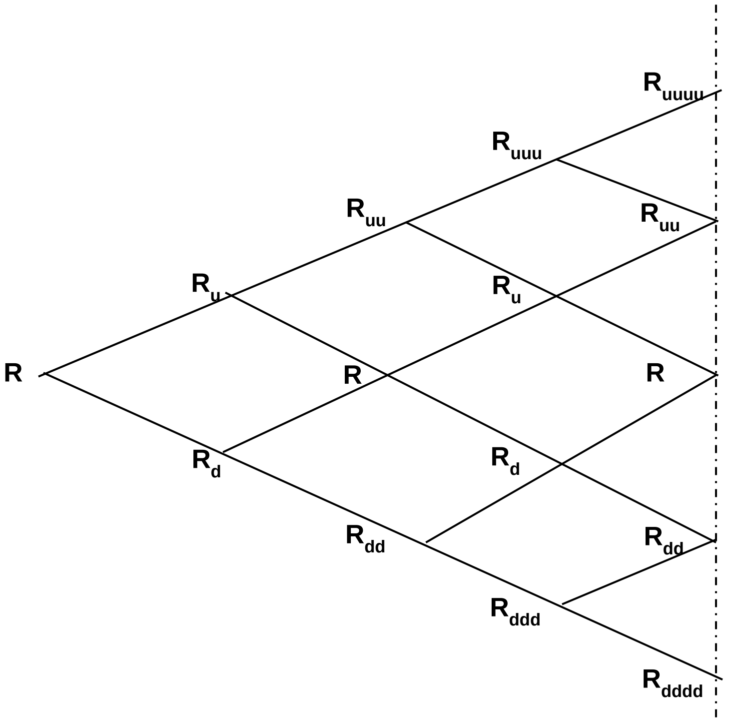


Figure 2-4 Four-Step Binomial Model of the Future Cost Movement of an Underlying Asset

To fully utilise the benefits of the binomial template, it will be essential to have an estimation of the likelihood of each future cost event, occurring in the respective time period. A probabilistic template proposed to evaluate the likelihood of future cost events, has been put forward by Ellingham and Fawcett (2006). The template proposed by Ellingham and Fawcett (2006), is based on the Negative Binomial probability distribution. According to Ayyub and McCuen (2011), the procedures of computing the likelihood of occurrence of future cost events, by the Negative Binomial probability distribution is based on the assumptions that :

- Future cost events are independent
- Each future cost event can have only two possible outcomes

- The probability of occurrence remains constant from event to event

The coefficients of the Negative Binomial probability distribution, has the progressive form, and can be derived as shown in Figure 2-5

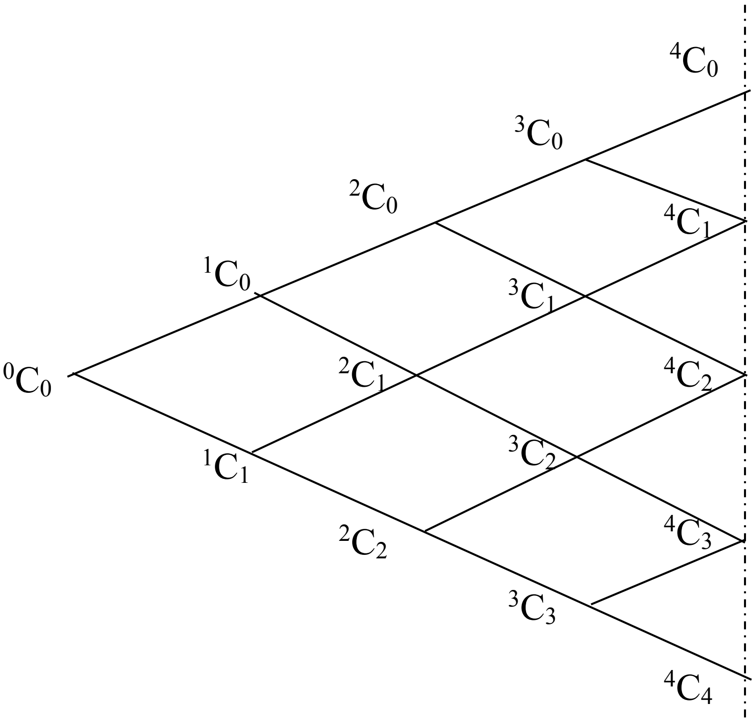


Figure 2-5   Coefficients of a Four-Step negative probabilistic binomial model

In this binomial model, the general equation for the series over a specified number of years, n, can be represented as:

$$^nC_0 + {}^nC_1 + {}^nC_2 + \ldots + {}^nC_{n-r} \qquad \text{(Eqn.2.1)}$$

Also, the general form of the binomial series can be expanded as follows:

$$^nC_r = \frac{n!}{(n-r)!\,r!} = \frac{^nC_{r-1}}{^nC_0 + {}^nC_1 + {}^nC_2 + \ldots + {}^nC_{n-r}} \qquad \text{(Eqn.2.2)}$$

In order to present the binomial series (which is effectively the Pascal's Triangle) in standard form, there is however, need to normalize the coefficients to ensure the probability value ranges between 0 and 1. The expression used in deriving the corresponding probability equivalent for each series index is deducible as follows:

$$Z_{n,r} = \frac{{}^{n-1}C_{r-1}}{\sum_{k=0}^{n-1} {}^{n-1}C_k} \qquad \text{(Eqn.2.3)}$$

Where, $Z_{n,r}$ = corresponding probability of the cost event,
k = number of years over which running cost changes,
n = number of years, and
r = number of combination elements

In the mathematics of whole-life costing, the Combination formulae in Equation 2.3, refers to the combination of "n" years taken "r" times. Combination, thus attempts to combine possible items from a collection, such that the order of selection does not matter. In whole-life costing, this approach is considered useful as it explores a significant number of discrete future cost scenarios, that can occur over the life of an asset, and the Negative Binomial probability distribution, provides the probabilistic likelihood of the occurrence of each of the future cost predictions.

The Black-Scholes RO theory approach, can also be derived from the binomial model, and they both share similar assumptions (Yao & Jaafari, 2003). According to Menassa (2011), the Black-Scholes RO theory, seems more suited to valuing European financial options. The value of the European Option is obtained by solving the option tree template backwards, starting from the last period, and using the associated discount rate.

The RO theory however, has its own limitations. It assumes the value of investments depends solely on the inherent economic variables (Busby & Pitts, 1997); it also fails to recognise the role of behavioural uncertainties influencing investment valuation (Adler, 2006, Ghahremani *et al.,* 2012, Chang, 2012). Chang (2012) identified "hold-up threat" as a type of behavioural uncertainty, that could affect the benefits of the RO approach in investment scenarios. Adler (2006) also advised that the RO approach, could easily promote dysfunctional behaviour of investment analysts.

There are also claims that the RO theory fails to deal with the problem of valuing non-financial or qualitative benefits, in projects (Adler, 2006). Besides, RO may not even be applicable, or desirable in certain scenarios, (Ghahremani *et al.,* 2012) because it can inhibit organisational certainty. The application of RO could also be hampered by legislative, or regulatory restrictions (Busby & Pitts, 1997).

To enhance the capability of the RO approach, decision analysis and dynamic programming are often incorporated into its framework (Chang, 2012). While the decision analysis and dynamic programming methodology, hold potentials to enhance the RO framework, they still do not address behavioural issues; and also cannot explicitly quantify the non-quantitative costs and benefits, in the investment valuation of retrofit options. In retrofit scenarios, social norms and behaviours, will no doubt, play a pivotal role in attaining and assessing the energy cost savings anticipated (Kelly, 2009, Xu *et al.,* 2014). Hence, investment appraisal techniques, need to take cognisance of behavioural aptitudes, in order to achieve, improved robustness and accuracy in its framework

Based on some of the concerns on investment appraisal techniques, a more flexible uncertainty modelling framework - fuzzy logic, is proposed for augmenting and improving on the whole-life cost valuation methodology. McCauley-Bell and Badiru (1996) inferred, that fuzzy logic provides a tool to address variability associated with human abilities and performances. Chan *et al.,* (2009) hinted that fuzzy logic is in better agreement with the workings of the human mind, and therefore, provides a more realistic estimation of events and phenomena (Zadeh, 2008). Sii *et al.,* (2001) also adds that, fuzzy logic provides a more flexible structure to combine qualitative and quantitative information.

The problem with fuzzy logic however, is that it jettisons precision in its efforts to realistically model uncertain events (Ross, 2009). The mathematical procedures of fuzzy logic, could also constitute difficulties for some building practitioners. It is however, clear that fuzzy logic provides a platform that accommodates behavioural aptitudes, and could prove invaluable, when combined with the RO approach in whole-life cost modelling.

In the whole-life costing of building investments, the New-Generation Whole-life costing model, developed by Ellingham and Fawcett (2006), already incorporates the decision analysis and the binomial model RO approach, in its methodology. However, the cumulative cashflow derivations are not clearly distinguishable from the Standard Whole-life costing approach, and the benefits of the probabilistic framework for modelling future cost events is not evident. Utilising the fuzzy approach in Whole-life costing could better highlight the benefits of incorporating a more advanced uncertainty analysis methodology, in the whole-life modelling of office retrofit building options. The aim of this study is therefore to apply the principles of fuzzy logic in the whole-life cost modelling of office retrofit buildings.

2.5 Summary

This chapter provides the first section of a two-part literature review, of this thesis. It commences with an overview of the proportion of office buildings in the UK, and then examines the imperative for retrofitting office buildings. The chapter also reviews the different initiatives for retrofit interventions in office buildings. The chapter goes on to discuss the technical specification of office retrofit building projects, which are broadly categorized as supply-side and demand-side initiatives. The chapter concludes with an elaborate outlook on energy quantification approaches, and a critical discussion on investment appraisal techniques in buildings.

Chapter 3 Mechanics of Whole-life costing in Buildings

"The whole is more than the sum of its parts"- Aristotle (384 BC – 322 BC)

3.1 Introduction

This chapter examines key considerations in the whole-life costing of buildings. It commences with a broad overview of the approaches to cost modelling. It discusses the concept of whole-life costing, and systematically considers the pertinent issues peculiar to the long-term cost implication of Office buildings. Concerted effort is directed at explaining the principles of existing whole-life costing techniques. A critical assessment of the features of existing whole-life cost models is undertaken, towards developing new whole-life costing techniques, which potentially improve on the current approaches to whole-life costing. This chapter also espouses on uncertainty modelling techniques, and explains various approaches of dealing with uncertainties in whole-life costing scenarios. The concluding section highlights the gaps in knowledge regarding the whole-life costing of retrofit options in office buildings.

3.2 Background on Whole-life Costing in retrofit buildings

Whole-life costing is intended to aid long-term, rational, and realistic decision outcomes in building investment appraisals (Ashworth & Perera, 2013). The evidence from the built environment literature however, raises doubt on the ability of existing whole-life costing models to robustly appraise office retrofit building projects. Menassa (2011) implied that a whole-life costing decision framework, that facilitates the process of evaluating retrofit measures, does not yet exist. Ma *et al.,* (2012) expressed that there are inherent challenges with identifying the most cost-effective retrofit measures. It is therefore, a pressing research imperative to investigate building retrofits with a view to developing a whole-life cost modelling template that address critical issues in retrofit investment scenarios (Heo *et al.,* 2012) . It is equally important, to highlight the specific issues of interest in the whole-life cost modelling of office building retrofits.

Cost modelling, is a scientific approach of evaluating relevant variables that influence the economic value of building facilities and projects (Ashworth, 2004).

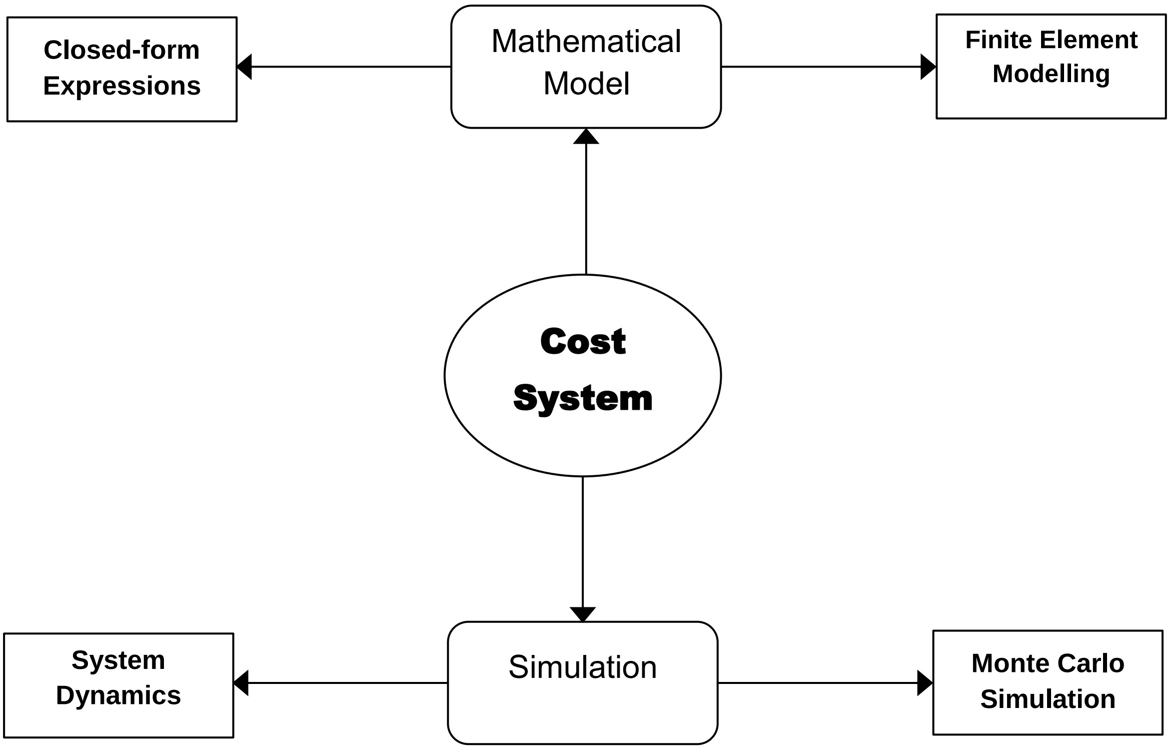


Figure 3-1 Approaches to Cost System Modelling (adapted from Farr, 2011)

As described in Figure 3-1, the paths to cost system modelling, are essentially a choice between mathematical models and simulation (Farr, 2011). Mathematical models can be represented by closed-form expressions or finite-element methods. Ross (2009) stated that closed-form expressions provide precise descriptions for systems with minimal complexity, and hence, assume little or no uncertainty. Current trends in cost estimation however, suggest increased complexities, and heightened uncertainties (Boussabaine & Kirkham, 2008). There is therefore a need to develop cost models that adequately provide for uncertainties, and associated complexities in their framework.

Finite-elements methods are structural models, used to represent mechanical properties, or response of a given structure to a set of static, dynamic or thermal loads (Ayyub & McCuen, 2011). They are generally expressed in terms of complex differential equations, and require great computational efforts. Besides the analytical demands of finite element methods, this approach seem better suited to experimental settings, where variables can be controlled, and the effects of mathematical variables can be more precisely documented.

Simulations, on the other hand, provide a cheaper, and highly beneficial way to conduct a simplified analysis on a system (Farr, 2011). Simulations are known to provide sub-optimal results, and often seek for satisfactory solutions (Boussabaine & Kirkham, 2008). Simulations tend to be computational black-boxes, and often fail in establishing fundamental relationships, between cost variables. In cost modelling, Simulation could be in the form of System-Dynamics or Monte-Carlo Simulation (Farr, 2011).

In whole-life cost scenarios, mathematical cost models however, hold promising potentials in systematically arranging, and handling input variables, as well as in methodologically translating them into outputs (Smit, 2012). Mathematical modelling effectively provides a relevant framework for assessing the investment potentials of office retrofit buildings, and remain the more predominant approach in whole-life cost scenarios (Kishk, 2005). It is however beneficial that uncertainty modelling techniques be used in augmenting mathematical whole-life cost modelling procedures, in order to achieve more realistic results (Kirkpatrick, 2000, Goh *et al.,* 2010, Fawcett *et al.,* 2012).

In semantic terms, uncertainties in whole-life cost scenario could be in the form of ambiguities, vagueness, or likelihood (Ayyub & McCuen, 2011). Ambiguity comes from the possibility of having multiple outcomes for processes or systems. Vagueness, on the other hand, is a product of the tendency of the human mind to reduce and generalize, when conceptualizing information, and results from imprecise nature of classifying certain information elements. Likelihood, can be defined in the context of ‘chances’ and ‘odds’, and has primary components of randomness and sampling (Ross 2009).

In modelling uncertainties, probability theory is often considered the traditional and widely-accepted mechanism, across various disciplines (Zadeh, 1995). Probability theory is however, best suited in dealing with a specific facet, - the ambiguity component of uncertainty (Ayyub & McCuen, 2011), and when combined with statistics can be effective in dealing with the likelihood aspects (Kishk & Al-Hajj, 2000). Vagueness aspects of uncertainty are more common, in the definition of certain parameters (usually qualitative) such as quality, experience, satisfaction, and comfortability. Zadeh (1995) explains that probability theory tends to be less effective in situations, where dependencies between variables are not well-defined; the knowledge of probabilities is imprecise, and incomplete; the systems are not mechanistic; and human reasoning, perceptions, and emotions are involved. These situations highlighted by Zadeh (1995) are arguably typical of whole-life costing scenarios, and hence, the applicability of fuzzy logic for uncertainty modelling, needs to be considered.

3.3 Principles of whole-life costing in Buildings

In the current Built Environment literature, two different structures of mathematical models have been developed. The first one, more commonly known in the building industry is the Standard Whole-life Costing technique. The second, and the more recent whole-life costing technique, termed the New-Generation Whole-life Costing technique, is attributed to Ellingham and Fawcett (2006). Table 3:1 reports on the essential attributes of these two mathematical whole-life cost models.

Table 3:1 Comparative Difference in Existing Whole-life Costing Techniques

	Property	**Standard Whole-life Costing**	**New-Generation Whole-life Costing**
1.	Mathematical Form	Closed-form Expression	Binomial Expansion
2.	Uncertainty Assumption of Cash flows	None	Bivariate
3.	Risk Analysis Methodology	Not Applicable	Probabilistic
4.	Effect of Inflation and Discounting	Inflation and discounting are jointly computed	Inflation and discounting are separately computed
5.	Evaluation mechanism	Discrete summation only	Discrete Summation and Decision-analysis and/or Dynamic Programming
6.	Time-Value of Cash flows	Exponentially Declining	Linearly declining or ascending

The application of the Standard Whole-life Costing technique emerged from procurement studies of military equipment in the United States, in the 1960's (Kishk *et al.,* 2003). Then, the general term, Life Cycle Costing, was adopted to describe the Standard Whole-life Costing technique. The principles of the Standard Whole-life Costing technique and New-Generation Whole-life costing technique are discussed, in more details, in the subsequent sections.

3.3.1 Standard Whole-Life Costing (WLC) Technique

Industry awareness on the principles of the Standard Whole-life Costing technique in the UK, dates back to the 1950's, when the Building Research Establishment (BRE) sponsored a research on the "costs-in-use" of buildings (Kishk *et al.,* 2003). Afterwards, professional bodies such as the Royal Institute of Chartered Surveyors (RICS) started taking more interest in the principles of Standard whole-life costing (WLC), as demonstrated in the work, published by Flanagan and Norman (1983), through a funded research, by the RICS Education Trust. Since then, there has been a progression of studies on the subject of Whole-life Costing. Kishk (2005) conjectured that there are many variants of the WLC, but they are all based on the same closed-form mathematical expressions.

Generally, the WLC technique, employs the present-value metric hinged on the discounting technique, to evaluate the whole-life cost of built facilities. Mathematically, the Standard whole-life cost formulae can be represented as:

$$WLC = \sum_{t=0}^{T} \frac{C_t^i}{(1 + D_R)^{\,t}} \qquad Eqn. 3.1.1$$

Where $\mathrm{C}_{\mathrm{t}}^{i}$ = Equivalent cash flow, $D_R = \text{real discount rate}$ and $\mathrm{t}, \mathrm{T} = \text{time (in years)}$

Conceptually, the WLC mechanism sums up the present-value figure, based on the respective time of occurrence (usually years), of an estimated cost. Kishk (2005) hinted that the WLC technique is more generally termed the "Net Present-Value" in whole-life costing scenarios. By way of definition, Whole-life costing should consist of cost elements, and exclude revenues. In many studies on costing, these distinction is not explicitly recognised. Essentially, the Net-Present Value (NPV) aims to aggregate the revenue and cost streams of a project, while whole-life costing focuses on the evaluation of the cost elements of a project, broadly categorised into distinct strands of initial costs and future costs (Ashworth & Perera, 2013).

The Present-Value for the total costs in respective years, is obtained based on the discounting technique, which involves the use of a discount-rate to exponentially scale-down the numerical value of the projected cost, relative to its expected time of occurrence. In essence, the farther into the future, a projected cost is, the lesser its value relative to the present time (Verbruggen, 2013).

An illustration on the WLC technique, is shown below. Assuming a building has an initial cost of £750,000, and the future costs obtained in each successive year is estimated at £150,000. Year 0, is taking as the year in which the building Construction cost or Installation cost occurs, while the Future costs occurs from Year 1 to Year 10. Assuming the expected inflation rate is 2.5% per year, and the real discount rate is 6% per year, as illustrated by Ellingham and Fawcett (2006), the whole-life cost over a 10-year period will be computed as follows, and shown in Table 3:2:

Table 3:2   Procedures to computing the Standard Whole-life Cost of a building

Year	***Cashflow***	***Real cashflow discounted by 6% per year***
0	£750,000	£750,000
1	£150,000	£141,509
2	£150,000	£133,499
3	£150,000	£125,943
4	£150,000	£118,814
5	£150,000	£112,089
6	£150,000	£105,744
7	£150,000	£99,759
8	£150,000	£94,112
9	£150,000	£88,785
10	£150,000	£83,759
WLC Estimate		**£1,854,013**

Another approach to computing the WLC, if the nominal cashflow values were available, is to multiply the rates of the discount rate (which is 6%) and the inflation rate (which is 2.5%). The nominal discount rate will then yield 8.65% (1.06 x 1.025 = 1.0865). The Standard Whole-life Costing approach is quite straight-forward and simple to follow through. The major challenge in this approach however, is that while Initial costs are relatively clear and predictable at the design stage, the Future costs are rather volatile and uncertain (Pellegrini-Masini *et al.,* 2010, CIFPA, 2011).

To overcome some of the shortcomings in the WLC technique, some authors have modified the mathematical form of the Standard Whole-life Cost formula. Bromilow and Pawsey (1987), are one of such, and proposed a Whole-life Cost framework, based on studies in University Buildings. This model is expressed as:

$$WLC = C_{0i} + \sum_{i=1}^{n}\sum_{t=1}^{T} C_{it}(1+r_{it})^{-t} + \sum_{j=1}^{m}\sum_{t=1}^{T} C_{jt}(1+r_{jt})^{-t} - d(1+r_d)^{-T} \qquad Eqn\ 3.1.2$$

Where

C_{0i} = the procurement cost at time, t = 0, including development, design and construction costs, holding charges, and other initial cost associated with initial procurement;

C_{it} = the annual cost at time, t ($0 \leq t \leq T$), of function i ($0 \leq i \leq n$), which can be regarded continuous over time such as maintenance, cleaning, energy and security;

C_{jt} = the cost at time, t of discontinuous support function j ($0 \leq j \leq m$), such as repainting, or replacement of components at specific times.

r_{it} & r_{jt} = discount rate applicable to support functions, i and j respectively.

d = the value of the asset on disposal, less costs of disposal; and

r_d = the discount rate applicable to asset disposal value.

The main feature of Bromilow and Pawsey's (1987) model, is the consideration of maintenance activities, as non-annual recurring costs, and those that remain continuous (Kishk, 2005).

Al-Hajj (1996) proposed a generic model for buildings, in order to simplify the whole-life cost modelling procedure. This mathematical model can be expressed as:

$$WLC = C_0 + \frac{1}{cmf}\sum_{i=1}^{n}\sum_{t=1}^{T} C_{(csi)i}(1+r)^{-t} - d(1+ r_d)^{-T} \qquad Eqn\ 3.1.3$$

Where

C_0 = Initial construction cost of the building

cmf = cost model factor (constant for various building categories).

$C_{(csi)i}$= cost significant items: decoration, roof, repair, cleaning, energy, management cost, rates, insurance, porterage

r = discount rate applicable to the running costs

r_d = discount rate applicable to the building disposal value

Kishk and Al-Hajj (2000) also developed and proposed, a whole-life cost model, which primarily caters for flexibility in the assignment of uncertainty levels, to various annual costs. The proposed model is expressed as:

$$WLC = C_{0i} + \sum_{m=1}^{nnr_i} F_{im}PWO_{im} + PWA\sum_{j=1}^{nar_i} A_{ij} + \sum_{k=1}^{nnr_i} C_{ik}PWN_{ik} - PWS.SV_i \qquad Eqn\ 3.1.4$$

Where

$$PWN_{ik} = \frac{1-(1+r)^{-n_{ik}f_{ik}}}{(1+r)^{f_{ik}}-1}$$

$$n_{ik} = \begin{cases} int\left(\dfrac{T}{f_{ik}}\right), & provided\ that\ rem\left\{\dfrac{T}{f_{ik}}\right\} \neq 0 \\ \dfrac{T}{f_{ik}} - 1, & elsewhere \end{cases}$$

Where

PWA = Present Worth of Annual recurring (Maintenance and Operating) Costs

PWN_{ik} = discount factors for non-annual recurring costs

PWO_{im} = discount factors for one-off non-recurring costs

PWS = Present worth of salvage value

F_{im} = Fuel cost

C_{ik} = Maintenance and Operating costs

A_{ij} = Annual recurring costs.

SV_i = Salvage value

The improvements in the proposed models, have bothered mostly, on peripheral issues, and have largely failed to touch on, the more critical issues of uncertainties, and the rather limited scope of the Standard whole-life costing technique. In more general terms, these proposed models still fail to robustly consider uncertainties in the cashflow prediction of Future costs, and also fail to evaluate the likelihood of occurrence of Future cost events. It is therefore implicit that these improved models are largely deterministic. Also, the more fundamental issues, relating to embedding opportunities for decisions-made in the future, are totally ignored. Some attention is given to modifying discount rates for different cost elements. However, this only addresses uncertainty in the time-value of money. It is not recognised, that uncertainty in whole-life cost scenarios are not solely time-related. Even with regards to the discounting philosophy, the scientific underpinnings remain insufficiently justified (Adler, 2006). Kishk (2005) conjectured that, all these improved WLC models are based on the same closed-form expression. Park and Sharp-Bette (1990) earlier inferred, that such closed-form expressions typically converge to similar values. Hence, there is a pertinent need to seek for more strategic ways, to improve on the whole-life cost modelling of buildings.

3.3.2 New-Generation Whole-life Costing (NWLC) Technique

The New-Generation Whole-life Costing (NWLC) technique introduced by Ellingham and Fawcett (2006), is an experimental departure from the Standard Whole-life Costing (WLC) technique. One crucial motivation behind this NWLC technique, is the incongruence in the outcome of Standard Whole-life Cost analysis, and the gut-feeling of decision-makers (Ellingham & Fawcett, 2006). Ellingham and Fawcett (2006) argued that, relaxing rigid assumptions of the WLC technique – that all decisions are made in year 0, and are irrevocable, increases whole-life cost value.

Verbruggen *et al.,* (2011), implied that, this brand of costing is an application of the "wait and learn" scenario of the Real Options (RO) literature. Yao and Jaafari (2003) buttressed, that the RO theory can support decision scenarios of "invest and grow", as well as "disinvest and shrink". Figure 3-2 describes a more elaborate decision scenario based on the real options theory, in the context of whole-life costing.

As seen in Figure 3-2, Simple options, tend to have little or no initial cost. Also, the future costs are not dramatically altered from the base case. Simple options include Options to Abandon, Contract, Expand, and 'Do-Nothing'. Compound options, on the other hand, involves more significant initial cost to alter the configuration of the building, and often have a more significant effect on the future cost projections afterwards.

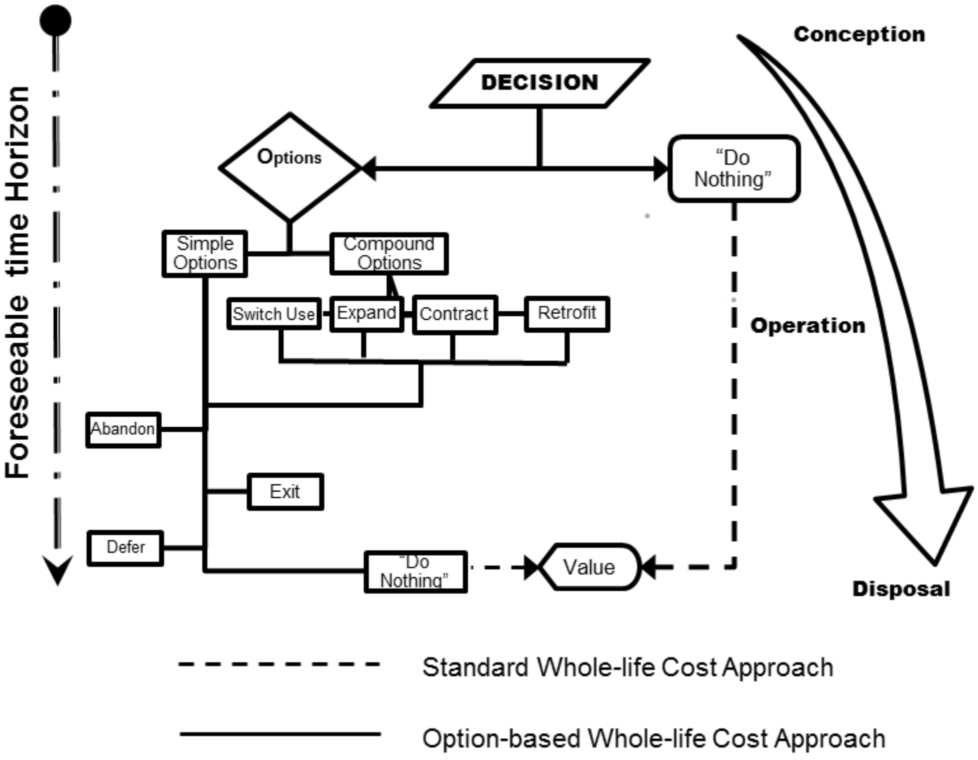


Figure 3-2 Mapping Whole-life Cost Real Options in Buildings

Retrofit options can be classified as Compound options, and are beginning receive increased attention in the published literature (Mansfield, 2009). Retrofit work tend to have significant effect on building performance, and long-term future cost savings (Menassa, 2014). Retrofit initiatives also constitute an overarching political imperative, as a result of growing interest in “future-proofing” buildings, with regards to energy needs, and mitigating Climate change. This study will focus on applying the principle of fuzzy logic in the whole-life cost modelling of office retrofit buildings.

The conceptual difference between the NWLC technique and the WLC technique, lies in the explicit inclusion of uncertainty in the model framework. The NWLC utilizes the Pascal or Negative Binomial probability distribution in evaluating the likelihood of occurrence of Future cost events. Hence, assumption regarding uncertainties in cash flow values, is represented in binomial form, – implying a proportionate increase or decrease in respective cashflows, over the expected life of a built facility. The probability values for the occurrence of cashflows, can be obtained by a normalized probability figure, based on the binomial theorem.

Unlike the WLC technique, the NWLC model is not solely used as a static investment appraisal framework, but can also be adapted into a dynamic decision-making template (Ellingham & Fawcett, 2006). In such cases, System-Dynamics and Decision-Analysis can be augmented with the Real-Options (RO) framework (Chang, 2012), and can be used in enhancing the New-Generation Whole-life costing model.

Repeating the earlier illustration on WLC from Page 64. Using the NWLC technique, for a building that has an Initial cost of £750,000, and for which the Future costs for respective years is estimated at £150,000 each. Assuming the expected inflation rate is 2.5% per year, and the real discount rate is 6% per year. The procedures of the New-Generation Whole-life costing technique are shown below, and will be followed:

In Figure 3-3, the binomial tree starts with the current Future cost of £150,000. In each of the successive years, it is believed that costs could rise or fall by 2.5%. In year 1, the higher costs and lower costs are given by:

$$higher\ cost \qquad V_1^U = V_0\ x\ U \qquad (Eqn. 3.1.5)$$

$$lower\ cost: \qquad V_1^d = V_0\ x\ d \qquad (Eqn. 3.1.6)$$

Where U is the upward ratio, in this case (1 + 2.5%) = (1 + 0.025) = 1.025, and d is the downward ratio, here 1/ (1 + 0.025) = 0.976.

In this illustration, the Standard Whole-life cost estimate, over the 10-year period is £1,854,014, while the New-Generation Whole-life cost estimate is £1,855,704. A marginal difference of £1,690! This proximity in the Whole-life cost values reflects that the underlying principles of the WLC and NWLC are quite similar, which is unsurprising. It is considered useful to compare the whole-life cost values from respective techniques, since the primary essence of whole-life costing is to compare competing alternatives.

In certain situation, for example, the illustration provided by Ellingham and Fawcett (2006), where the initial cost is £64,000 and the income is £9,600 and the inflation rate is 10%. Over a period of 10 years, the NPV using the standard discounting approach is £417, while the NPV using the binomial expansion probabilistic approach yields £1,861. This numerical difference perhaps seems more obvious in this instance. However, It should be expected that, based on similar assumptions, the NWLC estimate tend to have slightly higher values, than the WLC estimate, which reinforces the notion of the real-options (RO) approach, that uncertainty creates value.

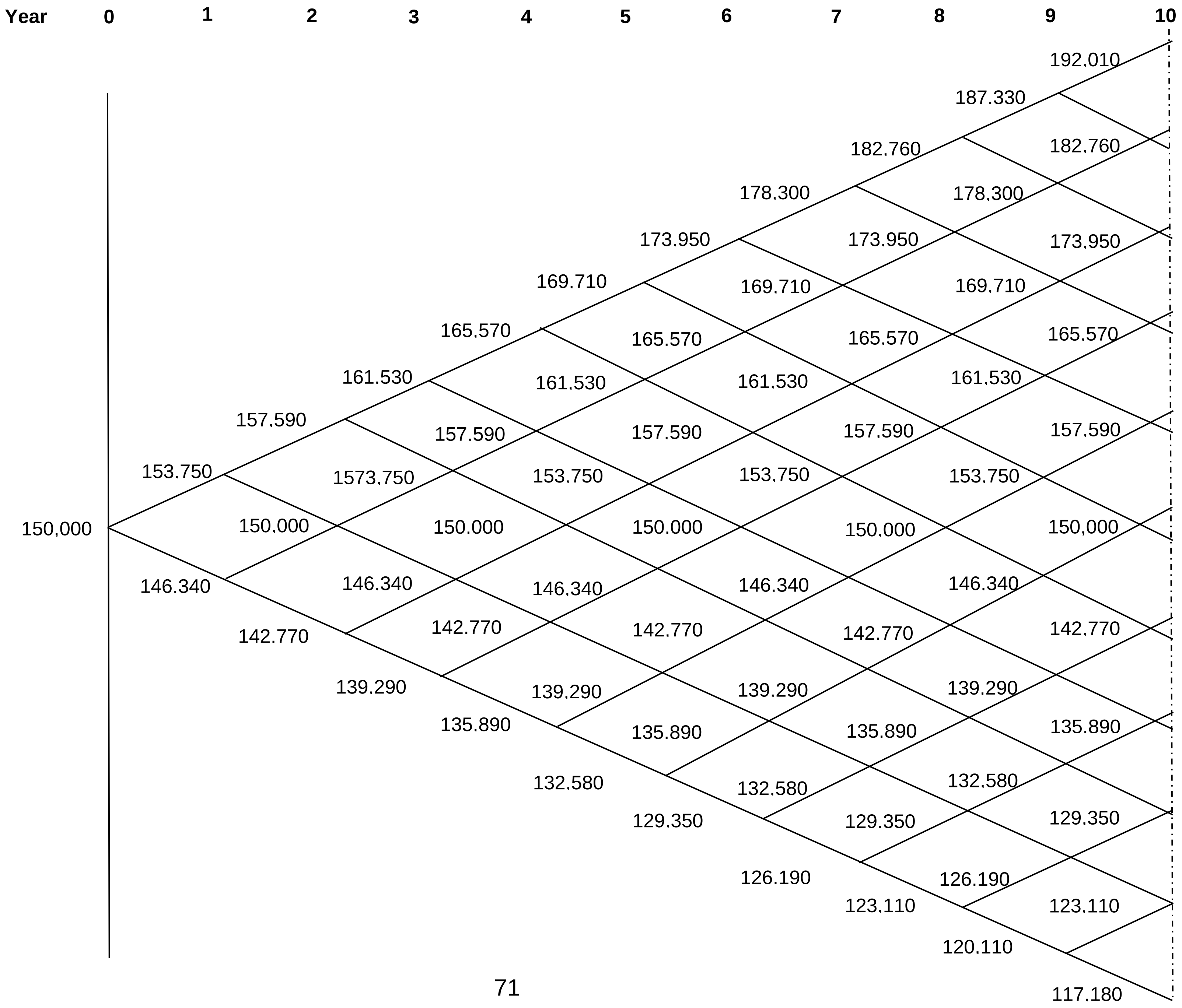


Figure 3-3   Cashflows projections in the New-Generation Whole-life Cost model (Values rounded to nearest Tens)

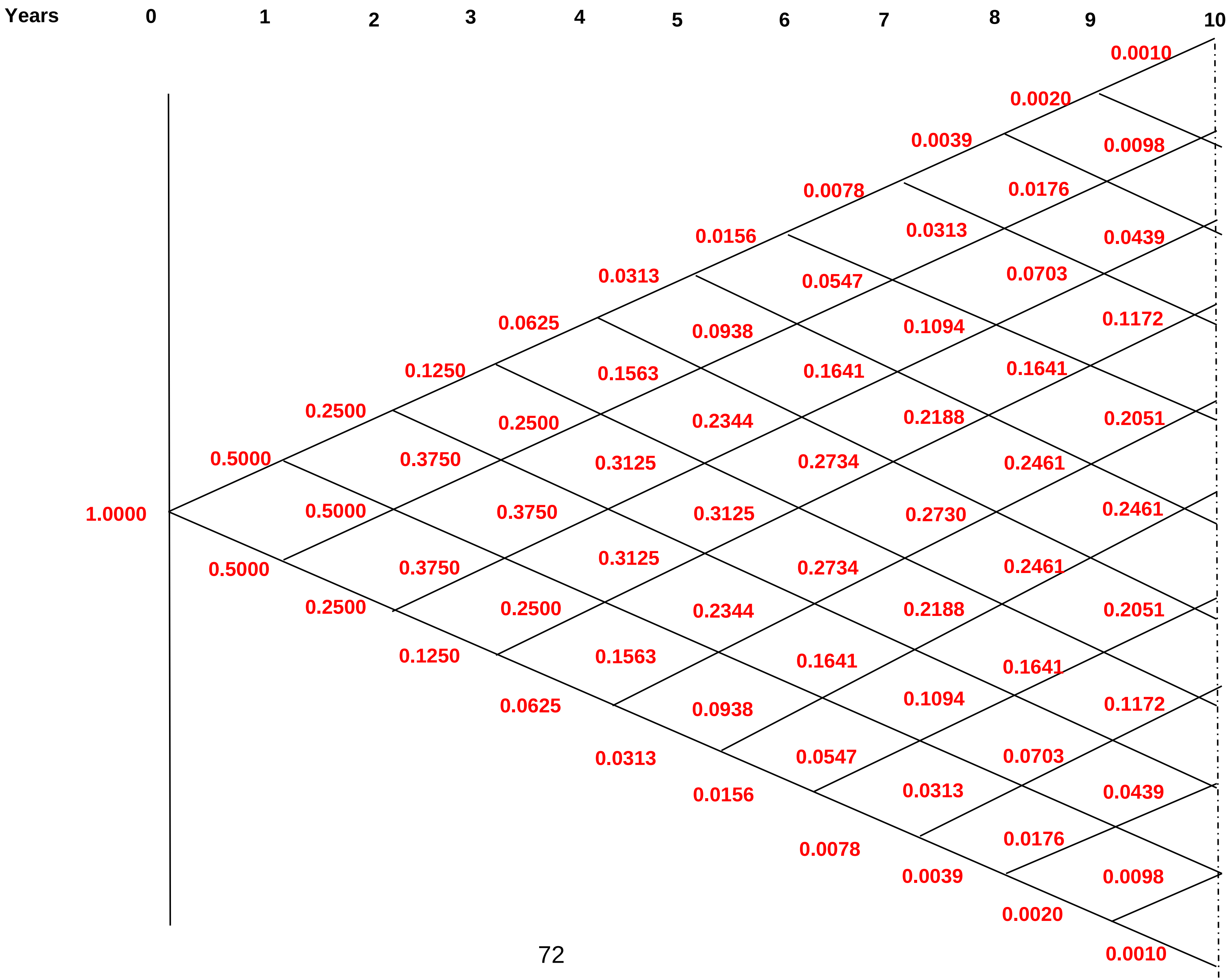


Figure 3-4   Probability coefficients (rounded to 4.d.p.) based on the Negative binomial distribution over a 10-year period

3.4 Critical Discussion on Whole-life Costing in Buildings

The subject of whole-life costing relates to the systematic evaluation of the cost of a facility, over its expected life. The Chartered Institute of Public Finance and Accountancy (CIFPA, 2011), defines whole-life costing as the systematic consideration of relevant costs, associated with acquisition and ownership, of a project, over its expected life. The primary essence of whole-life costing, is the comparison of competing project alternatives (Kishk, 2005).These choices could however, involve comparison of projects of different lives, or different balances between initial costs and running costs (Goh & Sun, 2015).

Despite the broad range of literature on whole-life costing across various disciplines, it remains to be proven whether existing models actually reflect the costing realities in built facilities (Ferry *et al.,* 1999, Clift & Bourke, 1999, Kirkpatrick, 2000, Kishk, 2005, Ellingham & Fawcett, 2006, Fawcett, 2011, Malik, 2012). A major concern on the performance of existing whole-life cost models relates to the difficulty in predicting future cost projections. Ferry *et al.,* (1999) reckons that the estimation of the 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. Goh and Sun (2015) buttressed that researchers tend to assume a higher running cost as a percentage of whole-life cost estimates for commercial office buildings, as a result of higher content of air-conditioning, mechanical and operating installations. It is therefore commonly acknowledged, that energy costs significantly impacts on the whole-life cost of commercial office buildings (Christersson *et al.,* 2015).

There have been suggestions regarding the incongruence in the practice and theory of whole-life costing (Ellingham & Fawcett, 2006, Fawcett, 2011, Caplehorn, 2012). Some authors have advised, that the logical approach to addressing this incongruence will involve the accumulation of data over a building's life, and comparing them to the predicted costs, from existing whole-life cost models. This approach will however, require enormous time and efforts, and could have procedural deficiencies. Equally, this approach is anticipated to undermine the role of psychological intuitions in the economic appraisal of building investments. Moreover, in the UK, Commercial offices are only legally obliged to keep cost data, over a period of three years, after which they can be discarded. Hence availability and reliability of cost data is questionable (Tietz, 1987, Kishk & Al-Hajj, 2000, Bordass, 2000). Even in instances, where such data have been meticulously kept, such exercise tends to be grossly intrusive, and give rise to privacy concerns (Callaghan *et al.,* 2009). It can be anticipated that the use of building information modelling (BIM) tools in construction projects, will better assist the retention, and recording of cost data (Kirkham, 2014). However, the potential benefits accruable are still speculative, and evidence on this remains inconclusive (Goh & Sun, 2015).

Another problem in whole-life costing, is the lack of consistency in the input parameters (Clift & Bourke, 1999, Cole & Sterner, 2000, El-Haram *et al.*, 2002, Goh & Sun, 2015). This implies that input parameters, introduced in the model framework, could be inadequate, or highly subjective, which leads onto differing estimates. A number of researchers in the building industry, have suggested that data used in many whole-life costing procedures, are suspect, due to the difficulty in verifying such cost information. This situation is exacerbated by the lack of appropriate, relevant, and historical cost data (Tietz, 1987, Ashworth, 1996, Kishk & Al-Hajj, 2000, Nicolini *et al.,* 2000, Bordass, 2000, Assaf *et al.,* 2002, Kishk *et al.,* 2004, Kirkham, 2005, Ellingham & Fawcett, 2006, Goh *et al.,* 2010, Pellegrini-Masini *et al.,* 2010). Although the situation is expected to improve, should there be an adoption of BIM on an industry-wide scale. The uptake of BIM by the industry is rather slow, and its benefits in whole-life costing, seems contingent on its widespread adoption.

Another concern with the data used in whole-life costing, lies in having its sole focus on fiscal or quantitative measures (Kishk, 2005, Caplehorn, 2012), and as such information regarding whole-life cost implication, is not fully harnessed. Healy (2015) advised that while quantitative information is valuable in making a case for a course of action, it does not constitute the whole story. Furthermore, reliance on quantitative information alone is inadequate in explaining situations involving risk, uncertainty, intangibles, and hard-to-measure attributes, which may lead onto sub-optimal evaluation (Verbruggen *et al.,* 2011). Thus, focusing only on tangible costs while disregarding other less quantitative measures, and intangible costs, will only provide a partial view of the decision-to-invest in buildings.

The representation of uncertainties in whole-life costing scenarios, tend to increase the complexity of the system. However, proper inclusion of uncertainty generally aids the robustness and integrity of whole-life cost forecasts. A number of publications on whole-life costing, (predominantly earlier works) have argued that whole-life cost evaluations ignore uncertainties in cost variables (Zhi, 1993, Byrne, 1997, Bordass, 2000, Coates & Kuhl, 2003, Skinne *et al.,* 2011). In more recent times, the problems with whole-life cost models have been with the insufficiency in the representation of uncertainties (Ferry *et al.,* 1999, Kishk & Al-Hajj, 1999, Kishk *et al.*, 2004, Gluch and Baumann, 2004, Kishk, 2005, Tan *et al.,* 2010).

A common approach used in modelling for uncertainties, in whole-life cost scenarios is by deterministically adjusting discount rates, to cater for risks associated with the time-value of money. Using an adjusted discount rate approach, for quantifying uncertainties may be grossly reductionist, as it only focuses on uncertainties regarding the time value of money (Gluch & Baumann, 2004). It is important to note that, the discount rate is also a subjective and arbitrary value, that is likely to change over a period of time (Greden, 2005, Jackson, 2010, Tan *et al.*, 2010, Goh & Sun, 2015, Christersson *et al.,* 2015, Ma *et al.,* 2012). Secondly the discounting mechanism generally hold bias towards Initial Capital cost (Nicolini *et al.,* 2000, Malik, 2012, Korpi & Ala-Risku, 2008). Lastly, the discounting process assumes a single trail of reality (Gasparatos, 2010), without allowing for decisions that may be taken at some point in the future (Christersson *et al.,* 2015, Ma *et al.,* 2012). An alternative approach to the use of risk-adjusted discount rate for handling uncertainty, is the use of Probability and Fuzzy Set Theory, to explicitly represent uncertainties in relevant cost variables. The merits and demerits of respective uncertainty modelling techniques, are further discussed in Section 3.5.

Existing whole-life costing models are fraught with a number of conceptual limitations. Perhaps the most obvious problem of whole-life costing, is that it is based on a number of assumptions, which are sometimes unrealistic and ill-informed (Cole & Sterner, 2000, Caplehorn, 2012). Some of the assumptions in whole-life cost modelling are that - same party bears both the Initial and Future costs (Bordass, 2000, Ferry *et al.,* 1999, Gluch & Baumann, 2004). While this may be true in owner-occupied facilities, this is often not the case with rented and leased building facilities. Dixon *et al.,* (2008) argues that non-owner occupancy status seems the more prevalent use of Office buildings in the UK

Pogue (2004) inferred that the WLC mechanism often uses discrete cashflows, hence the frequency of occurrence of cashflows in respective time intervals, has no effect on the model outcome. Ferry *et al.*,(1999) expressed doubts on the methodology of the WLC technique for its incapacity to deal with obsolescence. The WLC approach also implicitly reinforces the worldview of irreversibility of decisions made, at the sanctioning stage of the project (Reyck *et al.,* 2008, Christersson *et al.,* 2015).

An equally fundamental issue, with the WLC technique, is its assumption that future costs, over the life of a building, can be pre-determined during the initial design phase (Kirkpatrick, 2000, Kishk & Al-Hajj, 2000, Tan *et al.,* 2010, Vennström *et al.,* 2010) and fails to leave room for flexibility. The WLC technique also presumes that future costs can be predicted with certainty (Fawcett, 2011, Caplehorn, 2012). The New-Generation Whole-life Costing (NWLC) technique addresses some of the limitations in the Standard Whole-life Costing (WLC) technique, but has not been embraced in the Industry. One possible explanation for this might be the high level of comparability of results, from the NWLC and WLC techniques in building investments. It might also be reinforced by the conservative attitude, prevalent in the industry.

In the whole-life cost estimation of buildings, another challenge in the methodological framework is the inability of existing whole-life costing techniques, to establish the relationship between design decisions, over the buildings' life, and the information available to cost experts (Kishk, 2005, Kirkham, 2005), thus providing a poor depiction of reality (Ellingham & Fawcett, 2006). Another related concern is the static nature of the input-output modelling framework (Koskela *et al.,* 2008, Georgiadou *et al.,* 2012, Tan *et al.,* 2010). Georgiadou *et al.,* (2012) described such static cost framework, as "steady-state', and reckoned that they have little bearing on reality. Kodukula and Papudesu (2006) hinted that the Standard Whole-life costing framework only focuses on the downside of risk, and ignores opportunities that accrues over the life of a built asset. Although, Kishk *et al.,* (2003), argue that the principles of whole-life costing are well developed, there is compelling evidence that this is not the case, and there is a scope for improving on the theoretical weaknesses of existing whole-life cost modelling procedures.

Perhaps, given the concerns as documented in the literature on whole-life costing, it is rather unsurprising that there has been a prevalent lack of confidence and interest in long-term cost estimation (Tietz, 1987, Nicolini *et al.*, 2000, Boussabaine & Kirkham, 2008, Caplehorn, 2012). This lack of confidence in the principles of whole-life costing has fuelled a recourse to gut-feeling and experience, rather than rely on the results from objective whole-life costing analysis (Ellingham & Fawcett, 2006, Adler, 2006).

It is also worthy of note that some building researchers have mentioned the possibility for existing whole-life costing techniques, to foster incorrect decisions (Gluch & Baumann, 2004). Ellingham and Fawcett (2006) adds that the Standard Whole-life costing technique often classifies whole-life cost scenarios as a clear-cut "choose" and "lose" situation, and fails to highlight the "wait and learn" potentials, described in the real-options literature (Verbruggen *et al.,* 2011, Fawcett, 2011). There are therefore plausible suggestions, that existing whole-life costing techniques ignore future opportunities to enhance the value of building projects, through strategic attention to emerging additional information (Menassa, 2011).

Given the concerns on whole-life costing, there are claims of an industry-wide reluctance regarding the application of whole-life costing in building investment appraisals. Clift and Bourke (1999) reported that only about 25% of organisations conduct whole-life costing prior to sanctioning investments in buildings. Goh and Sun (2015) later concluded that there is a need for new concepts and methods of whole-life costing that will align the intentions of stakeholders and clients.

3.5 Uncertainty modelling in Whole-life costing of Office buildings

Smit (2012) defines uncertainty as the variance associated with data and assumptions in a cost model. Boussabaine and Kirkham (2008) have however, cautioned that the treatment of every uncertainty as variance, will be a fatal presumption. Molenaar (2005) inferred that uncertainties could exist as either "known-unknowns" or "unknown-unknowns". In which case, variances regarding known-unknowns could be quantifiable, while variances regarding unknown-unknowns tend to be inaccessible and consequently, unaccounted for. It equally follows that uncertainties in whole-life cost scenarios, could be ignored to minimize the complexity of the costing framework. However, this could negatively impact on the credibility of the whole-life cost system. Goh and Sun (2015) proffered that the application of whole-life costing techniques therefore, necessitates the use of uncertainty modelling tools.

There are different techniques for modelling uncertainties in whole-life cost scenarios. One approach used to model uncertainties in the time-value of money, is the use of the risk-adjusted discount rate (Spackman, 2011). The use of the risk-adjusted discount rate is a numerical contingency allowance, used to account for the variance in the time-value of future cost events. It is essentially a deterministic procedure, and focuses on the role of time-preference, and time-value in whole-life cost calculations. Other more advanced uncertainty techniques, which evaluate uncertainties explicitly, are the probability theory and the fuzzy set theory. The underlying approaches to uncertainty modelling in whole-life costing scenarios are further discussed.

3.5.1 Deterministic Techniques

Deterministic techniques are simplified physical models, in which all data are assumed to be known with certainty (Jackson, 2010). Deterministic techniques do not explicitly provide for uncertainties, and in situations where uncertainties need to be provided for, are lumped into a single, contingency, point estimate. In such instances, numerical averages usually derived through observation, expert assessment, and heuristics, are used as proxies to compensate for the expected variance. The benefit of the deterministic approach is its relative straight-forwardness, and ease to use (Uusitalo *et al.,* 2015).

The use of the risk-adjusted discount rate in whole-life costing scenarios, is one deterministic approach, that lumps the potential impacts of risk sources together in order to reflect the rate of return invested capital would otherwise yield, in comparable investments (Chang, 2012). The risk-adjusted discount rate implies the modification of the discount rate value, to embody risk premium of an investment, along with the time-value of money. The use of a discount rate in this manner, presumes that risk borne per period, is constant and uncertainty is resolved at a constant rate over time (Yao & Jaafari, 2003). Ghahremani *et al.,* (2012) opines that the use of discount rate in this manner is suspect and subjective. The major attractiveness of this approach is the convenience achieved in embodying the complex issues of uncertainty in whole-life costing into a single process. Hence, many whole-life cost calculations still adopt this mechanism in uncertainty evaluation.

3.5.2 Probabilistic Techniques

Probability is a branch of mathematics which addresses questions relating to “chance” and “odds”(Ayyub & McCuen, 2011). In the probabilistic approach, all uncertainties are assumed to comply with the behaviour of a random process (Kishk *et al.,* 2003). This implies that all uncertainties are a product of stochastic variability, and can be modelled by means of a discrete or continuous Probability Distribution Function (PDF). Common discrete probability distributions for random variables include: Bernoulli, Binomial, Geometric and Poisson (Ayyub & McCuen, 2011). From these basic four distributions, are others like Negative-Binomial, Pascal, and Hyper-geometric. Also, common types of Continuous Probability distributions include Uniform, Triangular, Gamma, Rayleigh, Beta, Normal, Lognormal and Exponential. In an empirical work on probability distributions, 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. Probabilistic risk techniques include Expected-Value analysis, Mean-Variance criterion, Coefficient Of Variation, Certainty-Equivalent technique, Monte-Carlo simulation and Decision-Analysis (Ma *et al.,* 2012).

Monte Carlo simulation is perhaps the archetype of simulation efficiency, as far as probabilistic techniques are concerned. Monte Carlo simulation allows the evaluation of multiple uncertain variables (Keršytė, 2012), in a manner that produces the fairest summary. The efficiency of the Monte Carlo simulation has enhanced its popularity in uncertainty modelling for different industrial applications, as well as in whole-life cost evaluations. There are a few conceptual shortcomings regarding the use of Monte Carlo Simulation for uncertainty modelling. Hollmann (2007), stated three of these, namely – dependencies between model variables are not properly considered; relationship between risk-drivers and cost outcomes are not explicit; and lastly relationship between market risk (which is, diversifiable) and technical risk (which is undiversifiable) is not been recognized. Monte Carlo simulation is also limited in accommodating asymmetries in cashflow distributions introduced by the recognition of real options (Keršytė, 2012).

3.5.3 Fuzzy Logic (FL) Techniques

Over the last three decades, a number of works have proposed alternative mathematical algorithms, to improve on the future cost forecasts of building investments in whole-life cost scenarios. These works include those by Bromilow and Pawsey (1987), Sobanjo (1999), Al-Hajj (1991), Al-Hajj and Horner (1998) and Kishk (2001). Many of these works, have had limited impacts on the practice of whole-life costing. It is therefore understandable, that the industry's perception of whole-life costing, has not changed much (Caplehorn, 2012).

A number of authors have considered using fuzzy logic (FL) in discounted cashflow procedures (Buckley, 1987, Byrne, 1997, Kishk & Al-Hajj, 2000, Kishk, 2001). Specifically, in the whole-life costing of buildings, FL has demonstrated promising potentials, in enhancing the quality of decision-making under subjectivity (Ammar *et al.,* 2013). Wang *et al.*,(2004) utilised FL to represent expert's knowledge, in order to address the problems of lack of historical data on future costs in buildings. Kishk (2004) used FL to represent whole-life cost variables within different numerical ranges. Wang (2011) also proposed a Fuzzy multi-criteria decision-making model for whole-life costing of buildings.

There are a number of works, which demonstrate the application of FL techniques in modelling uncertain variables in whole-life costing. These works include those by Kishk *et al.,* (2003), Kishk *et al.,* (2004), Kishk, (2004), and Kishk, (2005). The prevalent application of FL in these works is the representation of selected whole-life cost variables, using qualitative or imprecise variables. Also, their procedures are cumbersome, and could be difficult to follow, for experts unfamiliar with fuzzy mathematics.

FL was formally introduced by Zadeh (1965) as a calculus, used in formalizing intuitions about composition of graded categories (Kim *et al.,* 2006, Chan *et al.,* 2009). FL is a broad family of concepts and encompass the classical logic paradigm, – where degree of belonging is either complete or null, as well as other paradigms, whose degree of membership is partial and not well defined (Zadeh, 2008). Fuzzy logic embodies a mathematical approach that can be used to build models for different applications (Belohlavek *et al.,* 2009). FL technique intersperses the entire realm of mathematical modelling languages. Zadeh (2008) posits that mathematical modelling techniques include probability theory, differential equations, difference equations and closed-form expressions (functional analysis). All these techniques can be expressed in bivalent logical forms. FL is however, not restricted to bivalence (Zadeh, 2008). It does not have a uniquely defined mathematical form (Zimmermann, 2001), but an entire range of multi-valued logic (Chan *et al.,* 2009).

FL explicitly takes into cognizance, the behavioural peculiarities of human cognition in defining and representing variables. Kahneman (2011) described human cognitive aptitude as being inclined to description, rather than content. Ayyub and McCuen (2011) reckoned that the human mind tend to reduce and generalize, in the course of developing knowledge, and this invariably actuates a vagueness component of uncertainty. Zadeh (1995) previously expressed that FL was developed to model vagueness existent in human cognitive processes.

Arguably, fuzziness is prevalent in all areas in which human judgment, evaluation and decision-making is required (Zimmermann, 2001). Kosko (1990) surmised that fuzziness has both physical and sociological implications. In the physical realm, fuzziness connotes a gradual transition between possible states. Sociologically, fuzziness implies the possibility for an infinite degree of relationships between elements of a set, as opposed to just being “completely related” or “non-related”.

Belohlavek *et al.,* (2009) expressed that FL is a calculus, that can be used in formalizing intuitions, on composition of graded categories. Baloi and Price (2003) advised that, FL is not intended to diminish the principles of traditional mathematics, but to enhance the capacity of dealing with problems that lack mathematical rigour. The mathematical rules guiding the operations of FL, are broadly consistent with Classical logic rules. However, in situations where the elements of a mathematical set are fuzzy numbers, membership functions are the frameworks used to provide a description of the fuzzy set (Kim *et al.,* 2006).

The purpose of a membership function, is to express the degree of belonging of an element in a particular set (Long & Ohsato, 2008). A membership function equally provides an effective way to translate subjective terms, into mathematical measure (Kim *et al.,* 2006). In a broad sense, membership functions are used to represent the degree of similarity of different objectives of a defined parameter (Shaopei, 1998). Membership functions are usually denoted by the Greek letter, μ. One form of membership function is a “fuzzy number” (Dubois & Prade, 1988, Lorterapong & Moselhi, 1996), and this is the dominant form of membership function available in the extant literature

Assuming the elements in the sets, $\widetilde{A}$ and $\widetilde{B}$ have fuzzy numbers, (a, b) and (c, d) respectively, the fuzzy arithmetic for addition, subtraction, multiplication and division are as follows:

$\widetilde{A} + \widetilde{B} = (a, b) + (c, d) = [a + c, b + d]$ *(Eqn 3.1.7)*

$\widetilde{A} - \widetilde{B} = (a, b) - (c, d) = [a - d, b - c]$ *(Eqn 3.1.8)*

$\widetilde{A} \times \widetilde{B} = (a, b) \times (c, d) = [\min (ac, ad, bc, bd), \max (ac, ad, bc, bd)]$ *(Eqn 3.1.9)*

$\widetilde{A} \div \widetilde{B} = (a, b) \div (c, d) = [\min (a/c, a/d, b/c, b/d), \max (a/c, a/d, b/c, b/d)]$ *(Eqn. 3.2.0)*

Fuzzy relations are special cases of FL defined sets. Fuzzy relations can be defined as, a vague relationship between some fixed numbers of variables (Chan *et al.,* 2009, Zimmermann, 2001). Fuzzy relations are essentially the means of modelling the intensity between elements of a fuzzy set. Fuzzy relations generally emerge from Cartesian representation of two or more sets, on a universal scale (Bělohlávek & Klir, 2011). Relations, in this sense, are normative structures, which help to interpret attributes of fuzzy systems.

According to Ross (2009), a mathematical representation of the fuzzy relation, $\tilde{T}$ of two sets, $\tilde{R}$ and $\tilde{S}$ can be defined by the set-theoretic and membership function-theoretic format, mathematically expressed as:

$$\tilde{T}=\tilde{R}\circ\tilde{S} \qquad \text{(Eqn. 3.2.1)}$$

Where R is a fuzzy relation on the Cartesian space $X \times Y$. S is a fuzzy relation on $Y \times Z$, and T is fuzzy relation on X × Z. In cost estimation, R represents the set of cost predictors, and S refers to the set of standard values of tolerance for descriptors of project attributes.

A composition is a common mathematical operation that seeks to establish the relationships between similar elements, in different universe of discourse (Zimmermann, 2001). The compositionality assumption is a logical generalization which assumes the degree of membership, of a compound fuzzy set is a function of the membership degrees of each component. There have been debates on whether a single non-parametric operator is appropriately suited for modelling the ‘And’ or ‘Or’ context independently. The composition operation is however, one class of similarity relation that seeks to establish relationship between similar elements in different universe of discourse (Zimmermann, 2001). Two common forms of composition operations, are the max–product and max–min compositions. Zimmerman (2001) opines that the max – min composition is the most frequently used, and that these operations have their roots, in the extension principle, developed by Zadeh (2008).

Other possible variants of compositions include the max-max, min-min, max-average and sum-product (Ross, 2009). Essentially, the composition operation involves employing hybrid formulations of min, max, average and product, to arrive at some relationship structure; thereby specifying a range of mathematical values that could be tolerated, by a category (Carpenter *et al.,* 1992). Yager and Filev (1994) mentioned that the ‘max’ operator ignores reinforcement inherent in the overlapping of output fuzzy sets. Carpenter *et al.,* (1992) also explained that the ‘min’ operator helps highlight features that are critically present, whilst the ‘max’ operator flags-off features that are critically absent.

3.5.3.1 Max-min Composition

The max-min composition is commonly used when a system requires a conservative solution. Loetamonphong and Fang (2001, pp6) explained this approach as when the "*goodness of one value, cannot compensate the badness of another value*". Figure 3-5 shows a graphical illustration of the max-min composition. In Figure 3-6, the minimum value of two normal distributions, A_1 and B_1, are combined to produce a distribution C_1. The minimum of A_2 and B_2, are also combined to produce a distribution C_2. The maximum of distributions C_1 and C_2, then produces the distribution C', which is effectively the final aggregated value of the max-min composition. Ross (2009) pointed out that the max-min composition is analogous to approximate reasoning using the IF-THEN rules.

Mathematically, the max-min composition can be represented as:

$$\tilde{\mu}_{T(x,z)} = \vee_{y \in Y}[\,\tilde{\mu}_{R(x,y)} \wedge \tilde{\mu}_{S(y,z)}] \qquad \textit{(Eqn. 3.2.2)}$$

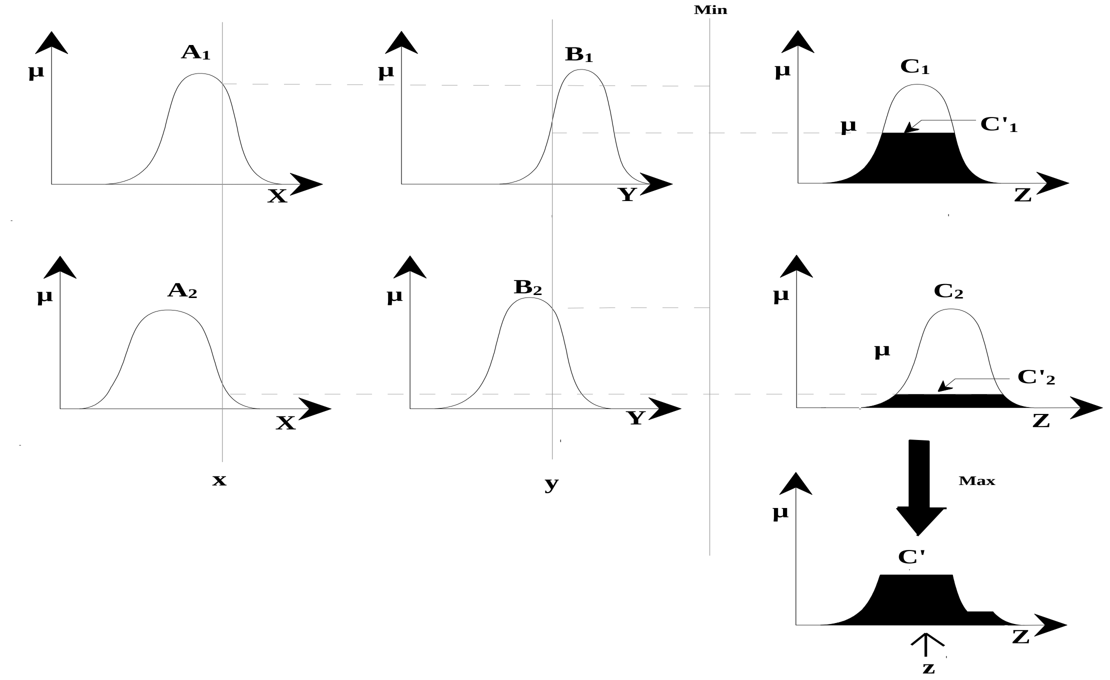


Figure 3-5 Graphical illustration of the max-min composition (Dubois & Prade, 2000)

3.5.3.2 Max-Product Composition

The max-product composition is considered by some researchers, as yielding better equivalent results (Loetamonphong & Fang, 2001, Ross, 2009) in compositional aggregation. One possible explanation for this, is that conventional risk calculus is presumed to have a combinatorial character.

Mathematically, the max-product composition can be represented as:

$$\tilde{\mu}_{T(x,z)} = \vee_{y \in Y}[\, \tilde{\mu}_{R(x,y)} \bullet \, \tilde{\mu}_{S(y,z)}] \qquad \textit{(Eqn. 3.2.3)}$$

The max-product composition is a fuzzy calculus, which expresses the relationship between similar elements. Figure 3-6 shows a graphical illustration of the max-product composition. In Figure 3-6, the product of two normal distributions, A_1 and B_1, are combined to produce a distribution C_1. The product of A_2 and B_2, are also combined to produce a distribution C_2. The maximum of distributions, C_1 and C_2, then produces the distribution C', which is effectively the final aggregated valued of the max-product composition. Ross (2009) illustrated the max-product composition to relate the rain gauge prediction of large storms to the actual pond performance during rain events. In this work, no practical examples on the application of the max- or min- composition are reported on building investment appraisal.

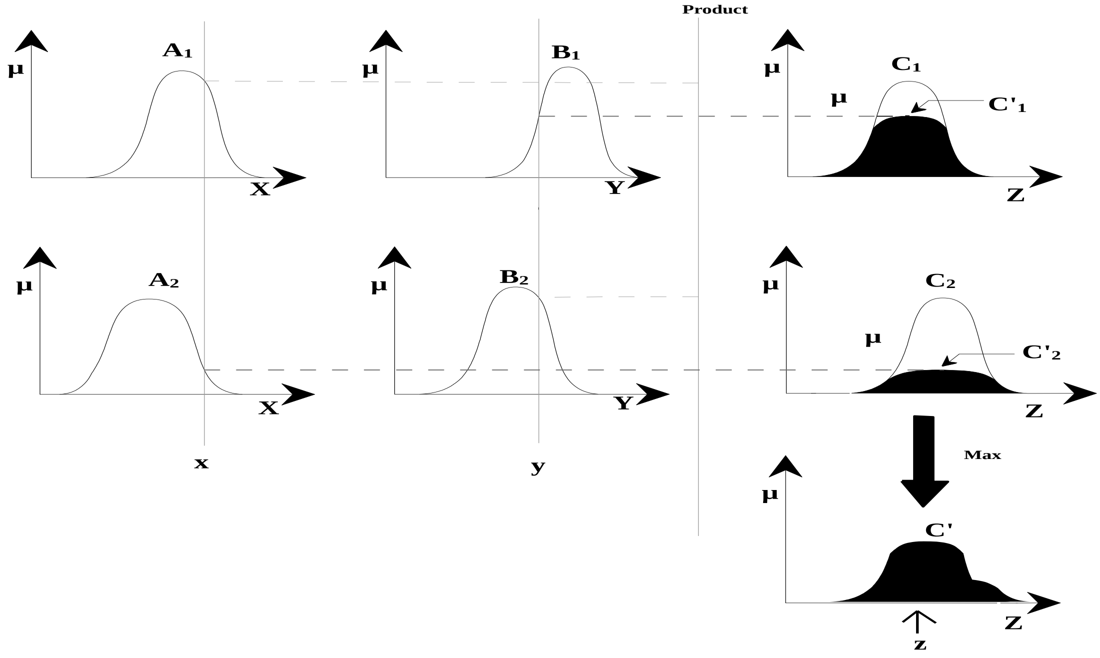


Figure 3-6 Graphical illustration of the max-product composition (Dubois & Prade, 2000)

3.5.3.3 Cosine Amplitude

The max-min composition and max-product composition, produces a comparable and conservative solution. The similarity metric of the cosine-amplitude has potential to provide an improved aggregation for developing a fuzzy relation (Ross, 2009). In general, similarity relations are a family of procedures, that attempt to determine some sort of structure, or similarity of pattern in data. The cosine-amplitude method utilizes the matrix properties of a problem. The method is related to the dot product of the cosine function. The cosine amplitude formulae, is based on the notion that when two vectors are co-linear (most similar), their dot-product is unity; and when the two vectors are at right angles to one another (most dissimilar), their dot product is zero (Ross, 2009).

The cosine amplitude formulae makes use of a collection of data samples, k, and assumes they form a data array, K

$$K = \{k_1, k_2, \ldots, k_n\}$$

Each of the elements, k_i, is itself a vector of length m, i.e. $k_i = \{k_{i1}, k_{i2}, \ldots, k_{im}\}$. Each element of a relation, r_{ij}, results from a pairwise comparison of two data samples, k_i and k_j, the relation matrix will be of size, n x n. The cosine method, described in Eqn.3.2.4, calculates, r_{ij}, in the following manner and guarantees that $0 \le r_{ij} \le 1$:

$$r_{ij} = \left(\frac{\sum_{l=1}^{m} k_{il} k_{jl}}{\sqrt{\left(\sum_{l=1}^{m} {k_{il}}^2\right)\left(\sum_{l=1}^{m} {k_{jl}}^2\right)}} \right) \qquad \text{Eqn.3.2.4}$$

In this work, the cosine amplitude formula is applied to the development of a fuzzy relation matrix, combining the Negative Binomial probability matrix and the binomial future cost cash flows. More on this is discussed in Chapter 5

3.5.3.4 *Fuzzy Logic Model Development Process*

Wang *et al.,* (2004) developed a generic fuzzy logic approach to model the whole-life cost of building elements. Although this model is based on the use of linguistic knowledge for membership function development, it highlights the critical features for a fuzzy whole-life costing modelling system. Figure 3-7 depicts a simple 5-stage generic fuzzy logic model development applicable to the whole-life costing of buildings.

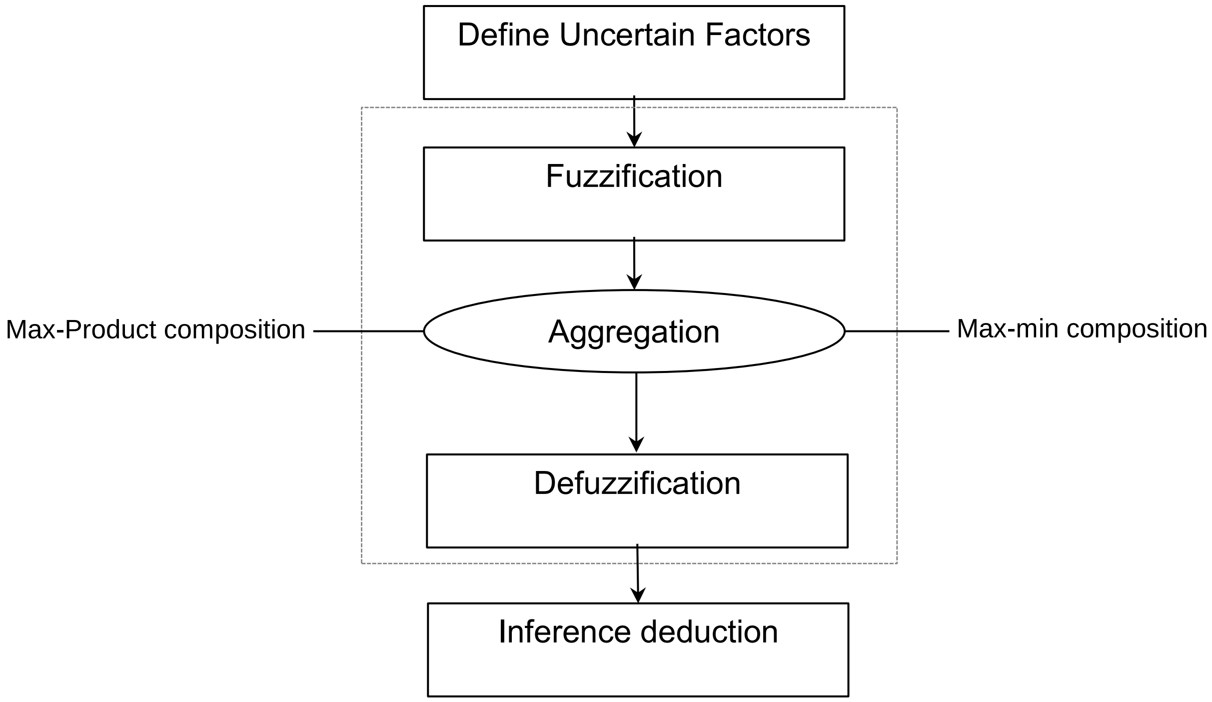


Figure 3-7   Fuzzy Logic Model Development Process

Fuzzy logic model development processes do not require any predictable regularities or posterior frequency, of any historic data (Shih-pin, 2007). As shown in Figure 3-7, the procedure for exploring fuzzy techniques commences with the identification and defining of uncertain factors (Ng.*et al.,* 2001). This is followed by assignment of membership values to each variable (Chan *et al.,* 2009). The next stage thereafter, involves the formulation or development of membership function. The membership function is then represented in a form to produce a fuzzy mapping (Ng. *et al.,* 2001). The fuzzy mapping depicts the range of possibilities of membership values. Consequently, the relationships between fuzzy values are developed to indicate the matrix equivalent of the aggregated fuzzy set (Zimmerman, 2001). Generally speaking, fuzzy relations are a special type of fuzzy sets, which are developed from aggregation of fuzzy variables (Ross, 2004).

The fuzzy relation is interpreted in order to be used for practical application. Often times, this interpretation comes in the form of defuzzification (Ng. *et al.,* 2001). Defuzzification is an operation that produces a non – crisp value that adequately represents the degree of satisfaction of the aggregated fuzzy number (Singh & Tiong, 2005). The defuzzified set allows for deduction of inferences with regard to the magnitude and impact of the uncertain variable. The max-min, and max-product composition operator can be used to defuzzify a fuzzy relation matrix into three-estimates - lower, mean and upper values, which represent the range of distribution of a finite set of fuzzy relational matrix. In this work, the max-min composition is utilised to defuzzify the fuzzy relation matrix, as reported in Section 5.3. The max-min is selected as an appropriate algorithm, due to the ease of following through its procedures, and its capacity to provide a broader range of distribution than the max-product algorithm.

3.5.3.5 Lambda-Cut Sets

Lambda-cut sets ($\lambda - cut$) or alpha-cut sets of a particular fuzzy set are interval-valued membership functions (Ross, 2009), where, $0 \leq \lambda \leq 1$. They are a crisp set derivable from parent fuzzy set. Lambda-cut sets provide a simplified, but adequately representative framework that provides a comparative, but less explicit representation of fuzzy sets. It should be noted that any particular fuzzy set can be transformed into an infinite number of $\lambda - cut$ sets, because there are an infinite number of values on the interval {0, 1}.

In essence, crisp sets, that contain all elements of the parent set whose membership grades in the set, are greater or equal to, the specified value of the lambda, constitutes the lambda-cut of the membership function of the set (Nieto-Morote & Ruz-Vila, 2011).

Dong *et al.,* (1985) proposed a step-wise approach termed the Day-Stout-Warren (DSW) algorithm to implement the lambda-cut procedures for fuzzy sets. The steps can be itemised as:

1. Select a λ value, such that,$0 \leq \lambda \leq 1$.
2. Establish the intervals in the parent fuzzy set corresponding to the selected λ value.
3. Using interval algebraic operations, compute the fuzzy set value of the aggregated operator.
4. Repeat the previous step for other values of λ as required by the problem.

The number of $\lambda - cuts$ depends on the function, to be calculated and the degree of accuracy needed. This work adopts the 11-point $\lambda - cut$, corresponding to the values between 0 and 1 inclusive, in increments of 0.1, as previously adopted by Ammar *et al.,* (2013). The $\lambda - cuts$ approach is utilised in the evaluation of the cost of disruption in retrofit office buildings, and shown in Appendix A-1.

3.6 Critical Issues in the Whole-life Costing of Office Buildings

Whole-life costing scenarios involves a complex set of decision events, actions, outcomes, with significant interdependencies (Verbruggen *et al,* 2011, Verbruggen 2013). Equally, there is a compelling case for the effects of uncertainties to be robustly addressed, and explicitly accounted for. These uncertainties need to be assessed in terms of their likelihood of occurrence, consequences of occurrence, and the significance of the consequences (Ayyub, 2014).

In the whole-life costing of retrofit options in office buildings, there are a number of uncertain decisions and outcomes, which will potentially influence the outturn of cost. The rationale for embodying the whole-life costing technique in the real-options (RO) framework, is primarily to allow for the explicit recognition, and inclusion of these uncertain decision alternatives. It is anticipated that incorporating the real-options approach in whole-life costing will enhance its robustness. Yao & Jaafari (2003) expressed that real options techniques tend to yield the same value, as discounted cash flow techniques, when it is assumed that there are no uncertainties regarding managerial decisions across outcome ranges.

Uncertainties, in the time-value of monetary outcomes, do not however constitute the totality of complex considerations in the whole-life costing of building retrofits. In retrofit options, the impact of uncertainties generally apply within the context of revocability, disruptiveness and time-discounting. Figure 3-8 highlights some of the complex consideration in the whole-life context. There are different ways of representing Uncertainties. Verbruggen (2013) stated that Risk situations embody shallow levels of doubt, Uncertainty situation tend to contain more doubt than Risk, while Ignorance is the highest intensity of doubt.

Time-value of money is generally measured by paying attention to discounting. However, alternative approaches to time discounting may need to be examined. Each of this phenomena are specifically discussed in the subsequent section.

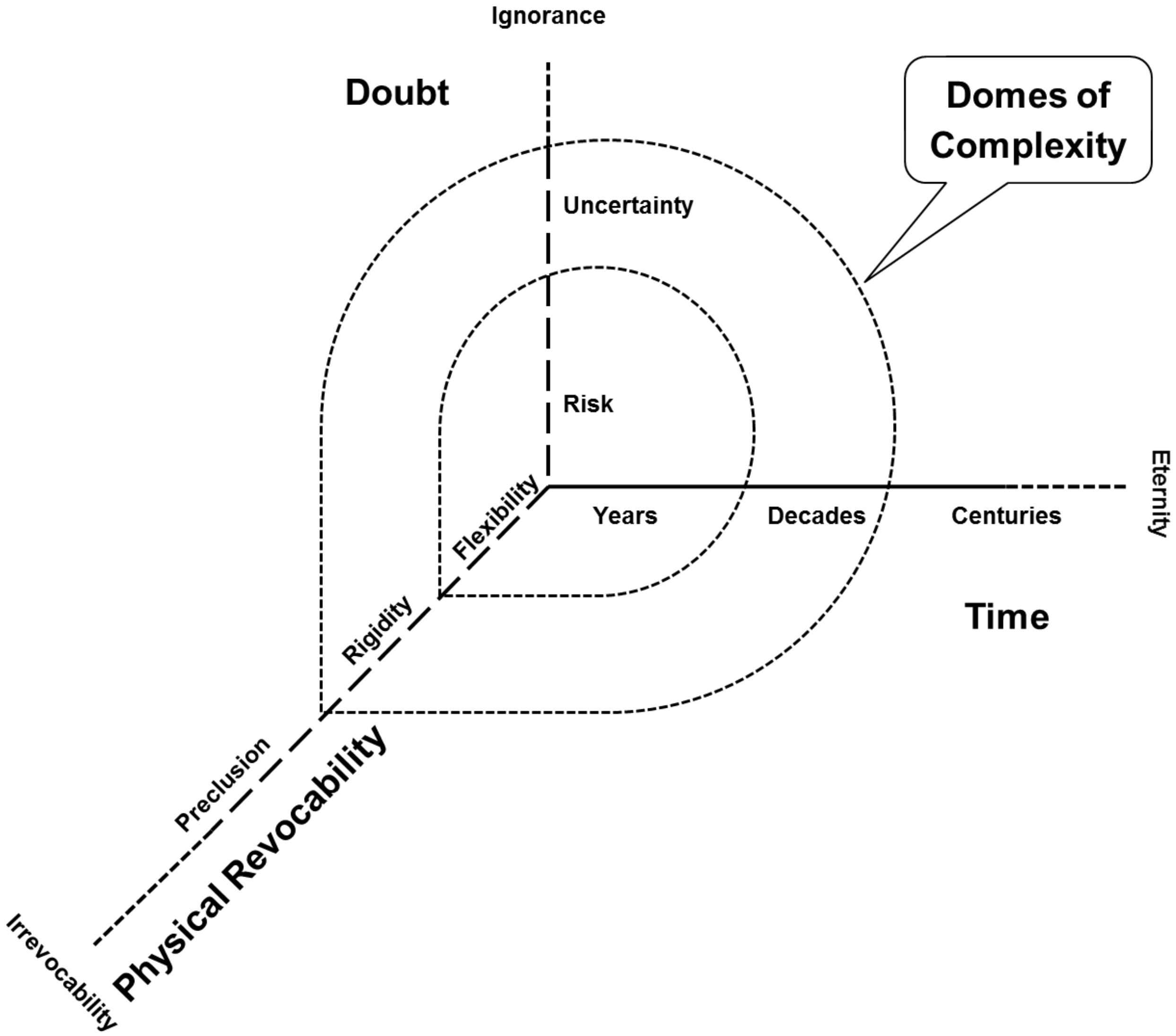


Figure 3-8 Decision Context in a Whole-life Costing Scenario (Verbruggen, 2013)

3.6.1 Revocability

Previous works have presented a case for the existence of a significant degree of economic and physical revocability in building retrofit projects (Verbruggen *et al.,* 2011, CLG, 2011, Verbruggen, 2013,). Many building researchers have also implied the existence of revocability in buildings, although the pioneer proponent of the terminology – Revocability, was Verbruggen *et al.,* (2011). In the context of buildings, lack of revocability (or irrevocability) can be termed a “lock-in” syndrome (CLG, 2011). This implies that once built, a certain level of efficiency, or inefficiency is locked into a building, which cannot be dramatically altered without significant costs.

Revocability can exist in physical and economic forms (Verbruggen *et al.,* 2011). Economic Revocability connotes the potential for variability in the future cost projections, in a building over its estimated life. Physical revocability in buildings is considered, as being contingent on the degree of flexibility in the building design, as represented in Figure 3.8. Lack of in-built flexibility is expressed as rigidity, and has a detrimental impact, for the exercise of future options. Preclusion, is the end of the spectrum on Physical Revocability, where any possibility for design alteration is considered infeasible. Economic Revocability addresses the economic aspects of buildings (Verbruggen, 2013), and this provides the more relevant context for whole-life costing. There is however, a linkage between Physical and Economic Revocability. Physical Revocability invariably impacts on the scope for economic revocability. This implies lack of embedded physical revocability, can limit the potential for economic revocability. It should be noted that, economic revocability can still exist even with limited scope for physical revocability. For instance, an inflexible building design is unlikely to have its economic value influenced by the owner (Fawcett *et al.,* 2011, Menassa, 2014). It is however, possible that a building's economic value can be based on other factors outside its design, such as the location, changes in legislation, obsolescence, as well as cultural and social issues (Kirkham, 2014).

Physical revocability connotes the difficulty associated with withdrawing resources already committed to a course of action, for alternative use (Verbruggen *et al.,* 2011). Verbruggen (2013), in an attempt, to evaluate revocability prescribed a qualitative five-level rating in building investments, as depicted in Figure 3-9. Adverse, Costly and Slow, Medium, Ready, and Perfect Revocability. Adverse revocability connote situations where cost of reversal increases over time. Costly and Slow revocability refers to those situations where reversal cost in the future is above the reference initial cost, but decays over time. Medium revocability refers to investment situations, where the undoing cost is higher than the initial cost at the current time, and for some years, but falling below initial cost in later periods. Ready revocability refers to investment situations where the investment could be undone without extra removal costs. In which case, the revoking costs consists mainly of the non-depreciated part of the initial cost of investment. Although, there are theoretical arguments for the existence of perfect revocability, it seems preposterous to assume a situation, in which any investment decision can be perfectly revoked at any time without any associated costs.

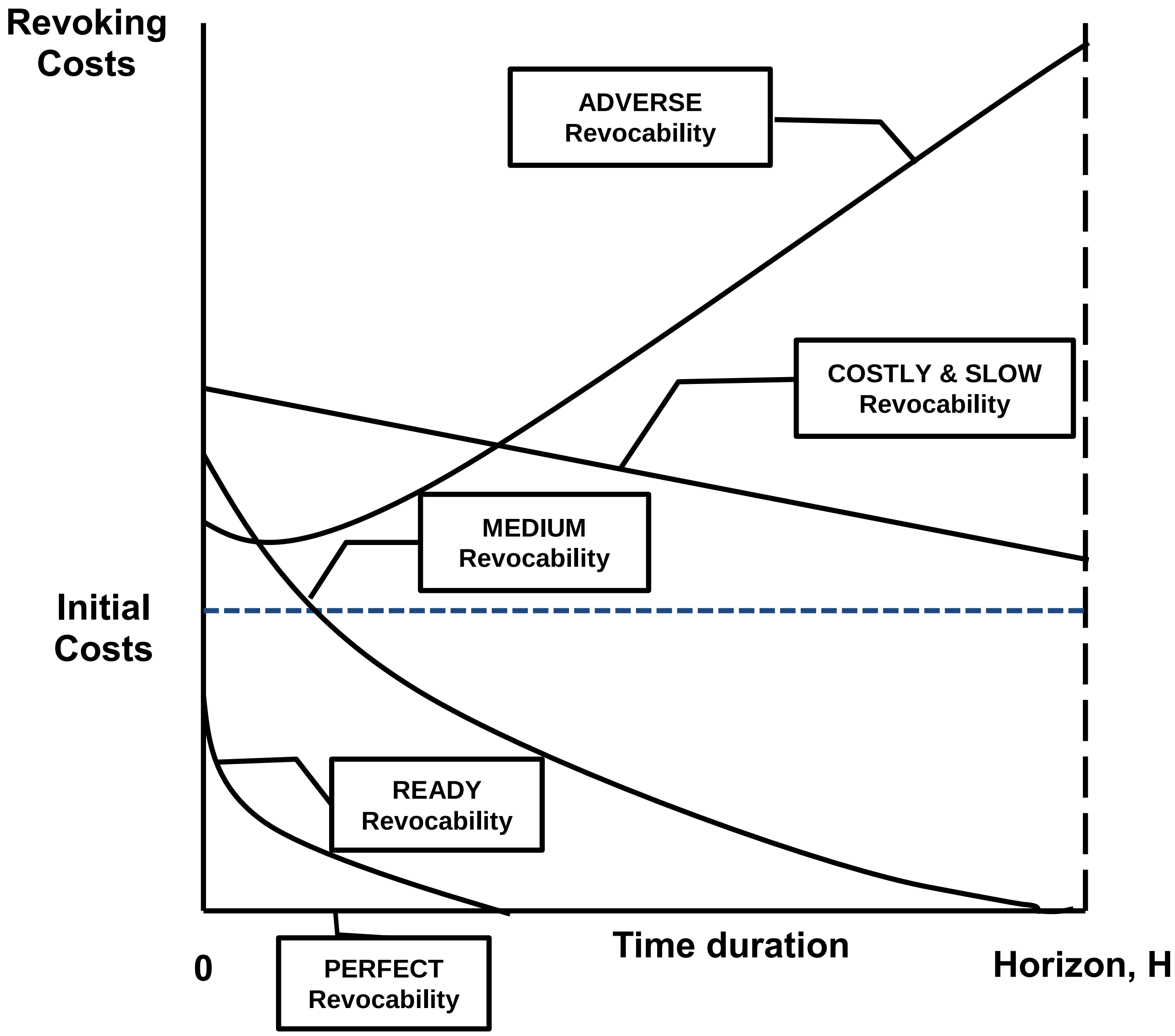


Figure 3-9 Revoking costs in the future for undoing an action and its impacts (Verbruggen, 2013)

In the whole-life costing of building retrofits, revocability can be expected to have far-reaching implications, on the cost outcome of particular courses of action. Previous whole-life costing models developed, have not considered the economic implications of revocability in buildings (Fawcett, 2011, Kirkham, 2014).

In a knowledge-driven age, where advancement in technologies and innovations are common-place, change and adaptability seems desirable in no small measure, and may translate into competitive advantage (Porter, 2008). It will therefore be expected that “’Ready’ and ‘Perfect’ revocability” will be desired by building investors.

Revocability is however difficult to precisely measure hence, the need for flexible appraisal techniques.

3.6.2 Disruptiveness

Investment initiatives in retrofit scenarios tend to involve some level of disruption to the normal operation of building occupants (Dixon *et al.,* 2008, Thomsen *et al.,* 2009, Gleeson *et al.,* 2011, Menassa, 2011). Depending on the scale of the disruption, this could significantly alter the business case, of the entire retrofit project. Verbruggen (2013) argues that, disruptive decisions tend to have disproportionate impacts and hence, a good cataloguing of outcomes will be essential. Gleeson *et al.,*(2011) conducted a disruption analysis on retrofit interventions (See Table 3:3), and provided a 3-scale assessment of Low (L), Medium (M), and High (H) levels of disruption.

Table 3:3 Disruption metric for various retrofit interventions (Gleeson et al., 2011)

Retrofit Interventions	L	M	H	Comments
Compact Fluorescent lamp	✓			None
Appliances	✓			None
Draught exclusion	✓			Access to all windows and doors. Remove curtains/blinds, prepare windows and frames
Cavity wall insulation	✓			Requires scaffolded access to façade.
Extract Fans	✓			Power disruption, running of cables, builder’s work
Loft Insulation	✓			Access to loft, clearance, loss of storage space
Photovoltaic	✓			Scaffolding, access to building for running cables and metre connections
Boiler and Controls		✓		Interruption to heating and hot water. Access to all radiators for TRVs. Power connections for boiler/controls. Builders work for flue
Cylinder		✓		Interruption to heating and hot water
Solar Thermal		✓		Scaffolding, power disruption, run cables, builder’s work, interruption to heating and hot water
Windows/Doors		✓		Access to all rooms, temporary security. Scaffolding
External Wall Insulation			✓	Requires scaffold access to façade. Potentially disruptions to all services supplies and drain connections. May impact on width of access and egress leading to extensive construction works, increase in building footprints
Internal Wall Insulation			✓	Total room disruption. May be programmed room by room. Will require removal/replacement of skirting, architrave, electrical outlets and switches
Mechanical Ventilation and Heat Recovery (MVHR)			✓	Total disruption
Floor Insulation			✓	Total disruption

The work done by Gleeson *et al.,*(2011) is an European-wide assessment on the impacts of retrofit interventions. The estimation of the number of days of disruption for comparable building typologies can be obtained by normalising and evaluating respective projects, and where possible, making approximate adjustment on the expected days of disruption. It can be seen in Figure 3-10, that in a typical building, the number of days of disruption for individual installation of retrofit technologies can range from 2 – 12 days. It is however expected that certain retrofit measures can be installed concurrently. Hence, project management considerations should be applied in the estimation of the period of disruption, caused by an individual retrofit measure, or a package of retrofit installations.

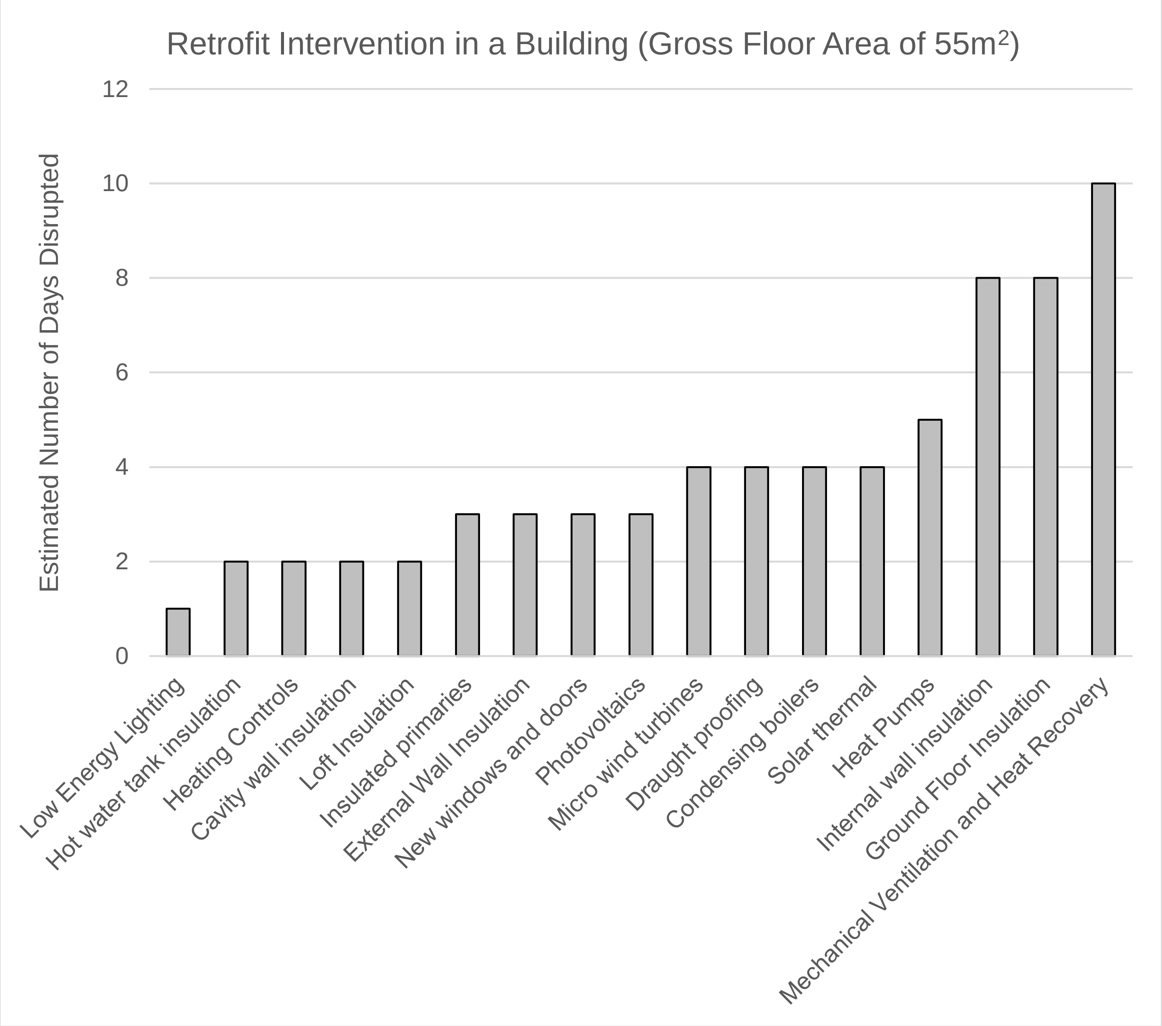


Figure 3-10 Disruptions levels caused by Retrofit Interventions (Gleeson et al., 2011)

Basically, some retrofit interventions effect partial disruption to normal occupants' lifestyle, and profit-earning activities, while other retrofit interventions cause total disruption (Gleeson *et al.,* 2011). In commercial office buildings, disruption disproportionately impact on the income levels of business outfits. For example, it can be seen from Figure 3-10, that floor insulation tends to be significantly disruptive, while draught exclusion could be minimally disruptive.

Millers and Buys (2008) posit that in existing multi-tenant commercial office buildings, any retrofit project will require the cooperation and participation of a wide range of stakeholders. It is therefore desirable for retrofit initiatives to be undertaken in a manner, less disruptive on business operations (Dixon *et al.,* 2008, Thomsen *et al.,* 2009). In developing a good catalogue of outcomes, Blyth and Worthington (2010) describe five methods that can be used in cataloguing outcomes, in whole-life cost scenarios - projecting from past experience, predicting, trend-spotting, scenario-building, and backcasting. These approaches are largely scenario forecasting methods.

There is no evidence that previous whole-life costing models have captured the economic effects of disruption, in potential retrofit interventions (Kirkham, 2005). Earlier works by the RICS (2002) alludes to disruption in whole-life scenarios but did not attempt to evaluate its implication on the outturn cost. It can therefore be argued that previous whole-life costing models has tendencies to downplay certain relevant variables that could influence the eventual cost out-turn of projects. In retrofit scenarios, the cost of disruption could impact on the whole-life costs, as the period over which a retrofit installation takes place could be relatively extensive.

Gleeson *et al.,* (2011), suggested that Low disruption could cause interference of up to two days; while Medium and High disruption, may cause interference of up to five and ten days respectively. It should be noted that the cost of disruption might be influential in the sanctioning of retrofit projects, and determine the attractiveness of specific retrofit options, especially in commercial buildings.

The cost of disruption has not been elaborately considered in existing investment appraisal literature (Gleeson *et al.,* 2011). Perhaps one explanation for this is that, traditional whole-life cost models have mainly focused on new buildings, in which case the costs of disruption is non-existent, and hence not considered in the model framework. Another possible explanation, is that the cost of disruption is imprecise, and more readily expressed in subjective and qualitative terms (Gleeson *et al.,* 2011). It is however reasonable for commercial building investors to take interest in the cost of disruption, since investment costs of retrofit packages in these buildings will exceed the nominal installation cost alone.

One possible approach to estimating the cost of disruption in office buildings is on the basis of opportunity costs. However, it can be expected that many offices will not fully suspend business operations simply to embark on a retrofit project, except in a grave emergency. In such a scenario, the opportunity costs may be the extra costs of renting or leasing an alternative location, over the course of the building retrofit work.

The limitation of this approach is its assumption of total disruption in business operations, which might not be the case. For example, changing light bulbs to energy-efficient compact fluorescent lamps (CFL) in an office could save up to 10% of its energy-costs (Gleeson *et al.,* 2011, Duffy *et al.,* 2015) without expressly disrupting business operations, in the office building. Equally, the ‘opportunity cost’ approach will not adequately appraise the effects of relocation on business prospects and patrons.

A suggested approach to evaluating the cost of disruption, which better considers varying potentials of disruption, in respective retrofit initiatives is to estimate the actual costs of running the office building, based on the maintenance and building operating cost and staff cost. Hughes *et al.*,(2004) based on published data, proposed a 1 : 0.4 : 12 ratio for the Construction cost, to Maintenance and Building Operating Cost, to Staffing and business operating cost, for commercial office buildings, over an estimated 25-year life period. A fraction of the staffing and business operating cost provides a numerical basis for estimating the cost of disruption in respective retrofit scenarios. This approach may however, be slightly preferable to the ‘opportunity cost’ approach, as information on the possible days of disruption could be more readily harnessed. This approach is also specific for particular retrofit packages, and thus could be useful for comparative purposes. Cole and Sterner (2000), as well as Holness (2010) had previously utilised this approach in estimating the staffing cost over the life of a building. It will however, be essential for future studies to investigate and suggest alternative approaches for evaluating the cost of disruption in retrofit scenarios.

It can be expected that fuzzy logic techniques, along with other qualitative evaluation techniques such as Dempster-Shafer and Evidence theory, will offer a useful means to evaluating the disruptiveness of retrofit technologies in building investments. One reason for this, is that disruptiveness is perhaps not readily measurable in monetary terms, but can be represented in linguistic terms (Gleeson *et al.,* 2011). The benefit of fuzzy logic lies in its capacity to accommodate subjective input parameters (Zadeh, 1995, Ammar *et al.,* 2013). Hence, linguistic variables could be converted into membership values. Previous work by Fayek and Sun (2001) have utilised linguistic variables in describing factors affecting a construction project. Zadeh (2008) asserts that linguistic descriptors are perhaps one of the most powerful application of the fuzzy logic technique. Arena (2014) however, advised that Dempster-Shafer and Evidence theory, are better poised at dealing with ignorance and lack of knowledge in systems, rather than evaluating subjective knowledge. This study will therefore examine and evaluate the disruption cost of retrofit technologies based on fuzzy logic techniques.

3.6.3 Discounting

According to the Green Book published by HM Treasury, (2011) discounting is a technique used to compare costs, that occur in different time periods. It is based on the principle of time preference. Seifritz (1997) define discounting as the valuation of future monetary values, based on a socially collective consciousness. This perspective demonstrates that discounting aims to capture two phenomenon – the potential investability of money, as well as the periodic preference of individuals or groups, to possess money now, rather than a later period (Gluch & Baumann, 2004). Discounting rates therefore, tend to be subjective and volatile (Spackman, 2011).

The discounting process is the widely-accepted mechanism for deriving the equivalent value, today, of a future expenditure (Ellingham & Fawcett, 2006, Farr, 2011, Malik, 2012). Previous studies in investment analysis have however, suggested insufficiency in the discounting mechanism of cash flows (Byrne, 1997;

Niccolini *et al.,* 2000; Verbruggen, 2013), leading to unrealistic estimation and in some instances, incorrect decisions (Gluch & Baumann, 2004). Korpi & Ala-Risku (2008) have also questioned the discounting convention, which invariably elevates the place of Initial capital cost over the Future costs. Chan (2012) hinted that the problem with the conventional discounting mechanism might be embedded in the cultural perception of time as a homogeneous numerical order.

According to Harrison (2010), there are two approaches to selecting the appropriate discount rates in whole-life costing scenarios. A 'descriptive' approach based on the opportunity cost of capital used in the building project. This approach focuses on appraising the potential benefits accruable to society from divesting funds on an investment project in comparison to its performance, if invested in the private sector. This descriptive approach, gives attention to inflation and interest rates (I_R). When cost and benefits are measured in real terms, (that is, adjusted for inflation) they are discounted with a risk-adjusted discount rate (D_R). Otherwise, the costs and benefits will be discounted with a nominal discount rate (D_N). The mathematical procedures to deriving the risk-adjusted discount rate (D_R) are as follows:

Risk-adjusted discount rate (D_R)

$$D_R = \frac{1 + D_N}{1 + I_R} - 1$$

For example, a nominal discount rate (D_N) of 3.5%, and an inflation rate (I_R) of 0.5%, will yield a risk-adjusted discount rate of 3%.

Another approach to selecting the appropriate discount rate, is based on a 'prescriptive' approach that derives from ethical views about intergenerational equity (Kula, 1988, Spackman, 2011). Since this approach relies on subjective judgment across different economic climes, it generally provides a broad and differing range of numerical values for discount rates. Given historical evidence that, on average, each generation has continually invested and improved the standard of living of subsequent generations (Harrison, 2010), the prescriptive approach might not necessarily produce differing discount rate values on the long run. Harrison (2010) reported on the real discount rate values and their respective sources in selected countries of the world, as shown in Table 3:4. Harrison's (2010) work reveals that discount rate values, depending on the country of interest, can range from 3% - 15% per annum.

Table 3:4 Discount Rate Values in Selected Different Countries (Harrison, 2010)

S/N	Country/Affiliate	Agency	Discount Rates (%)
1.	Philippines		15[a]
2.	India		12[a]
3.	Pakistan		12[a]
4.	International Multi-lateral development bank	World Bank	10 – 12[a]
		Asia Development Bank	10 – 12[a]
		Inter-American Development Bank	12[a]
		European Bank for Reconstruction and Development	10[a]
		African Development Bank	10 – 12[a]
5.	New Zealand	Treasury and Finance Ministry	8[g]. From 1982 – 2008, it was 10[abf]
6.	Canada	Treasury Board	8[ab] Used 10 from 1976 - 2007
7.	China		8[a]
8.	South Africa		8[d]
9.	United States	Office of Management and Budget	7 (Used 10[a] until 1992
10.	European Union	European Commission	5[a] Used 6[a], from 2001-06
11.	Italy	Central Guidance to Regional Authority	5[a]
12.	The Netherlands	Ministry of Finance	4[e] (risk-free rate)
13.	France	Commissariat General du Plan	4. From 1985 – 2005, 8[ab] was used.
14.	United Kingdom	HM Treasury	3.5 (declining to 1% for costs and benefits received more than 300 years in the future) from 2003. Used 10[a] from 1969-78
15.	Norway		3.5 7[ab] was used from 1978 -98
16.	Germany	Federal Finance Ministry	3[a] 4[ab] used from 1999 - 2004
17.	United States	Environmental Protection Agency	2-3[a]

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[a] Zhang et al. (2007, table 4, pp.17 – 18, 20), [b] Spackman (2006, table A.1, p.31). [c] Treasury Board of Canada (2007, p.37, 1998, p.45). [d] South African Department of Environmental Affairs and Tourism (2004, p.8). [e] Van Ewijk and Tang (2003, p.1). [f]. Use of the 10 per cent rate by New Zealand Government departments is confirmed by Young (2002, p.12); Abusah and de Bruyn (2007, p.4). [g] New Zealand Treasury (2008) recommends a default rate of 8 percent (after adjusting the market risk premium of 7 percent for gearing).

The choice of discount rates, is perhaps the most influential variable in assessing a building investment in whole-life costing scenarios (Gluch & Baumann, 2004). The discount rate helps in assessing the relative desirability of an option over other competing alternatives (Jackson, 2010, Tan *et al.,* 2010). According to Goh and Sun (2015), the prevalent discount rates in the whole-life costing of building investments, range between 2%and 10%. This range is consistent with the work, carried out by Harrison (2010), as seen in Table 3:4, which ranges between 3% and 15% per annum. It is also noteworthy that discount rates tend to have much lower values, in more recent times.

Verbruggen (2013) surmised that constant discounting, at positive rates, over very long-term periods are problematic. Kodukula and Papudesu (2006) add that discounting at positive rates focus solely on the downward side of risk, and reinforces a disproportionate worldview. One suggested approach to overcoming the limitations of the discounting technique, is to conduct sensitivity analysis over a range of plausible discount rate values (Harrison, 2010, HM-Treasury, 2011). The limitations of the Sensitivity Analysis technique are however, clear in the extant literature, and is discussed in Section 4.3.2 Sensitivity Analysis. There have also been proposals of declining discount rates over time (Verbruggen, 2013). In the United Kingdom, HM Treasury (2013) published a guidance on declining discount rates as displayed in Table 3:5:

Table 3:5 Suggested discount rate values (HM Treasury, 2013)

Period of years	0 – 30	31 – 75	76 – 125	126 – 200	201 – 300	301+
Discount Rate	3.5%	3.0%	2.5%	2.0%	1.5%	1.0%

However, there has not been much consensus regarding the declining discount rate approach (Verbruggen, 2013). Equally, an (0.5 – 1)% difference in the discount rate values as specified by the HM-Treasury, over the estimated building life (of say, 50 to 100 years) may not significantly alter and impart decision outcomes in retrofit scenarios. The declining discount rate approach however, reveals a commitment to address the issue of intergenerational equity over time. There is no evidence from current studies, that the declining discount rate schedule has been well-received by the building industry, and relevant professional bodies. However, the declining discount rate schedule in Table 3:5, will be used in the evaluation of office retrofit options in the building projects, and will be appraised in this study.

3.7 Data Classifications in Whole-life Costing of Buildings

According to Al-Hajj *et al.,* (2001), data requirements can be broadly categorized into four types. The first category of data required in a typical whole-life costing (WLC) exercise is the economic data, regarding the discount and inflation rates, and the analysis period. This study will adopt the declining discount rate and inflation rate schedule guidance, provided by HM Treasury (2013), since it provides a reliable, up-to-date and robust information source, for economic appraisal in the United Kingdom. The declining discount rate schedule provides an attempt to correct the misperception of time (Kirkham, 2014), and better aligns with the goal of intergenerational equity. There is no documented studies in which declining discount rates have been considered in the whole-life costing of buildings. Hence, this novelty will further enhance the contribution to knowledge base of this work.

The second category of data required in a typical WLC exercise include, the Initial cost, Maintenance cost and Utilities cost. The Initial capital cost can often be provided by Contractors. However, these evaluations are based on elemental breakdown of work, and often include the overhead, which may be variable. The information on the Initial Capital cost, can also be estimated from proprietary cost database, such as the Building Cost Information Service (BCIS) in the UK, or CoStar group, in the United States. Proprietary data sources of this kind, tend to provide generic information based on the Gross Floor Area and Location (BCIS 2012).This study obtained initial cost data from Contractors on the SPACE building project examined. This was considered the best means of obtaining the data from selected building projects, as the incorporated retrofit solutions, which constitute the bulk of the retrofit work, are new products unique to Specialist contractors. The operating and maintenance cost data, and utilities cost data of the base case, was directly obtained from the Project team and owners of the SPACE and MS building projects.

The maintenance cost and utilities cost in a typical WLC study, as well as the staff and business operating costs constitute a significant proportion of the running costs (Hughes *et al.,* 2004), although in some cases, disposal costs could be included. The maintenance cost is dependent on the behaviour of the occupiers, and the quality of building materials, and components used. Sources of maintenance data include historical data from clients and surveyors' records, cost databases and maintenance price books (Kishk *et al.,* 2003). In this study, the maintenance costs are obtained from the Project team and owners of the buildings.

A significant part of Utilities cost are energy costs. Energy costs, at the current time, tend to be a small percentage of total occupancy costs (Wade *et al.,* 2003b). However, there is a possibility that this may significantly change in the coming years. A report by Radian, estimated that average energy bills in the UK are likely to quadruple over the next 10 years (Gleeson *et al.,* 2011). Energy costs can be estimated largely from calculation-based and measurement-based approaches (Wang *et al.,* 2012). The energy quantified using any of these approaches can be multiplied by the unit rate publicly available from energy service companies (ESCOs). Energy costs however, tend to be volatile, and may be difficult to predict on the long-term (Pellegrini-Masini *et al.,* 2010).

Another possible source for Maintenance and Utilities cost data in a typical WLC study, is by the use of average proportions. Holness (2010) stated that in the life-cycle of a building, initial construction cost represents only 2%; operational and energy cost are 6%, while the rest of the 92% is the cost of occupants. This distinction is however not specific enough and the classification of cost in this manner seems rather unclear. Evans *et al.,* (2004) under the aegis of the Royal Academy of Engineering, conducted a study on the long-term cost of owning and using buildings, and proposed that the construction cost, maintenance cost, and business operating cost of commercial office buildings in the UK, over their lifetime have a ratio of 1 : 5 : 200 respectively. Hughes *et al.,* (2004) have contested this ratio, and based on another set of published data opined that the more realistic ratio is 1 : 0.4 : 12, over an estimated life of 25 years. It can be inferred that the ratio of the maintenance costs to business operating costs in commercial office buildings, over a 25-year life time in the studies by Evans *et al.,* (2004) and Hughes *et al.,* (2004) are 1 : 40 and 1 : 30 respectively.

This current work however, focuses on retrofit scenarios, and will utilise the ratio of the maintenance cost to business operating cost in providing implicit assumptions for the disruption analysis conducted on retrofit options. Hughes *et al.,* (2004) clarified that building operating costs include operating cost, maintenance, cleaning, housekeeping, energy, water, sewerage, waste management, interior landscaping, exterior landscaping, fitting-out and alterations; while business operating costs consists of business support services and staff salaries and wages. There is less details on the cost constituents of the work carried out by Evans *et al.,* (2004). Hence, the assumptions used in this work will align more with the work carried out by Hughes *et al.*,(2004). Goh and Sun (2015) surmised that researchers tend to assume higher running costs for commercial buildings, in whole life cost evaluations, especially when building life span is outside the 30 – 50 year range. This assumption might be due to the presence of higher content of air-conditioning, mechanical and electrical installations in commercial building typologies (Wade *et al.*, 2003a, Wade *et al.,* 2003b).

The third category of data in a typical WLC study includes the times in the life cycle of the project, when cost-associated activities are carried out. Cort *et al.*,(2009) suggested that at some point in the life of an office building, some sort of retrofitting or refurbishment, would take place. However, there is an uncertainty regarding when this initiative may be embraced. It can however, be expected that insights on the cost consequence of the decision-to-retrofit, will be better assessed, based on the recognition of the degree of revocability in building options. The distinct strands of Initial and Future Costs, will provide adequate framework for the whole-life costing exercise.

The final category of data in a typical WLC study, refers to the expected life of building components. The actual life of a building will depend on a number of factors including the type of building, physical characteristics of the building materials, exposure to the elements, maintenance regime, frequency of use, as well as the behaviour of the occupiers (Cort *et al.,* 2009). According to Ashworth and Perera

(2013), there are different school of thoughts on the building’s life. One school argues that buildings should be designed with short lives, and be disposable after a life of about twenty years. The other school, ascribed to Alex Gordon, argues that buildings should be designed upon long-life, loose fit and low energy. There is thus, an inexactness about actual building life. Hence, various building lives will be considered in this study on whole-life costing, in order to accommodate the various perspectives on building lives.

Wade *et al.,* (2003a) estimated that the average UK office building, has a life expectancy of 30 – 40 years. Goh and Sun (2015) inferred that a reasonable estimate of the economic life of commercial office buildings should range between 20 – 60 years. More generic estimates of the life-span of buildings are provided. Gleeson *et al.*,(2011), opined that the life expectancy of commercial office buildings, should range between 50 – 80 years; Menassa and Baer (2014), estimated that the lives of commercial office buildings should range between 30 to 70 years. Energy Information Administration (EIA, 2009) in the US, suggested that the average life of commercial office buildings, based on analysis of data from the Commercial Buildings Energy Consumption Survey (CBECS) range from 65 to 80 years. Blyth and Worthington (2010), suggests the life of a building structure can generally range from 30 – 300 years. Ashworth (1996) however, cautioned that building life, should be about how long it is retained, rather than how long it will last.

Bullen (2007) argues that most office buildings are designed for short life cycles. The actual life of buildings in whole-life scenario is however, uncertain and hence Sensitivity analysis will be employed to assess discrete variations in the building life. Based on published literature, the estimated building life of office buildings considered in this study will be over 20, 40 and 60 years (Kishk *et al.*, 2003, Caplehorn, 2012, Kirkham, 2014). This range, cover a reasonable span for most whole-life cost evaluation in the built environment literature (Ashworth & Perera, 2013).

These four categories of WLC data are the usual inputs in traditional whole-life costing exercises. It will however, be necessary to generate and collect data on the cost of revocability and disruption, in order to test and examine their impacts in whole-life cost estimation. This work will also appraise the decision-impacts of revocability and disruption in office retrofit building projects. The possible approaches to obtaining these data will be discussed, in the Research Methodology Chapter. The prevalent practice in the industry is to estimate Future cost-associated activities in annual terms, while Initial cost figures are estimated as a one-off Lump Sum. This convention is consistent with documented whole-life costing exercises, and compliant with International Financial Reporting Standards (IFRS).

3.8 Data Sources in Whole-life Costing of Buildings

Three main sources of data in whole-life costing, are historical records, manufacturers and supplier's specifications, and predictive models (Flanagan *et al.,* 1989, CIFPA, 2012). Historical data are obtainable from existing buildings. These types of data, are useful in establishing a base case for retrofit scenarios. However, they may not prove useful for capturing benefits in retrofit scenarios. Historical data tends to be applicable in particular contexts, and may not be readily transferrable to other contexts (Ashworth & Perera, 2013).

Ferry and Flanagan (1991) advised that extensive historical data are not indispensable to whole-life cost modelling. A more fundamental prerequisite is an intricate knowledge of the relative proportion of Initial and Future costs, in the whole-life cost model. Goh and Sun (2015) analysed some historical information on different categories of buildings, and found that consistent patterns and trends, are observable. Hence, historical data on buildings, could provide a means of testing the performance of whole-life cost models.

In recent times, collection of historical information on buildings are perhaps more reliable due to the availability of more precise, and technology-oriented approaches of data retrieval and recording (Boussabaine & Kirkham, 2008, Kirkham, 2014). This is perhaps one area where Building Information Modelling (BIM), shows promising potentials (Goh & Sun, 2015). Ashworth (2004) advised that historical cost data alone, no matter the level of detail will never fully provide solutions to data needed in whole-life cost modelling and, some form of judgment will still be required. The reasoning behind this assertion is that historical cost data often reflects what is affordable rather than the resources expended in acquiring a particular object or service (Emblemsvåg, 2003).

Manufacturers and suppliers could be useful in providing information on the expected life, optimal maintenance regime, and the associated costs of building components. The information however, tend to be of commercial nature, and the estimations may be skewed to unwittingly promote certain products at the expense of others. Hence data of this kind, could be of doubtful validity (Kishk *et al.,* 2003). Ashworth (2004) also mentioned that Manufacturers and Suppliers data may be representative of an ideal or perfect scenario, which seldom occurs in practice.

Predictive Mathematical models can be used to estimate the Future costs of buildings (Al-Hajj *et al.,* 2001), and can be classified as parametric, analogy and detailed cost estimation models. Parametric cost estimates are derived from statistical correlation of historic data, with performance and physical attributes of the system (Farr, 2011). The drawbacks of parametric estimates are that, they are not well suited to quantification in the early stages of a project, - when the project is still in its formative phase; where details are sparse; and, ideas are diverse (Seo *et al.,* 2002). It should however, be noted that parametric cost estimates are useful in providing indicative estimates at the conceptual stage of projects (Farr, 2011). One drawback of parametric estimation is their applicability to only cost variables, which can be numerically measured.

Cost estimation by analogy seeks to identify a similar product or component, and adjust costs based on observable desirables or undesirables, between the real object and the analogous one (Seo *et al.,* 2002). The drawback of cost estimation by analogy is its dependence on obtaining a similar product, which might be unavailable. This reliance on analogous products could limit the potential to identify cost drivers in models (Smith, 1997). This approach could also mistake availability, for desirability in employing comparisons.

Cost estimation by detail, is element-specific, and seeks to estimate costs based on the activities/product/resource consumed in the course of procuring the object (Ashworth & Perera, 2013). The drawback of cost estimation by detailed form, is its sole focus on tangible resources, as sole contributors to a facility's make-up, which leaves little room for quantifying the "intangibles", which might optimise resource usage.

Molenaar (2005) reckons that cost estimation techniques and tools should be dynamic and adaptable, to the various phases of project development. Farr (2011) captures some of the applicability potential of established cost estimation techniques in Figure 3-11, over a typical life-cycle of a facility.

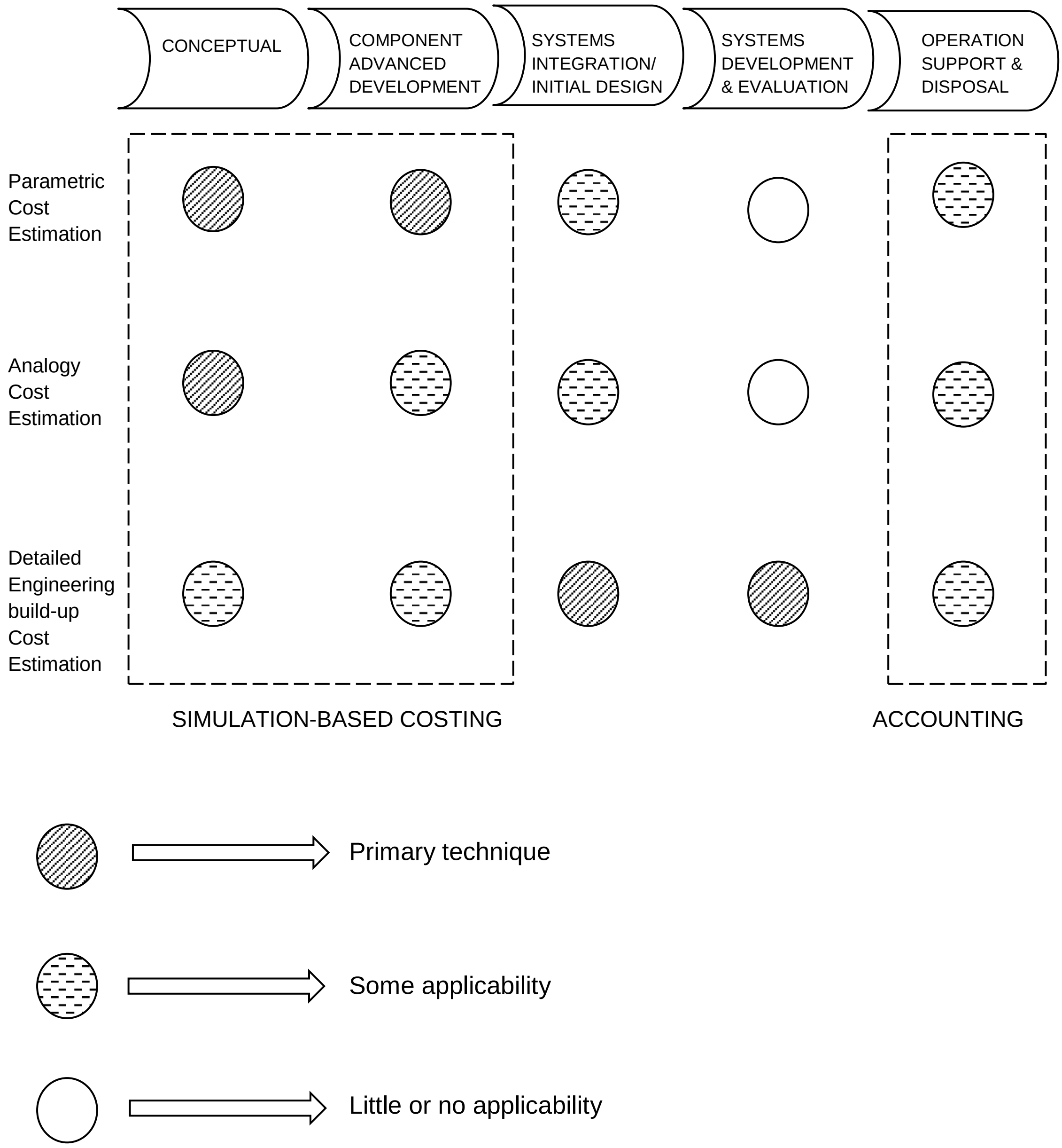


Figure 3-11 Costing technique across a typical building lifecycle (adapted from Farr, 2011)

3.9 Gaps in Knowledge

There has been growing interest in the principles and techniques of whole-life costing (Capelhorn, 2012), it is however, still considered a black art, and the concepts and methods available from the literature are suspect (Kishk, 2005, Caplehorn, 2012, Ashworth & Perera, 2013). One major problems with whole-life costing relates to the unavailability and unreliability of data (Kishk, 2003, Kirkham, 2005, Goh & Sun, 2015). Data used in whole-life costing tends to be highly diverse and inconsistent (Clift and Bourke, 1999, El-Haram *et al.,* 2002). The current practice of whole-life cost modelling which provides a single estimate, for such diverse range of data, therefore allows for vulnerability in generating erroneous results (Gluch & Baumann, 2004), as well as unrealistic predictions (Ellingham & Fawcett, 2006).

Mathematical models have been the prevalent approach in whole-life cost modelling (Kirkham, 2005, Kishk, 2005, Caplehorn, 2012). Alternative approaches such as Finite Element methods, and Simulation (Farr, 2011) have not been sufficiently considered in the generic development of whole-life cost models for buildings. Closed-form mathematical models tend to assume minimal complexity, and assume little or no uncertainty (Ross, 2009). Hence, they provide whole-life cost values that seldom capture the diversity of cost data, involved in a building's life.

Asides the conceptual approach to whole-life cost evaluations, the prevalent approach to modelling uncertainties has been probability theory (Ellingham & Fawcett, 2006, Ma *et al.,* 2012). While probability theory is useful in handling certain aspects of uncertainties, it tends to be less effective, in situations where dependencies between variables are not well-defined, and the probabilistic information is not sufficient (Zadeh, 1995). Uncertainties regarding the drivers of Future cost elements, differ from uncertainties pertaining to the time-value of money. Regarding the time-value, it should be noted that many whole-life cost models, are based on a constant discount rate, which in itself assumes that uncertainty borne per period is constant and can be resolved continuously at a constant rate over time (Yao & Jaafari, 2003).

In whole-life cost evaluations, there are uncertainties related to the time-value of money, as well as uncertainties regarding the Future cashflows themselves, which can be highly variable and volatile, and will be dependent on a number of variables including Government policies, and other factors outside the control of building owners. There could also be scope for altering the actual Future cost implications of buildings, as a result of internal decisions and policies. Uncertainties in future cost outcomes of buildings, can be captured by paying attention to the concept of revocability (Verbruggen, 2013).

In retrofit scenarios, another important cost, which perceptibly adds up to the Initial cost of installation or construction of building, relates to the Cost of disruption. While traditional whole-life cost models seem accustomed to new-builds, and often fail to consider the implication of disruption, this is not the case with alterations in existing buildings. In existing buildings, the cost of disruption could significantly alter the decision-to-build (Miller & Buys, 2008). This does not only pertain to the monetary value of the existing building re-configuration, but could also relate to the social, cultural, environmental and use value. It will therefore be useful for whole-life cost modelling to adopt a broader outlook on cost and value in retrofit building projects.

The science of whole-life costing has traditionally polarised cost elements over the life of a building into substantive components of Initial cost and Future cost, without exploring the inter-relationships between them. Implicitly, the science of whole-life costing assumes that the same party bears the Initial and Future cost obligations, over the life of the building (Ferry *et al.,* 1999). It can therefore, be expected that in instances, such as in rented, or leased building facilities, where different parties tend to bear the cost obligations of the buildings, at different times, the appeal of whole-life costing to the building owner could be limited.

Many whole-life cost evaluations also tend to aggregate the revenue and cost streams of buildings in whole-life cost computations (Kishk, 2005, Ellingham & Fawcett, 2006, Jackson, 2010). This approach is essentially a Net-Present Value summation, and could be useful, in establishing whether a proposed project should go ahead or not. The problem with aggregating revenue and cost streams is that, it detracts from the primary objective of whole-life costing, which is to identify the best alternative, among a set of competing options. Some researchers in whole-life costing including Kishk *et al.,* (2003), and Ellingham and Fawcett (2006), seemed to have evaded this aspect of whole-life cost modelling, and provided models whose framework detract from the primary objective of whole-life cost modelling.

Lastly, whole-life cost modelling has traditionally focussed on “hard-data”, which are quantitatively defined (Healy, 2015), and have failed to harness subjective, and less-quantitatively defined data, which could ameliorate the unreliability of data in whole-life cost modelling, and enhance the credibility of whole-life cost predictions. This work therefore utilises some qualitatively defined data through the application of the principles of fuzzy logic in the whole-life cost modelling of office retrofit buildings. More specifically, qualitatively defined variables are evaluated in the newly developed Fuzzy New-generation whole-life cost model for office retrofit buildings.

3.10 Summary

This chapter provides an account of the mechanics of whole-life costing in buildings. It commences with a discussion on cost modelling in general, and goes on to examine the distinctive forms of mathematical whole-life cost models – the Standard Whole-life Cost technique, and the New-Generation Whole-life cost technique. A critical discussion on Whole-life costing is reported thereafter, and the gaps in knowledge based on the review are highlighted, in the concluding section. This chapter constitutes the concluding section of the two-part literature review section of this thesis.

Chapter 4 Research Methodology

4.1 Introduction

This chapter reports on the theoretical and practical considerations adopted, to direct the research procedures, in this work. It commences with the research philosophy, and highlights the logical thought processes in the work. It then, moves on, to the core principles adopted, in the course of addressing the research question. The last two sections details the data analysis techniques used, and the summary of the entire chapter. Concerted attention is also given to the caveats of the research methods used in the study.

4.2 Research Philosophy

The research philosophy highlights peculiar assumptions regarding the epistemological perspective, for the chosen line of inquiry. Amarantunga *et al.,* (2002) advised that, the discussion of philosophy is a necessary imperative prior to embarking on a research work. Epistemology can be described as the philosophy of knowledge, especially with regards to methods, validity, nature, sources, limit and scope (Jonker & Pennink, 2010). Two perspectives in the realm of epistemology are the realist and the relativist perspective. The realist perspective assumes the existence of a single reality, independent of any observer, while the relativist perspective acknowledges multiple realities having multiple meanings hence, interpretations are subject to the observer's viewpoint (Yin, 2014).

This work, adopts a realist perspective in applying the principles of fuzzy logic to the whole-life cost modelling of office retrofit buildings. The realist perspective is considered appropriate in identifying empirical, and verifiable variables, which meaningfully contribute, and influence the whole-life cost estimate in retrofit scenarios of office building projects.

The research philosophy is essential in delineating the boundaries of the study, and broadly consists of the research paradigm, methodology, techniques, and its specific instrument. Each aspect of the research philosophy of this work will be discussed:

4.2.1 Research Paradigm

Research paradigm refers to the underpinning values and rules, that govern the thinking and behaviour of the researcher (Jonker & Pennink, 2010). The essence of a research paradigm, is to establish a central focus, and articulate the commonality of perspectives between the current study and previous works. Two common and distinctive research paradigms are the Positivist and the Constructivist traditions.

Positivist traditions claim that laws and principles are empirically discoverable (Fellows & Liu, 2009), and can be applied to problems, in a manner that is consistent and verifiable. Positivist traditions generally seek to challenge the traditional notion of absolute truth embedded in a body of knowledge, and tends to identify and assess causes that influence outcomes (Creswell, 2013). The Positivist tradition canvasses for an objective scale of measurement, and tends to reduce and operationalise the whole, into units of analysis (Amarantunga & Baldry, 2001). There are a number of deficiencies in the positivist tradition. Amarantunga *et al.,* (2002) surmised that positivist paradigms tend to be inflexible, and artificial. They however, tend to be fast, economical, and understandable, especially with the increase in computer tools and techniques, that can aid researchers in speedy, and more accurate analyses of data.

Constructivist traditions, on the other hand, tend to address the process of interaction among individual researchers, and focus on extracting meanings, which other individuals construct about situations. The Constructivist tradition dates back to the last half of the twentieth century (Amarantunga & Baldry, 2001). Knowledge and insights in the constructivist tradition therefore, require a consensual understanding of phenomena, in order to create solutions that are suitable, understandable, and applicable. Constructivist traditions tend to be subjective, and will involve sense-making of participants. Analysis and interpretation of data tend to be more bespoke in a constructivist paradigm (Amarantunga *et al.,* 2002). There is equally a perception that the Constructivist tradition is embraced by researchers incapable of the rigours of quantitative techniques (Sherratt, 2013). Hence, this approach sometime tends to be ‘untraditional’, and falls under increased scrutiny in the Built Environment discipline.

In the whole-life costing of office retrofit buildings, it is argued that the variables of interest can be depicted, operationalized, tested and verified. Hence, the positivist tradition provides a more befitting paradigm, to examine the issues of interest in whole-life costing. The positivist tradition could however, tend to be reductionist, as only the variables considered important by the researcher are examined. This work adopts the systematic procedures suggested by Jonker and Pennink (2010), in implementing the positivist tradition, and develops this approach in three steps:

4.2.1.1 *Diagnosis*: Create a clear problem definition

In the whole-life costing of office retrofit buildings, there is no existing framework that robustly addresses the pertinent considerations in building retrofit options. There is no evidence, at least in the extant literature, to support the claim that the popular Standard Whole-Life Costing technique (WLC) traceable to Flanagan and Norman (1983), and the New-Generation Whole-Life Costing (NWLC) technique developed by Ellingham and Fawcett (2006), are robust enough to deal with building retrofit scenarios.

Firstly, these models are implicitly based on the assumption of new-build projects. Equally, the Standard Whole-Life Costing (WLC) model does not explicitly allow for possible variations in future cost projections, over the estimated life of the building (Fawcett, 2011).The WLC model also utilises discount rate estimates in a manner that only accounts for the optimistic side of future cost events (Yao & Jaafari, 2003). This could potentially, underestimate investment opportunities (Kodukula & Papudesu, 2006).

It is also worthy of mention that, the WLC model is mostly based, on a single discount rate, which in itself, assumes that uncertainty-borne per period is constant, and the uncertainties in cashflows are resolved continuously, at a constant rate over time (Yao & Jaafari, 2003). Furthermore, the WLC technique tends to be simplistic in its ideology, as it considers decisions in buildings, as an irrevocable allocation of resources (Ellingham & Fawcett, 2006). Hence, there is no flexibility in altering the future cost implication of projects, over its expected life. In practice and in the extant literature on whole-life costing, many of these conceptual limitations have been acknowledged and identified. However, there has been a limited attempt at revamping the framework of whole-life costing in buildings, especially with regards to emerging building typologies.

A number of researchers have proposed alternative whole-life costing models in building investment appraisal scenarios. Published works on these alternative whole-life cost models include Bromilow and Pawsey (1987), Al-Hajj (1991); Al-Hajj and Horner (1998); Kishk and Al-Hajj (2001). Bromilow and Pawsey (1987) further separated maintenance cost elements into more distinct categories, such as recurring costs and non-recurring costs. Al-Hajj and Horner (1998), also simplified the whole-life cost modelling process by utilising a model factor for future cost building elements. Kishk and Al-Hajj (2001) assigned different levels of uncertainty to the various running cost elements. The principles of these models have been discussed under Section 3.3.1, and constitute benign modifications to the WLC formula (Kishk, 2005).

The New-Generation Whole-Life Costing (NWLC) technique, introduced by Ellingham and Fawcett (2006) is an experimental departure from the WLC technique, and strategically improves on the drawbacks of the WLC approach, especially in areas of allowing for variability in future cost projections. The New-Generation Whole-life costing technique effectively challenges assumptions in the WLC framework , that, all decisions are made at year 0; and are irrevocable (Ellingham & Fawcett, 2006). The NWLC technique incorporates a “wait and learn” scenario into the whole-life costing framework, as opposed to just a “choose or lose” scenario.

The NWLC technique exhibits, and demonstrates promising features. However, it considers all uncertainties in the cost projections as a product of variations in the cost events. Boussabaine and Kirkham (2008) have argued, that the treatment of every uncertainty as variability, is a fatal presumption, and could permit sub-optimal evaluation of investment alternatives. Besides, the NWLC technique does not provide a means of including cost variables that are not quantitatively defined.

In order to address these conceptual limitations in existing whole-life costing techniques, there is a pertinent need to question these implicit assumptions in the modelling framework. These can be done by highlighting and identifying, the phenomena that impacts on cost, as well as evaluating variables, in a less deterministic manner. This will involve paying attention to the different categories of uncertainties regarding future costs. It will also involve providing a robust mechanism to evaluate qualitatively defined variables.

Another point of interest is that the WLC technique totally ignores the existence of revocability in its investment evaluation framework. Revocability has been touched upon in Section 3.6.1 Revocability, in physical terms, implies that once built, a certain level of efficiency or inefficiency, is locked into a building, which cannot be dramatically altered without significant costs. The New-Generation whole-life costing model, thus attempts to consider the effects of revocability, albeit in a simplistic manner, presuming dichotomous possibilities of equal proportions in succeeding years.

Besides, none of these modelling techniques, have considered the economic effects of disruption to the normal lifestyles of building occupants, during the implementation of retrofit projects, and how this influences, the decision-to-retrofit. It may however, be argued that the non-consideration of the cost of disruption, for instance, pertains more to the user of the technique; rather than the technique itself. It is therefore, considered a pressing research imperative for a robust framework of whole-life costing, which considers the highlighted phenomena – revocability and disruption, impacting on cost in retrofit scenarios. This new framework holds potential to enhance the purpose of whole-life costing, and allow for more meaningful consideration of competing retrofit investment alternatives.

In summary, existing whole-life costing techniques have some inherent deficiencies, and there is scope for improvement. Also, both models are not specific to retrofit options, and although the phenomena of time discounting supposedly caters for uncertainties in the time-value of money (Malik, 2012); the approach is somewhat limited, and there are as yet, no records where the possibilities of declining or variable discount rates are utilised, to better correct the misperception of ‘disappearing’ future cashflow projections in office retrofit building investments.

4.2.1.2 Design: Design a solution

Having reviewed a number of modelling approaches, it was decided that a fuzzy logic approach to modelling uncertainties, and qualitative variables in the New-

Generation Whole-Life costing (NWLC) template, will address conceptual limitations in existing whole-life cost models. In addition to the use of fuzzy logic, the new model will consider the effects of time-discounting (using declining rates), revocability, and disruption. These modifications are expected to foster an improved and robust approach to whole-life cost modelling in office retrofit buildings.

The limitations of the WLC technique and the NWLC technique in appraising retrofit scenarios, necessitated the application of the principles of fuzzy logic in the whole-life costing of office retrofit buildings, having as its purpose the realistic evaluation of office retrofit buildings, in accordance with the aim and objectives of the current research. More specifically, a Fuzzy New-Generation Whole-life cost model has been developed. This new model provides, a robust analytical framework within which the strength of influences of identified cost variables, can be examined and understood. Fuzzy logic has been previously used in the evaluation of qualitatively-defined variables, in whole-life cost scenarios (Goh & Sun, 2015) and in the modelling of uncertainties (Fayek & Sun, 2001; Ammar *et al.,* 2013). The fuzzy logic approach also has a proven reputation in providing realistic evaluations, in whole-life costing (Kishk *et al.,* 2003).

Given that a number of relevant cost variables tend to be more suitably expressed in qualitative terminologies (Boussabaine & Kirkham, 2008, Ayyub, 2011), the fuzzy logic approach provides a useful and appropriate platform, to appraise future cost implications in office retrofit scenarios. Byrne (1997) adds that fuzzy logic allows for more meaningful, robust and systematic investment appraisal, of retrofit building options. The pertinent issues – Disruption, Revocability and Discounting, influential in the whole-life costing of building retrofit options for office buildings are examined and incorporated in the Fuzzy New Generation Whole-life Costing Framework. The cost of disruption is evaluated as a one-off cost, incurred during the implementation of a retrofit initiative. Revocability pertains to the variability prospects in Future costs in respective years, based on external economic trends, as well as internal decisions by building owners and occupiers. Time discounting, is the widely accepted mechanism for deriving the present-value of a future expenditure, and is based on the principle of time preference (HM-Treasury, 2013). These three issues, as well as the associated uncertainties will be considered, and their influence on office building retrofit options are examined.

4.2.1.3 Change: Implement a solution

The development of a Fuzzy New-Generation Whole-life Cost model aims to provide a more robust and realistic template, to evaluate retrofit options, over their expected lives. However, since the essence of whole-life costing is to systematically select among a range of competing investment alternatives, this work will utilise the Spearman's rank correlation test, to appraise office retrofit building options, in selected case study projects. A number of retrofit options for selected projects, will be ranked according to the whole-life cost values. Wherein the least whole-life cost is considered the most preferred by the decision-maker, and would therefore rank progressively higher than retrofit options, with higher whole-life costs. The statistical differences in the rankings of whole-life cost models, will then be measured using the Spearman's rank correlation test. This will provide an indication of the significance of the identified issues of discounting, revocability and disruption in the whole-life cost modelling of selected office retrofit projects.

4.2.2 Research Approach

The essence of the research approach, is to ensure a connect between the researcher's actions, the nature of the question, and the desired solutions (Jonker & Pennink, 2010). In determining the appropriate approach, to adopt in the course of conducting a research work, it is needful to establish a logic, that links data collection and analysis, in order to yield useful results; and thence conclusion, onto the main research question been investigated (Fellows & Liu, 2009).

Established research approaches are Quantitative and Qualitative methods. These approaches are however, not dichotomous, but refer to separate ends on a continuum of research inquiry. Qualitative research, provides a mechanism for exploring and understanding the meaning, individuals or groups ascribe to a social context (Creswell, 2013), while Quantitative research is useful in testing objective theories, and examining the relationships among variables. It can be argued that Qualitative research is a precursor to Quantitative research (Fellows & Liu, 2009). This is because, Qualitative research provides information on an area of study, which is not well developed, while Quantitative research, tends to better advance understanding in a field where knowledge is relatively developed (Fellows & Liu, 2009). Quantitative research is characterised by adherence to tradition, distinct work and production of reliable figures (Jonker & Pennink, 2010). Qualitative research has more subjective elements than Quantitative research, and the considerations and assumptions of the researcher will need to be explicitly stated.

Quantitative method of research stem from an established academic tradition, and draws it validity from familiar and established scientific techniques (Amarantunga *et al.,* 2002). Quantitative research methods include surveys, true experiment, quasi-experiments, correlational studies, complex experiments, and elaborate structural equation models (Creswell, 2013). Qualitative methods, on the other hand, include ethnography, grounded theory, case studies, phenomenological research and narrative research (Creswell, 2013). It should be noted that, case studies could embody Quantitative and Qualitative elements, and often involves a heterogeneous mix of research methods (Hartley, 1994). In certain situation, the quantitative and qualitative research methods could be combined sequentially or concurrently, and this is often termed a 'mixed-method' research approach (Amarantunga *et al.,* 2002; Fellows & Liu, 2009).

4.2.2.1 Research Method

In this current study, a case-study research method is considered suitable for investigating the critical issues in whole-life costing, and provides a useful basis for testing, the developed new whole-life cost framework for retrofit options in office buildings. The case study research method allows for an elaborate understanding of underlying realities (Amarantunga & Baldry, 2001). The case study research method encompasses heterogeneous activities covering a range of research methods, and techniques (Hartley, 1994).

Yin (2014) defines a case study as an empirical inquiry, that investigates a phenomenon in-depth, especially when the boundaries between phenomenon (in this case, whole-life costing), and context (that is, office retrofit building projects) may not be clearly evident. Miles and Huberman (1994) add that, a case-study is the best-suited approach to deepen understanding and explain processes in building scenarios. This implies that, information on mere frequencies or incidences are unlikely to provide a sufficient basis, in fulfilling the aim and objectives of the research work. In a case-study method, behaviours cannot be manipulated, which allows researchers new insights into the performance of a system under investigation. The essence of a case study approach is therefore to illuminate a decision, or sets of decisions, why they were taken; how they were implemented; and with what results (Yin, 2014). Amarantunga and Baldry (2001) posit that, case studies are useful in identifying, articulating, and understanding patterns and linkages of theoretical importance.

According to *Gleeson et al.,* (2011), the case-study method has been the most common research method used in examining retrofit initiatives. Case-study buildings could however, relate to real-life or virtual prototypes. Ma *et al.,*(2012) reckons that most studies on retrofit buildings are a product of virtual, rather than real-life prototypes. This results from the need to circumvent the lack, and unreliability of data prevalent in building studies (Caplehorn, 2012). It could also be a product of the complex considerations, which affect building investment situations. In which case, virtual prototypes provide a more convenient, and economical way of investigating the complex interactions of building elements (Farr, 2011).

The sources of data in a case study includes documentation, archival records, interviews, direct observation, participant-observation, and physical artefacts (Yin, 2014). The selection of cases in a case-study research approach, tends to involve discretion and judgement, and choices are often informed by accessibility and exhibition, of appropriate features (Amarantunga & Baldry, 2001). Other considerations in the selection of cases relate to, the availability of resources and time for the research work.

Given the relatively limited information on office retrofit projects, one retrofit building case in the UK (SPACE project), and another building case in the US (Medium-sized (MS) building) were selected, to examine the identified issues in the whole-life costing of office retrofit buildings. The SPACE project, has been selected as a result of being one of the most innovative retrofit office projects in the United Kingdom, and in which cutting-edge retrofit interventions have been used. The Medium-Sized (MS) office building was also selected as a result of the availability and access, to a robust set of proprietary cost data, collected by a group of researchers in the United States. These two cases are used to provide data for the study on the whole-life costing of office retrofit buildings. The evidence from multiple case-studies has often been considered more compelling, than individual cases alone (Amaratunga & Baldry, 2001, Rowley, 2002, Yin, 2014). Hence, these two building projects will enhance the robustness of the study, and establish a more convincing basis for the contribution to knowledge. The focus on two case studies will also establish a basis for literal replication, and it is anticipated that this can be extended to other case studies.

A common criticism of the case-study method, nonetheless, is its acclaimed lack of rigour and predisposition to bias (Amarantunga & Baldry, 2001, Rowley, 2002). Yin (2014) adds that the perceived inability to generalize findings to any broader level dissuades some researchers from utilising the case study approach in some situations. Sherratt (2013) argues that generalisation is not the sole purpose of research, and there is a more fundamental task of capturing the facets of reality. There is however, need to emphasize that, the case study method provide a powerful means of conducting research into complex situations, involving contextual conditions.

4.2.3 Research Design

The case study method provides a robust research approach for understanding the issues associated with the whole-life costing of office retrofit buildings. It is however, important to identify and conceptually appraise the critical issues that influence whole-life cost estimates in office retrofit buildings. It is equally important, to establish the place of elaborate uncertainty representation, in the whole-life costing framework. The cost data used in this study has been operationalised, and tested, and therefore provides a sufficient basis for examining, how retrofit decisions are influenced by revocability and disruption, in whole-life cost scenario. This work also investigates the prospects of reaching more-informed decisions in office retrofit building projects. This study commenced with highlighting perceived deficiencies in existing whole-life cost models, and developed an improved framework to assist decision-makers in office retrofit building scenarios.

According to Yin (2014), a research design provides the blueprint for the research work, and addresses four main questions – what questions to study?; what data are relevant?; what data to collect?, and how to analyse the results? The research design therefore, describes a flexible set of assumptions and considerations that connect theoretical notions, and elements to a dedicated plan of action (Jonker & Pennink, 2010).

Rowley (2002) highlights five components of the research design that are especially important in a case study method. These are –

1. The study question,
2. The study proposition,
3. The unit of analysis,
4. The data analysis technique and
5. The method for interpreting the findings

4.2.3.1 Study Question

The **Study question** in this study is:

"How are retrofit decisions influenced by revocability and disruption, in whole-life cost scenarios?"

Given the complex and intricate issues in whole-life cost modelling, focusing on specific issues in the whole-life costing of office retrofit buildings, provides an avenue for assessing and enhancing the performance and credibility of whole-life cost models, and ultimately providing better decision-support, for stakeholders in retrofit building scenarios.

The concepts of revocability and disruption in office retrofit building projects, has been identified as relevant issues in the Built Environment literature (Gleeson *et al.,* 2011; Verbruggen *et al.,* 2011). Revocability, connotes the potential for variability in future cost projections in a building, over its estimated life. Disruption relates to the diminished building use, or unusability, over a period of implementing a retrofit initiative. The newly developed whole-life cost model incorporates revocability and disruption into its framework, and appraised their impacts on the whole-life cost estimates of buildings.

4.2.3.2 Study Proposition

A **Study proposition** directs attention to something that should be implemented and examined within the scope of the study (Yin, 2014). This work therefore proposes to apply the principles of fuzzy logic, to modelling uncertainties in the future cashflows in the New-Generation Whole-life cost model, as well as the cost of disruption, in office retrofit building scenarios. The uncertainties of interest, in the future cashflows, will refer to the probabilities of occurrence of cashflows, and the variability in cashflow values, over successive time periods. Fuzzy logic will also be used in evaluating the cost of disruption based on the various retrofit technologies, identified in specific projects.

The study also proposes to rank the estimates of this newly developed model, and compare the outcomes with existing whole-life cost models. This statistical comparison is based on the Spearman’s rank correlation test, and has the benefit of highlighting the ordinal differences in the ranking preferences of the existing whole-life cost models, and the newly developed Fuzzy New-Generation Whole-life Cost model.

4.2.3.3 Unit of Analysis

The **Unit of analysis** are selected cases of Office retrofit building projects. Two cases are utilised in this study. The first case is a Grade II listed building in the UK, called the SPACE retrofit building project, which was first constructed as a primary school building in the 1930s, and is currently being converted into a multi-tenanted office building. The current occupants of the SPACE building, consist mostly of social enterprises and community charities. The building has a net lettable area (NLA) of approximately 1,800m^2 of office accommodation. The second case is an office retrofit building in the US; 3-storeys tall, and is a typical masonry medium-sized (MS) building (meeting the ASHRAE 90.1-1989 Code), approximately 5,500 m^2 net lettable area (NLA). Prior to the retrofit work, the MS building has been in existence, for twenty years. The distinctive features of the building includes single-pane windows with 20% glazing, and roof-top, packaged air-conditioning.

4.2.3.1 Data Analysis Technique

The **Data analysis** techniques used in this study are Sensitivity analysis, Scenario analysis, and Pattern matching. Pattern matching has been considered one of the most desirable techniques, in case-study analysis. According to Yin, (2014) four analytic strategies used in evaluating case study data include relying on theoretical proposition; working data from ‘ground-up’; developing a case description, examining plausible rival explanations. Amarantunga & Baldry (2001) posit that the overall quality of pattern matching in case study method, can be enhanced by using statistical quantitative measures. This work will therefore utilise the Spearman’s rank correlation test, to compare the rankings of respective whole-life cost estimates, and will analyse the Spearman’s correlation coefficient by examining plausible rival explanations using the Critical Values provided by Hayslett (1981).

4.2.3.4 Method of Interpreting Findings

This approach is used to link the data, to the study proposition. This comparison implemented in two different cases, helped in strengthening the internal validity of the exercise. The data analysis procedures will be expounded upon, in subsequent sections. Finally, attention is given to the construct validity, reliability and generalizability, of the study. Hypothesis generated in the Spearman’s rank correlation in which, a *P-level* of 0.01 and 0.05, is used to demonstrate that the observed findings are statistically significant, and therefore, provides a basis to draw robust conclusions. The limitations of correlational studies are also touched upon in the subsequent sections.

4.2.4 Research Techniques

According to Yin (2014), the essence of a case study, is fundamentally to illuminate a decision or sets of decisions; why they were taken, how they were implemented and with what results. The case study, in itself, does not intend to mimic a sample of a larger population, but to provide a basis for literal replication (Amarantunga *et al.,* 2002). However, retrofit options generated within selected case study projects, could provide data amenable to analytic generalisation.

4.2.4.1 Data Collection Procedures

Data collection primarily involves accumulation of relevant information on a subject matter, such that maximum amount of accurate information is meaningfully acquired by the researcher(s). Data can be collected ‘first-hand’ or ‘second-hand’. First-hand data are raw data about the immediate situation, while ‘second-hand’ data are derived from first-hand sources, and are contained in reports and other documents (McNiff & Whitehead, 2009).

First-hand data was obtained on the SPACE building project. This involved obtaining documents and reports on the project, as well as interviews, with the project team – Client (Castle Rock Edinvar) and Green Energy Partnerships (Environmental Consultants, report and cost consultant). Some of the information obtained on the SPACE building project, were processed and further developed, to include more retrofit options than the alternatives considered by the project team. This was done by conducting a dynamic energy simulation analysis, on the virtual prototype using the IES <VE> software. This involved strategic identification of plausible retrofit options, and was informed by trends in the literature.

Second-hand data was also obtained, from the works of Hendricken *et al.,* (2012) on a masonry medium-sized (MS) office building project. Additional cost data – initial cost, maintenance cost, and utilities cost, was provided by Hendricken and his team, upon request. Information on the building characteristics, and primary cost estimation sources, were provided by the Energy Efficiency Hub (EEH) team. The data obtained from EEH provided exhaustive information on 98 retrofit options, and the cost estimates reported were matched with sources from a proprietary database.

The energy consumption data in the MS project, was modelled using the EnergyPlus energy simulation software.

The biggest advantage of utilising second-hand data, is that it saves considerable time, energy, and resources in data collection (McNiff & Whitehead, 2009). Equally, due to the sensitive nature of cost data, second-hand data sources could provide more depth and breadth, than first-hand data. Also, second-hand data collection could be more appealing, if the data is collected with professionalism and expertise, which could sometime, not be possible for an individual researcher. Second-hand data could however, have serious limitations. The information available may not be specific to the subject of interest, and to the researcher's need (Jonker & Pennink, 2010). There is also a tendency for information to be incomplete, and not readily available. These circumstantial limitations of second-hand data, could affect the quality of the research, and put to question, the suitability of the data. The data could also be far-back in time, and as such, findings could be outdated. The availability of a second-hand data source could however, complement first-hand data, and allow for broader access to scarcely available, commercially-sensitive, data.

4.2.4.2 Sampling

According to Fellows and Liu (2009), the objective of sampling is to provide a practical means of data collection and processing, while ensuring sufficiency in the target population. In retrofit options, sampling is important in order to obtain a representative population on which further analysis can be conveniently conducted, such that the findings can be statistically generalised for the entire population. The full population of retrofit options will consist of an identification of retrofit options, and will involve a permutation of available retrofit technologies. This will yield a number of building configuration permutations (BCPs). Some of these permutations could however, be possible, only in theory, and hence, there could be a need to moderate such permutation exercise, by preference and experience.

The factorial simulation exercise, will require random sampling to be conducted. Random sampling tends to be appropriate, when there is evidence of variation in the population structure. In such situations, there is no reason to ignore the structure in the population, and the sample is sufficiently large (Bryman & Bell, 2015). Non-random sampling, is another type of sampling, and possible categories are systematic sampling, stratified sampling, cluster sampling, convenience sampling and snow-ball sampling (Fellows & Liu, 2009). Systematic sampling involves some elements of randomness. Having determined the sample size, every nth member of the population is sampled. Stratified sampling and cluster sampling, are appropriate when populations exist, in distinct groups or strata. Convenience is used when the nature of the research questions, and the population do not indicate any particular form of sample. Snowball sampling, involves data sources, which are rather difficult to access. Hence, data collection is based on sources, encountered, as the data collection progresses. The snow-balling thus continues, until no new sources are being identified (McNiff & Whitehead, 2009). The snowballing technique yields limited validity, and generalisability in the findings.

In this study, the sampling procedures are more suited to random sampling, although the retrofit options are moderated based on experience and availability. This approach has been termed an “intelligent walk” approach, by Hendricken *et al.,* (20123). Out of the 99 retrofit samples identified in the MS project, only 22 options were recognised as having competing whole-life cost estimates, and these were selected based on comparing the Initial Capital costs and Future costs. The 22 retrofit options identified and used, in the study, are a summary of the options, which are considered as having potentials for economic savings, over the life of the building.

In the SPACE project, only 5 retrofit options were considered in the original work. This was due to the classification of retrofit solutions, which essentially consists of a package of retrofit technologies. Upon further research and discussion with the cost consultant and project team members, an additional five retrofit options were added in order to aid the comparability and robustness of the exercise. Thus, 10 retrofit options were considered in the SPACE case study project, in this work.

4.2.4.3 *Simulation Packages Used*

Energy simulation play a vital role in analysing the performance of retrofit options (Ma *et al.,* 2012). In this study, the Integrated Environmental Solutions Virtual Environment (IES<VE>) software, has been used in the SPACE project. Energy data obtained on the MS Office building, was modelled and evaluated, using the EnergyPlus software for dynamic energy simulation, and this was used in assessing the energy performance of the buildings. In an empirical study by Kensek *et al.,* (2013) it was found that the choice of the energy simulation software, does not significantly alter the predicted energy consumption pattern. It is however, important to utilise a versatile energy simulation package, in order to improve the reliability of the energy-performance predictions of retrofit options in respective buildings.

4.2.4.4 Assumptions used in Simulation

Energy simulation packages are based on a number of assumptions. Some of these assumptions are difficult to discover (Kensek *et al.,* 2013). The characteristics of the IES<VE> and EnergyPlus softwares, are used in this study, and their major assumptions are explained. The IES<VE> software has dynamic thermal simulation capabilities, and allows robust comparison of retrofit technologies (Parker *et al.*, 2012). The IES<VE> is an integrated suite of applications linked to a common user interface, and provides an environment for the detailed evaluation of building and system designs, allowing them to be optimized with regards to energy use (Crawley *et al.,* 2013).

EnergyPlus works based on a thermal balance method, which considers elements in the model as independent surface (Kensek *et al.,* 2013). It tends to utilise simultaneous modelling procedures (Wang *et al.,* 2012). It is versatile, and is a highly popular energy simulation package, widely used in both research and industry (Heo *et al.,* 2012).

Based on the compilations of Crawley *et al.,*(2013), IES<VE> and EnergyPlus provide sufficient and relevant platforms, for energy-quantification of retrofit options in office buildings. The respective unit cost of energy – electricity and gas, for the SPACE project was obtained from the energy providers of the client. As of the time of this investigation, Gazprom supplies gas at a unit cost of 2.88p/kWh, while Swalec supplies electricity at a unit cost of 11.28p/kWh. The unit costs of electricity and gas in the MS office building projects, were obtained from the U.S. Energy Information Agency (EIA) for both Natural Gas and Electricity prices, in the commercial sector. According to the EIA, electricity in the MS office building project will cost 10.83 c/kWh and Gas will cost 8.06c/kWh, based on the year 2015 estimates.

4.3 Data Analysis Method

Data Analysis is an important step in interrogating data, towards deriving and identifying patterns, that could be useful in providing improved insights and understanding of the research problem being investigated. Data analysis is an organised, systematic, and objective approach of assembling information towards making inference deduction. The purpose of analysing data, is to provide information about variables and, the relationships between them (Amarantunga *et al.,* 2002). Rowley (2002) advised that, in case studies, the preferred strategy for analysis is to develop propositions, which aligns with the objectives of the study, and considered in the data collection process. In this research, Scenario analysis, Sensitivity analysis and Pattern-matching, are the data analysis techniques, employed in analysing the data from the case study projects.

4.3.1 Scenario Analysis

Porter (2008) defines a scenario, as an internally consistent perception of the future, and constitutes one possible outcome. Scenario analysis, involves the development of different sets of scenarios, commencing from the present situation, and the extrapolation of issues considered important in a framework. Scenarios are invaluable tools in taking a long-term view of events, in a world of great uncertainty (Blyth & Worthington, 2010). Scenarios help highlight reasoned, underlying judgments about the future, and give explicit attention to sources of uncertainty without necessarily turning them into a probability (Goodwin & Wright, 2009). The problem with scenario analysis however, is that it examines the future based on the current situation, and an unanticipated event can render prospective scenarios redundant. Equally, there is a limit to the number of scenarios that can be realistically generated, and this approach is therefore limited. An approach that allows for better use of the scenario analysis techniques will involve the use of system dynamics techniques, to simulate the scenarios, as events unfold (Greden, 2005). However, system dynamics will require better understanding of the significance of the effects of these identified issues in whole-life cost scenario. Hence, the study will highlight the plausible scenarios for a discrete range of future outcomes.

In the whole-life costing of retrofit office buildings, the pertinent issues identified for investigation are Discounting, Revocability and Disruption. These issues will be evaluated in the following scenarios

Scenario 1: Time Discounting and Revocability

Scenario 2: Time Discounting, Revocability and Disruption

The whole-life cost estimation in each scenario will be examined, and Sensitivity analysis on the discount rates, over a specified numbers of years, will be conducted. The rankings of the whole-life cost estimates will also be analysed, based on the Spearman’s rank correlation test, and the results are interpreted and discussed.

4.3.2 Sensitivity Analysis

Goh and Sun (2015) had previously stated that, the application of whole-life costing necessitates the use of sensitivity analysis. Sensitivity analysis can be defined as the study of the effects of uncertainty on the output of a model (Saltelli *et al.,* 2010). Sensitivity analysis helps to identify, and examine, the extent of robustness of the choice of an alternative, based on systematic variation of a base case. Ma *et al.,* (2012) reckons that the whole-life cost of building retrofits, is subject to only small changes, so long as optimal strategies are chosen. This suggests that a strategic comparison of competing building retrofit options, should require the use of sensitivity analysis.

According to Farr (2011), the premise of any sensitivity analysis lies in the “what-if” concept of decision-making. The procedure for implementing sensitivity analysis involves isolating key variable(s), thereby evaluating the effect of changes in the values assigned to the key variable(s). Usually, this is achieved by examining a discrete number of points, around the deterministic value, for the economic parameter. For the current study, the discount rate is considered a key uncertain variable in whole-life costing, and the declining discount rate values suggested by the HM Treasury (2013) will be implemented in the whole-life cost estimation of retrofit options.

Sensitivity analysis helps in determining the impact of variables on a projects' expected outcome, by assuming a given variation in each significant variable at a time, with other variables held constant (Keršytė, 2012), and could provide information on the area that requires most managerial attention. Sensitivity analysis however, has its drawbacks; it assumes that only one variable changes at any one time, and that there will be no corrective or preventative measures, taken in response to any change in that variable (Yao & Jaafari, 2003). It also does not consider the probability of occurrence, associated with both the variable and project outcome (Keršytė, 2012).

4.3.3 Pattern-matching

Pattern matching is one of the most desirable techniques in analysing case study data (Yin, 2014). In Built Environment literature, Pattern-matching has been used in analysing the skill requirement for IT project managers' (Napier *et al.,* 2009). Pemsel & Wiewiora (2013) also used pattern-matching in analysing the functions of project management offices. Pattern matching is particularly useful, in comparing an empirically-based logic with a predicted one. In the study of office retrofit building projects, the whole-life cost values of the two projects under consideration – SPACE and the MS office building unit, can have their patterns assessed for theoretical replication. In using pattern-matching, the basic comparison could involve statistical criteria, and in this situation, the Spearman's rank correlation test, provides a relevant framework to compare the rankings of different whole-life costing techniques. The pattern-matching technique is implemented in order to compare the results of the newly-developed, Fuzzy New-Generation whole-life costing technique with existing whole-life costing techniques. This specific objective is pivotal in highlighting an important contribution to knowledge of this study.

Recourse to ranking is necessary, in instances, where a researcher who possesses quantitative values may question the suitability of such for comparison, and wish to draw conclusions only from the order of magnitudes observed (Fisher & Yates, 1974). Rank correlation therefore becomes a useful procedure in interrogating whole-life cost data. The rationale behind focussing on the order of magnitudes, rather than only the exact values, is based on the conceptual purpose of whole-life costing, as primarily enhancing the systematic comparison of competing alternatives. The Spearman's' rank correlation test is used to compare the relationship between ordinal or rank-ordered variables. The correlation ratio represents the proportion of variance, accounted for, by the population membership (Cohen, 1988).

In order to assess the significance in the difference in rankings of the whole-life cost techniques, a hypothesis could help in establishing clear-cut levels of statistical significance. A hypothesis connotes a conjecture of the relationship between certain variables, believed to be influencing the behaviour of a system. These variables are commonly classified into, dependent variables and independent variables. The dependent variable is the response, which is presumed to be influenced by the independent treatment condition. Three outcomes on the dependent variable that are worthy of being noted in a hypothesis testing scenario, are the direction of observed change, amount of change, and the ease with which the changes occur (Creswell, 2013). The hypothesis also plays a vital role in establishing the central focus of a study by delineating the boundaries of the study (Fellows & Liu, 2009). It equally becomes a necessary imperative that a hypothesis be positive, testable, and expressed in clear and unambiguous language (Schick & Vaughn, 2007).

In the assessment of the rankings of respective whole-life costing techniques of retrofit options, two sets of hypotheses are tested. Each hypothesis proposed is aptly defined in terms of the null hypothesis and the alternative hypothesis. The Null Hypothesis suggests that the observation is the result of chance circumstances only, while the Alternative Hypothesis argues that, the observation is the result of certain variable(s).

The first set of hypotheses in the pattern-matching exercise can be explicitly stated as follows:

The **Null Hypothesis** can be generally expressed as:

$H_{0,\,n,r}$ – The rankings for the “X”’ technique and the “Y” technique are independent at a discount rate of n% over a r-year period.

On the other hand, the **Alternative Hypothesis** can be expressed as:

$H_{A,\,n,r}$ – The rankings for the “X” technique and the “Y” technique are positively correlated at a discount rate of n% over a r-year period

Where, n is the discount rate values, (which can be 3%, 5%, 7% and 9%) broadly consistent with the range specified in the expansive works by Harrison (2010), and Goh and Sun (2015); r is the projected number of years in this study (which can be either 20, 40, or 60 years), also consistent with the expected life-span of retrofit technologies, in line with the BREEAM requirement, and also noted in the study by Ashworth and Perara (2013). It also represents a plausible range across the building and construction management literature.

The “X” and “Y” techniques could refer to any of the following techniques - Standard Whole-life costing (WLC), New-Generation Whole-life costing (NWLC), Fuzzy-Lower New-Generation Whole-life costing (FL-NWLC), Fuzzy-Mean New Generation Whole-life costing (FM-NWLC), and Fuzzy-Upper New-Generation Whole-life costing (FU-NWLC).

Each set of hypotheses are tested at confidence levels of 0.01 and 0.05, to allow a broad range of tolerance, and avoid Type-1 and Type-2 statistical errors. Type -1 errors refer to the probability of rejecting the Null hypothesis when it is true, while Type-2 errors refer to the probability of accepting the Null hypothesis, when it is incorrect (Creswell, 2013).

According to Corder and Foreman (2009), the Spearman’s rank correlation order is designed for situations where the sample size is more than, or equal to four. Gaten (2000) however, argues that the realistic sample size should range between 7 and 30. One of the most quoted works on Spearman’s rank correlation was carried out by Cohen (1988). Cohen’s’ work provided a description on the relative strengths of correlation coefficient as shown in Table 4.1

Table 4.1.*Relative strength of Correlation Coefficient (Cohen, 1988)*

Correlation Coefficient for Direct Relationship	Correlation Coefficient for Indirect Relationship	Relationship strength of the variables
0.0	0.0	None/trivial
0.1	-0.1	Weak/Small
0.3	-0.3	Moderate/Medium
0.5	-0.5	Strong/Large
1.0	-1.0	Perfect

Cohen's (1988) work however, has limited applicability especially for the current investigation on whole-life costing. First, the relative strength of the correlation does not provide an informative basis for testing hypothesis outside the prescriptive values specified. Also, Cohen's work is largely based on behavioural science research, so the values could be limited in built environment research. These values however, suggest a basis for discussing the range of period, over which the validity of whole-life costing may be specified.

Hayslett (1981) provided a table of critical values, shown in Table 4:1, for testing the hypothesis based on the number of samples. The critical values reported in Table 4:1, is used in testing the null and alternative hypothesis, for the building configuration permutations, in the SPACE and MS office retrofit building projects, as it provides a more relevant basis for the research questions, addressed in this work.

Table 4:1 Critical Value of Spearman's rank Correlation Coefficient (Hayslett, 1981)

Number of Items	**α-values (one-sided)**	
	0.05	**0.01**
4	1.000	-
5	0.900	1.000
6	0.829	0.943
7	0.714	0.893
8	0.643	0.833
9	0.600	0.783
10	0.564	0.746
12	0.504	0.701
14	0.456	0.645
16	0.425	0.601
18	0.399	0.564
20	0.377	0.534
22	0.359	0.508
24	0.343	0.485
26	0.329	0.465
28	0.317	0.448
30	0.306	0.432

The mathematical formula for the Spearman's' rank order correlation, if none of the rank values are tied is:

$$r_s = 1 - \left(\frac{6\sum D_i^2}{n(n^2 - 1)} \right) \qquad (Eqn\ 4.1.1)$$

Where n = number of rank pairs and D_i = Differences between ranked pairs

If ties are present in the values, the formulae for the Spearman's rank order correlation is as follows:

$$r_s = \left(\frac{(n^3 - n) - 6\sum D_i^2 - (T_x + T_y)/2}{\sqrt{(n^3 - n)^2 - (T_x + T_y)(n^3 - n) + T_x T_y}} \right) \qquad (Eqn\ 4.1.2)$$

Where

$$T_x = \sum_{i=1}^{g} (t_i^3 - t_i) \qquad (Eqn. 4.1.3)$$

and

$$T_y = \sum_{i=1}^{g} (t_i^3 - t_i) \qquad (Eqn. 4.1.4)$$

Where g = number of tied groups in that variable and

t_i = the number of tied values in the tied group.

The alternatives to the Spearman's rank coefficient test, are the Kendall's Tau coefficient and the Fisher-Yates Coefficient. They both provide comparable result 'to the Spearman's coefficient, and all lie between ranges of -1 to +1. The major difference between the Kendall's Tau coefficient, and the Spearman's correlation coefficient, is that the Spearman measures the magnitude of the difference regarding observed data, which are in the same order, versus observed data that are not, in the same order. The Kendall's Tau coefficient on the other hand, measures the magnitude of the probabilities of observed data that are in same order, versus observed data that are in different orders. Hence, the Spearman's rank correlation measures magnitude; while the Kendall's Tau measures probabilities.

The Fisher-Yates Coefficient also called, the Normal Scores, is obtained by replacing paired ranks by scores, defined marginally then calculating the product-moment correlation coefficient (Fisher & Yates, 1974). The Fisher-Yates method, has greater power of discrimination, than both the Kendall's Tau, and the Spearman's, but is more computationally demanding. The Fisher-Yates coefficient are however, less used in practice, and the Spearman's rank correlation provide a sufficient context for the current work.

4.3.4 Caveats about the Study

It is expected that every research work will be based on certain pre-conceived notion of the researcher(s), and will by implication give certain procedures, more attention, over and above, some others. In this study, the critical issues associated in whole-life costing are discounting, revocability and disruption. In order to justify and rationalise these choices, these study will state certain caveats, which needs to be considered in the following measures:

4.3.4.1 Construct Validity

Construct validity refers to the degree to which a conceptual model accurately reflects the specific theoretical concepts that the researcher is intending to measure (Jonker & Pennink, 2010). The Construct validity of this work has been addressed by using multiple sources of knowledge, and two case study projects from different geographical locations as well as different data sources.

4.3.4.2 External Validity

External validity refers to the degree, to which the result obtained in one study, can be replicated or generalised, to other samples, research settings, and procedures (Fellows & Liu, 2009). The external validity in this work is considered moderate, as the intention is to establish analytical generalisation rather than statistical generalisation, for office retrofit building projects. The framework could however, be extended to other retrofit projects in the future, and could also include more qualitative cost variables.

Specifically, Semi-structured interviews were conducted with six members of the project team on the SPACE project, to externally validate the basis of the proposed model. The kind of interview carried out is a qualitative research interview, and its primary purpose, is to gather interpretations of the worldview of the interviewee with respect to the basis, of the newly developed model. This approach follows on the guidelines stipulated by King (1994), in that, the interview is conducted after a quantitative study has been carried out, and the interviews aim to validate particular measures, or clarify and illustrate the meanings of the findings. In this case, the interviews are used to test the basis of the newly developed Fuzzy New-Generation Whole-life Cost model. The results from this validation, has been reported upon, in Chapter 9 of this thesis.

4.3.4.3 Internal Validity

Internal validity refers to the degree to which a researcher, draws accurate conclusions about the effect of an independent variable (Fellows & Liu, 2009). The internal validity focuses on the manner in which the results supports the conclusions. In other words, internal validity provides a check on whether or not, what was identified as the causes, actually produce what has been interpreted as the "effect" or "responses" (Amarantunga *et al.,* 2002). The statistical measure of the correlation coefficient of respective models, have been assessed based on Hayslett's (1981) critical value of the Spearman's rank correlation. This comparison implemented in two different case studies, helped in strengthening the internal validity of the exercise, and enhanced the internal validity of this work.

4.3.4.4 Reliability

Reliability refers to the degree of replicability of the study, if conducted again (Yin 2014). The goal of reliability is to minimise errors and biases, in a study (Amarantunga *et al.,* 2002). It basically draws its value, from the integrity of the research design, and the explicitness of the research methodology. The reliability of this work is enhanced by the explicit reporting procedures, and the principles of the models, that have been discussed. This chapter also mentions some caveats about the entire study.

4.4 Summary

This chapter reports on the research methodology aspect of this work. It commences with the research design, and highlights the logical trail of the work – research paradigm, research style, research techniques, and then, the data analysis techniques. The principal considerations of the study has been made explicit, and the rationale behind the research approach has been documented. This chapter also examines the possible limitations of the research style, and the steps taken to minimise pitfalls in the conduct of the research.

Chapter 5 A Fuzzy New-Generation Whole-life Cost Technique

5.1 Introduction

This chapter embodies the major contribution of this work. It details the procedures for implementing the Fuzzy New-Generation Whole-life Cost model as well as the principal assumptions and considerations, in the model framework. The chapter commences with highlighting the parameters of the Fuzzy New-Generation Whole-life Cost model. It then, provides a flow-chart that itemises the procedural step to implementing the Fuzzy New-Generation Whole-life Cost model, for office retrofit buildings. The chapter also discusses the potential benefits of the Fuzzy New-Generation Whole-life Costing model, compared to the existing whole-life cost models.

5.2 Features of the Fuzzy New Generation Whole-life Cost Technique

Having considered the deficiencies in existing whole-life costing models, it was decided, that a fuzzy logic approach to uncertainty modelling and the explicit inclusion of qualitative variables, has the potential to enhance robustness in whole-life modelling. One benefit of this approach is that the effects of time discounting (using declining rates), revocability and disruption, will be evaluated, and considered in office retrofit buildings. This new model aims to provide a robust analytical framework within which the strength of influences of identified cost variables, can be better examined and understood.

Fuzzy logic has also been previously used, in the evaluation of subjective variables in whole-life cost scenarios (Kishk *et al.,* 2003, Goh & Sun, 2015), and this constitutes a tangible benefit in office retrofit buildings where relevant cost variables could be more readily expressed in linguistic terms. The fuzzy logic approach is also reputed to provide more realistic evaluations in whole-life costing scenarios (Kishk 2004, Wang *et al.,* 2004, Ammar *et al.,* 2013). The critical issues in the whole-life costing of office retrofit buildings, includes cost of revocability, cost of disruption, and time discounting of money. However, another important recognition is that, uncertainty intersperses all the identified issues in the whole-life costing of office retrofit buildings. It can therefore be argued that, the principal phenomena in whole-life costing, remains the modelling of uncertainties.

The Fuzzy New-Generation whole-life cost model, is based on a mathematical algorithm. The rationale for this approach, is to address the limitations in existing whole-life cost models. It is suggested that future research should explore alternative cost modelling procedures, in whole-life costing of office retrofit buildings. It is anticipated that a robust mathematical whole-life cost model, will serve as a useful benchmark, for the application of alternative cost modelling techniques, in whole-life costing scenarios. The Fuzzy New-Generation whole-life costing framework therefore, permits the examination of relevant issues, in retrofit scenarios. It is however, expected that the variables identified in the Fuzzy New-Generation Whole-life Cost model, can also be represented in a Simulation and Finite-Element framework. It is also anticipated that these alternative cost modelling approaches, will generate new insights on the science of whole-life costing and hence, future research could explore this area of inquiry. Future research should also consider the development of hybrid whole-life cost modelling techniques, which can bring together the strengths of mathematical modelling and simulation in the whole-life costing of buildings. The next section will provide an overview of the procedural implementation of the Fuzzy New-Generation Whole-life Costing model for office retrofit building projects.

5.3 Procedural implementation of the Fuzzy New-Generation Whole-life Costing Technique

The Fuzzy New-Generation Whole-life Costing technique, provides an alternative mathematical framework, to appraise the whole-life costs of office retrofit buildings. The principal inclusion of the Fuzzy New-Generation Whole-life Costing technique is the evaluation of the cost of revocability, and the cost of disruption. The Fuzzy New-Generation Whole-life Costing Technique yields, three variants of whole-life cost estimates termed the Fuzzy Lower NWLC, Fuzzy Mean NWLC and Fuzzy Upper NWLC. The Fuzzy New Generation Whole-life costing technique, has an explicit procedure, and there is a need to itemise the procedural steps in office retrofit buildings. The Fuzzy New Generation Whole-life Costing technique has been summarised in a 10-step process flow chart as shown in Figure 5.1 below. Each step is subsequently explained:

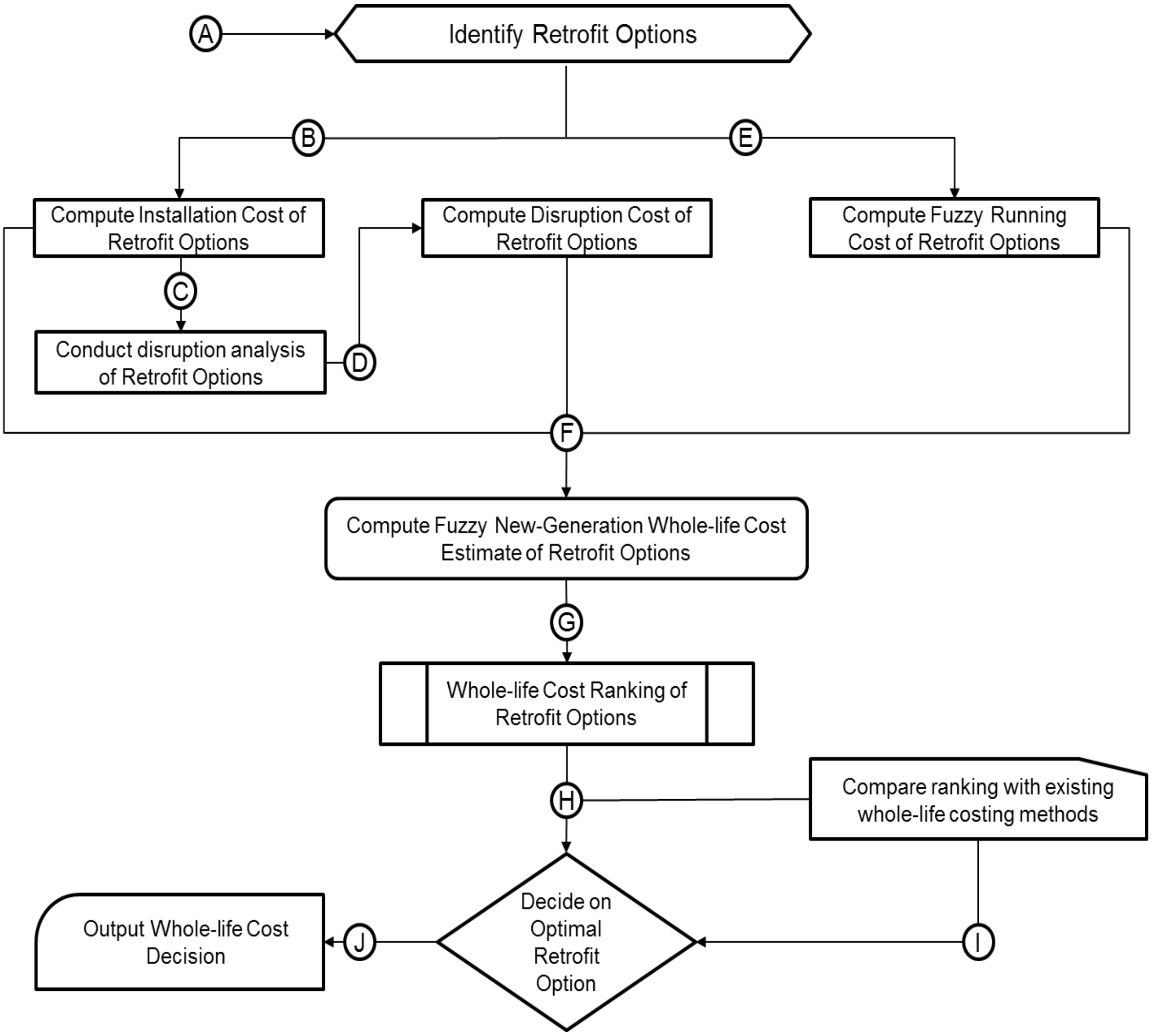


Figure 5-1 Process Flowchart for the Whole-life Cost Evaluation of Retrofit options

STEP A – Identify Retrofit Options

Prior to an estimation of the whole-life cost, the identification of retrofit configurations applicable in respective buildings, needs to be carried out. Ma *et al.,* (2012) advised that each building is unique with different characteristics, hence, retrofit solutions need to recognise the building characteristics, as well as the preference of building stakeholders. Considering the diverse approaches to retrofit solutions, an exhaustive identification of retrofit options will involve a factorial simulation of possible building configuration permutations (BCPs). The numerical formulae for defining the full factorial simulation is given by:

$$N_{BCP} = \prod_{i=1}^{k} n_i \qquad Eqn\ 5.1.1$$

Where, i refers to each sub-system, n_i is the number of energy conservation measures per sub-system, and k is the number of subsystems. The advantage of conducting a full factorial simulation is that it achieves the most exhaustive search for BCPs. The disadvantage of a full factorial simulation is that, the large number of BCPs that requires to be simulated. For example, if there are only three levels for five sub-systems, the total number of simulation required is 243 (3^5). This approach will therefore be computationally demanding, and could yield configurations that are technically infeasible.

An approach to moderate the full factorial simulation is common in practice, in which, a base case energy model can be modelled, after which, the user defines, combines, and simulates BCPs, based on experience and preference. Hendricken (2012) referred to this approach as an "intelligent walk mechanism". The advantage of this intelligent walk approach, is that, it lessens the computational efforts in generating BCPs. However, this approach brings subjectivity into the simulation procedures, and one could potentially miss out, on cost-effective and efficient, retrofit configurations.

This work will therefore attempt to implement a full factorial simulation for the SPACE building project, as the innovative technologies used are two in number and combining them only yields four model runs, which is manageable. An additional 5 runs have been included in the SPACE building project, bringing the total retrofit options to 9. This was done in order to better harness the benefit of whole-life costing in the project. However, the secondary data obtained on the MS office building utilised an intelligent walk approach. This intelligent walk approach provided a total of 98 BCPs, but this has been reduced to 22 BCPs based on like-for-like comparison of competing building retrofit options.

STEP B – Compute Initial (Installation) Cost of Retrofit Options

The installation cost of identified retrofit options can be obtained from a variety of sources. The Installation Cost of retrofit projects, can be provided by contractors (Ashworth, 2004), and tender documents could provide an indication of the possible costs. It should however, be recognised that such cost values obtained from return bids, tend to be variable when different contractors are involved, as they contain the overhead of respective organisations. There is therefore, a significant scope for variability in the installation costs, provided by contractors. More so, the installation costs from Contractors, are mostly based on only one building configuration permutation (BCP). Other sources of Installation costs include historical data, predictive models, and professional judgment (Kishk *et al.,* 2003).

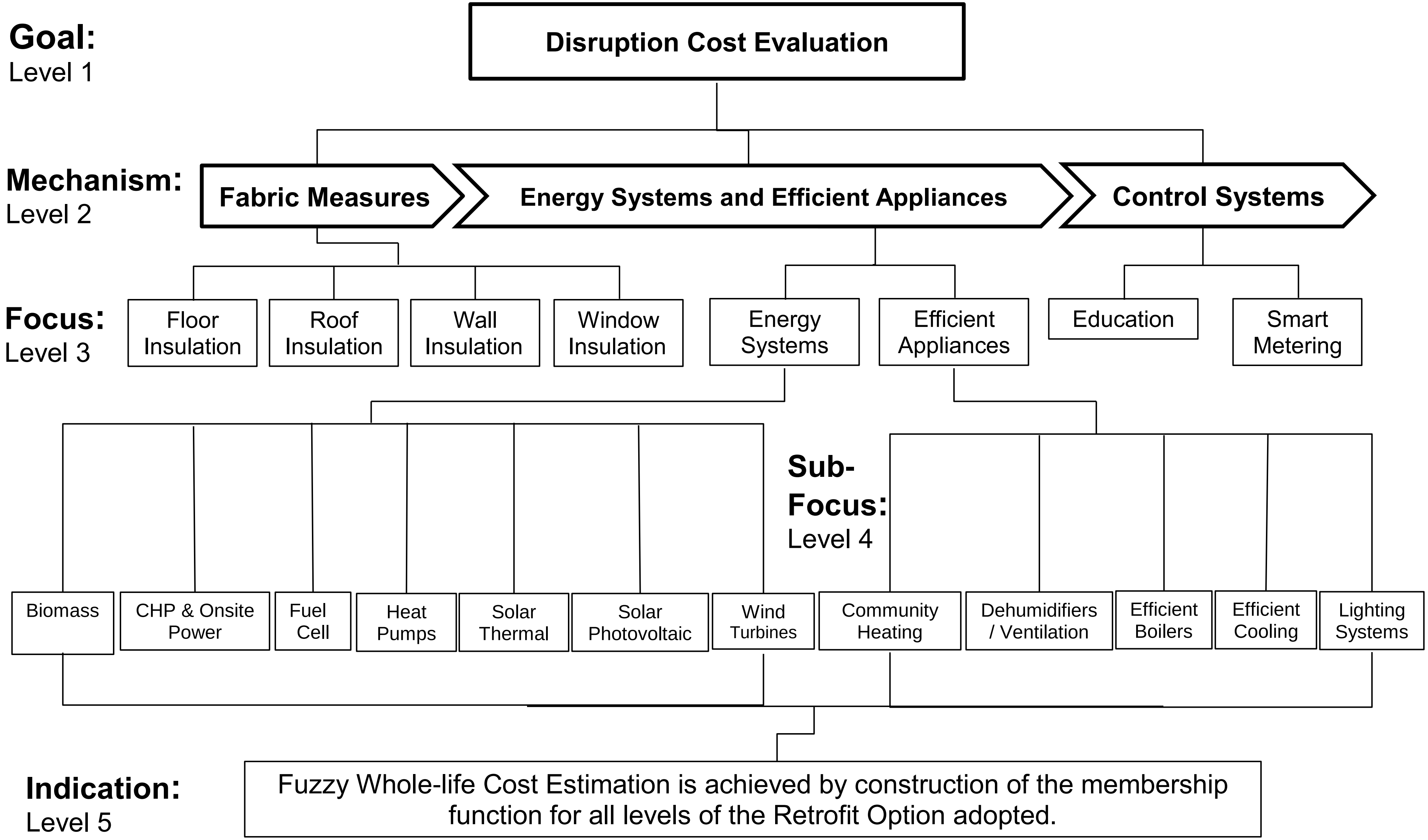
Considering the novel technologies deployed in the SPACE project, Specialist contractors provided the cost estimates of the retrofit solutions. The installation costs for the BCPs in the MS project, was obtained from the work of Hendricken *et al.,* (2012), and the EEH team. Their work utilised the CoStar building database, a proprietary database filtered for cost data on commercial office buildings, in the Greater Philadelphia Metropolitan Region. More on this will be discussed in Chapter Six of this thesis.

STEP C – Conduct disruption analysis of Retrofit Option

The disruption costs of retrofit options can be evaluated, based on the Factor Chart analysis presented in Figure 5-2. It is reasonable to assume that the actual level of disruption will be moderated by project management considerations. The Factor Chart analysis proposes a logical approach to implementing retrofit solutions in buildings. The factors potentially affecting the disruption of business operations, have been mindfully chosen, to reflect the internal relationship between retrofit mechanisms. In Figure 5-2, five levels are hierarchically constructed as Goal: Level 1; Mechanism: Level 2; Focus: Level 3; Sub-Focus: Level 4; and Indication: Level 5. This approach draws from previous risk/revenue evaluation framework by Ayyub (2006).

The rationale behind the Factor Chart analysis is the need to adopt a cost-effective strategy to the implementation of retrofit solutions. The hierarchy of initiatives in the Factor Chart Analysis, also reflect current industry practice. It is advised that fabric measures should precede the use of Energy Systems and Efficient Appliances, after which Control Systems should be adopted (Gleeson *et al.,* 2011, ZCH,2011). Hence, the period of disruption, tend to be incremental, in this order. The use of fuzzy mathematics, as described by Ross (2009), is proposed as more realistic in summing up the time period of disruption. Based on an estimate of the time period of disruption, the overall cost of disruption can be computed.

Also, in terms of the fabric measures, floor insulation tends to be highly disruptive (Gleeson *et al.,* 2011). Internal wall insulation and external wall insulation, tend to be substitute initiatives. Energy Systems and Efficient appliances, can be concurrently implemented, depending on the scope of the retrofit work, skills of the contractors as well as the availability of capital, for the retrofit projects. Smart metering are often minimally disruptive. However this is supplementary, to the existing fabric measures, energy systems, and efficient appliances. The factor chart analysis thus helps, to identify, and bring together project tasks, that can be done concurrently, so as to avoid superfluous measures of the overall disruption time period in the retrofit project.



Fuzzy Whole-life Cost Estimation is achieved by construction of the membership function for all levels of the Retrofit Option adopted.

Figure 5-2 Factor Chart Analysis for Disruption Cost Evaluation in Office Retrofit Building Projects

STEP D – Conduct disruption cost of Retrofit Option

The potential for disruption in retrofit scenarios needs to be considered, prior to embarking on a retrofit initiative (Holmes, 2000). The cost of disruption is a fuzzy estimate, and has often not been given attention in retrofit scenarios. There is however, growing awareness on the effects of disruption in retrofit scenarios (Gleeson *et al.,* 2011, Verbruggen, 2013). There is no evidence that previous research has appraised the effects of disruption in office retrofit buildings. Gleeson *et al.,* (2011) provided a disruption analysis for retrofit initiatives. However the cumulative costs of disruption in office retrofit building scenarios, have not been evaluated.

It is conceivable that the cost of disruption will depend on the nature of operation of the building occupier. 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.

This work will adopt the tolerance values specified by Ayyub (2006), in evaluating the respective cost of disruption, as shown in Table 5:1.

Table 5:1 Table showing Fuzzy Set Values for different levels of Disruption

$ß_j$	**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

Although the work by Ayyub (2006), is based on the variation of elements in a risk/revenue evaluation framework, its procedures are equally relevant for risk/cost evaluation in retrofit scenarios. The disruption of each retrofit initiative on the overall cost is embodied in vague measures of Low, Medium, and High. The disruption levels of retrofit initiatives, according to Gleeson *et al., (2011),* can be classified as Low, Medium, and High. These vague metrics of Low, Medium, and High will be considered as corresponding to lambda-cut values of 0.2, 0.5, and 0.8. These values have been selected to represent levels of disruption over categories of lambda-cuts, which are not less than 1.0, and provide a measure of uncertainty in each retrofit option. Previous work by Ammar *et al.,* (20113) suggest that lambda-cut values of 0.2, 0.5 and 0.8 provide equivalent cost values analogous to the 25%, 50% and 75% percentiles of probability distributions.

Based on the lambda-cut value of 0.5, the membership function of a retrofit initiative with Medium disruption can be expressed as:

$$\mu_{0.5} = \frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8} \qquad Eqn\ 5.1.2$$

Also, the membership function of a retrofit initiative with High disruption, based on the lambda-cut value of 0.8, will be expressed as:

$$\mu_{0.8} = \frac{0.7}{0.8} + \frac{0.9}{0.9} \qquad Eqn\ 5.1.3$$

Gleeson *et al.,* (2011) reckoned that the disruption days for Low, Medium and High will correspond with, up to 2 days, up to 5 days, and up to 10 days. Gleeson's work is however, based on the disruption level, in typical UK house building, which is a two-storey dwelling, and has a total floor area of 96m^2. To adopt this data, for office buildings, the disruption values will have to be normalised. Normalisation will effectively scale up, or scale down, the days of disruptions, based on the size of the building, as realistically as possible. Each of the retrofit initiative will then be aggregated. Since the disruption level of each retrofit initiative is represented as a lambda-cut set. An illustration of this can be shown in Figure 5-3:

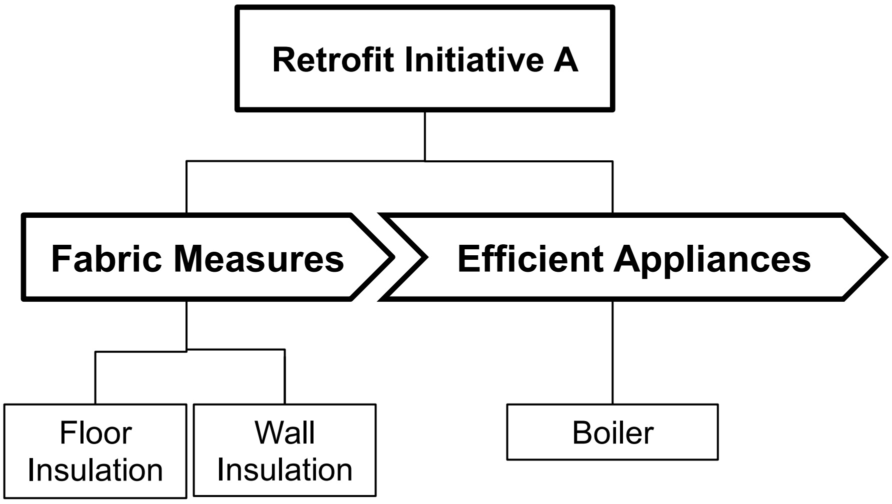


Figure 5-3   Illustrative Retrofit Option for evaluating the Disruption cost.

The disruption level for fabric measures, and efficient appliances, in Retrofit Initiative A, will be estimated based on the disruption values, provided by Gleeson *et al.* (2011)

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

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

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

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

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

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

Using the Max-min composition operation, the Fuzzy Lower, Fuzzy Mean and Fuzzy Upper, for the number of disrupted days in Retrofit A, will now be computed as:

$$\mu_{Disrupted\ days\ for\ Retrofit\ A} = [3.2\ days,\quad 4.8\ days,\qquad 5.6\ days]$$

The estimated number of days of disruption will be based on evaluating the contributions from respective retrofit initiatives, based on the Factor Chart analysis in Figure 5-2. The procedural computation of the cost of disrupted days for each retrofit option, in the SPACE project, are reported in Appendix A-1.

The process adopted here in estimating the cost of disruption in office retrofit building projects, has certain limitations especially due to limited information, on the economic implication of disruption in retrofit projects. This approach is considered to provide, an indicative estimate of the cost of disruption. It is however, advised that future studies should seek alternative ways of appraising the ‘cost of disruption’ in existing buildings. The cost of disruption in this work is computed, by multiplying the cost of disruption for each day in the respective building, by the membership function for number of disrupted days in the retrofit initiative.

Previous work by Hughes *et al.,* (2004), estimated that, in commercial office buildings, the average proportion of “Staff and business operating cost” to “Maintenance and Building Operating Cost” is 30:1. A previous work by Evans *et al.,* (2004) found that average proportion of “Staff and business operating cost” to “Maintenance and Building Operating Cost” ratio is 40:1. Both works surmise that the ratios are estimated for a 25-year operational life.

In order to estimate the disruption cost, expenditures on Staff and business operating cost will have to be estimated. The Maintenance and Building Operating Cost per Year of the Retrofit A in the SPACE project is £143,800 (to nearest hundredth). The estimated Annual Staff and Business Operating Cost of Retrofit A can be estimated as (30 x £143,800) / 25 = £172,600 (to nearest hundredth).

Assuming a 253 Working Day in a Year. The daily cost of disruption incurred in the Retrofit wok for the SPACE project, is estimated to an equivalent sum of £680 per day.

For Retrofit A, the cost of disruption can now be estimated as

$$\mu_{Disrupted\ days\ for\ Retrofit\ A} = [3.2\ days, \quad 4.8\ days,\ 5.6\ days]\ \text{x}\ \text{£680}$$

$$Cost\ of\ Disruption\ for\ Retrofit\ A\ (C_d) = [\text{£2200}, \quad \text{£3300}, \quad \text{£3,800}]$$

The disruption cost of £2200, £3200 and £3800, correspond to the Fuzzy Lower, Fuzzy Mean, and Fuzzy Upper, cost of disruption. This implies that for the **Retrofit A** option, the overall cost of disruption will range between £2,200 and £3,800 in the course of installing the retrofit solutions.

STEP E - Compute Fuzzy Future Costs of Retrofit Options

The Fuzzy future costs of retrofit options will be conducted in three steps involving the derivation of the fuzzy relations matrix, aggregation of the fuzzy future cashflows and the defuzzification into Fuzzy lower, Fuzzy mean and Fuzzy upper estimates, denoted as E1, E2 and E3 respectively. For Retrofit A, the input parameters for estimating the whole-life cost can be given as:

Current Annual Future Cost estimate = £32,000

Declining Discount rate = 3.5% (constant over the expected life of the building)

Estimated life of building = 30 years.

The first four years of the Future costs, as shown in *Figure 5-4* based on the binomial option theory will yield the following:

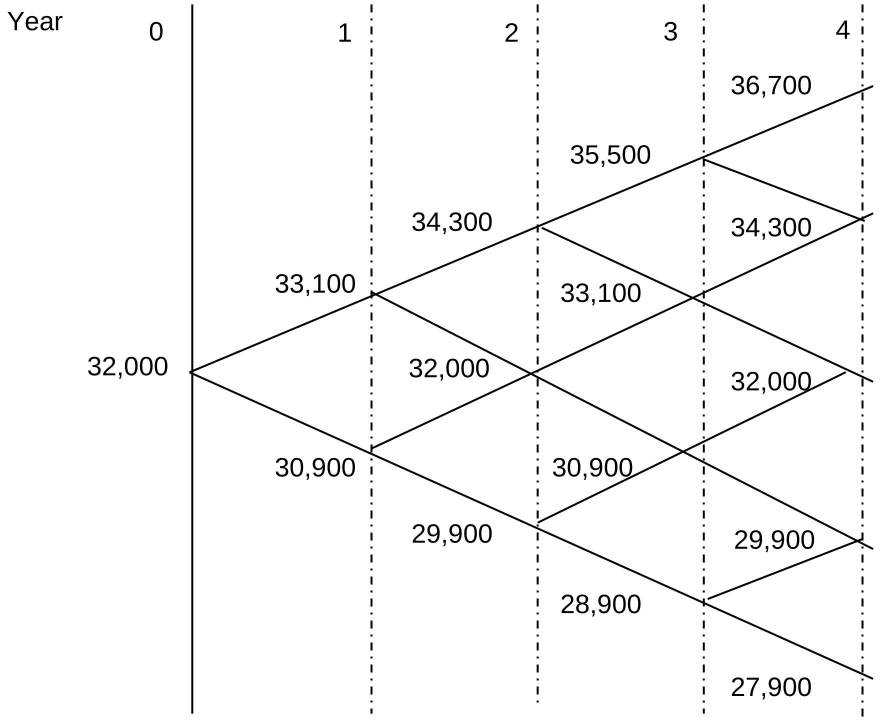


Figure 5-4 Future cost values using the binomial tree framework over 4 years (to nearest, 00)

The procedures for evaluating the future costs, of the newly developed Fuzzy New Generation Whole-life Costing technique, will be presented in the three steps - E1 to E3, below:

E1: Derive Fuzzy Relations Matrix

The Fuzzy Relations matrix is derived, based on the matrix properties of a costing framework (Ross, 2009). The Pascal triangle, as shown in Figure 2-5, represents the respective probabilities of cashflow values, and can be transformed into Matrix form, as shown in Figure 5-5. The benefits of a matrix transformation, is to facilitate the computation of the fuzzy-derived future cost values, which is also in matrix form. A mathematical algorithm has been developed using Python® script, as shown in Section 5.3.1, which converts the entire probability distribution, into a fuzzy relation, using the cosine amplitude formulae, provided in Eqn.3.2.1. This Python® script is used to transform the Negative Binomial probability distribution into a fuzzy relation. The Fuzzy relation, provides a robust template to aggregate the fuzzy values of the Initial installation cost, Cost of disruption, Future costs, and the Cost of revocability. The Fuzzy Relations matrix thus yield, different fuzzy future cost values.

$$\begin{bmatrix} 1.00 & & 0.82 & & 0.72 & & 0.66 & & \cdots & \\ & 1.00 & & 0.95 & & 0.89 & & 0.85 & & \cdots \\ 0.82 & & 1.00 & & 0.98 & & 0.94 & & \cdots & \\ & 0.95 & & 1.00 & & 0.99 & & 0.96 & & \cdots \\ 0.72 & & 0.98 & & 1.00 & & 0.99 & & \cdots & \\ & 0.89 & & 0.99 & & 1.00 & & & & \cdots \\ 0.66 & & 0.94 & & 0.99 & & 1.00 & & \cdots & \\ & 0.85 & & 0.96 & & 0.99 & & 1.00 & & \cdots \\ \vdots & & \vdots & & \vdots & & \vdots & & \ddots & \\ & \vdots & & \vdots & & \vdots & & \vdots & & 1.00 \end{bmatrix}$$

Figure 5-5 Fuzzy Relation Matrix for the probability of occurrence of Binomial Cashflows

E2: Aggregate Fuzzy Future Cash Flows

The Fuzzy future costs are obtained, by aggregating the fuzzy relations matrix derived from the Negative Binomial probability distribution, and the respective cashflow. The operation used to aggregate the Fuzzy relations matrix, is the Max-min composition operator. The procedures of the Max-min composition, have been discussed under Section 3.5 Uncertainty modelling in Whole-life costing of Office buildings. The aggregated Fuzzy whole-life cost for an office building, with a current annual Future cost of £32,000, over a 30-year period, and an estimated discount rate of 3.5% produces a matrix that has the form, as shown below:

$$[\mathbf{560,000};\quad \mathbf{680,000};\quad \mathbf{790,000};\quad \mathbf{780,000};\quad \mathbf{850,000};\quad \mathbf{820,000};\quad \mathbf{880,000},\quad \cdots]$$

E3: Defuzzify into Fuzzy Lower, Fuzzy Mean, and Fuzzy Upper

Considering the number of external and internal factors, that influence the eventual whole-life cost of office buildings, it is argued that it will be helpful for the whole-life cost estimate, to be represented over a range, rather than a single figure. Previous work by Morrell (1993) have implied that the benefits of risk analysis is diminished, if cost estimates are presented as single figures. Many cost estimates however, still seek to reflect precision, often at the expense of credibility (Ross, 2009). An approach to providing representative range of figures, is to utilise the Defuzzification operation to provide a lower, mean, and upper value. This will involve an arithmetic operation for selecting the values lowest, average, and highest whole-life cost values from the aggregated set of fuzzy whole-life cost estimates. The respective Fuzzy lower, Fuzzy Mean and Fuzzy Upper whole-life cost value for the overall annual future cost estimate of £32,000 over a period of 30 years, at a discount rate of 3.5% will yield the following:

$$[\pounds\mathbf{561,000} \qquad \pounds\mathbf{850,000} \qquad \pounds\mathbf{910,000}]$$

5.3.1 Automation of the Fuzzy Future Cost Computation

The procedures of step E1 to E3 have been automated in a software program developed using Python® Scripts, and implemented on the Rhinoceros software. The software program comprises the following 11 steps.

1. This function generates probabilistic coefficients of the Negative Binomial distribution.

2. This function sums up the probabilities of each row, to facilitate the normalisation into standard probability values, between 0 and 1.

3. This function normalises the probability values between 0 and 1.

4. This function positions the probability values in order to correspond with the future cost equivalents.

5. This function achieves the formulation of a square matrix, by inserting zeros into empty columns and rows, in order to allow matrix aggregation.

6. This function aggregates the new matrix developed, by combining the future cost values, into a fuzzy relation.

7. This function limits the decimal point of normalised probability coefficients, into a rounded string.

8. This function computes the progressive future costs, over the expected life, based on the revocability rate.

9. This function converts the array of future cost events, into a square matrix.

10. This function generates a continuum of fuzzy cumulative future cost values for the matrix.

11. This function generates the fuzzy lower, fuzzy mean and fuzzy upper, cumulative future cost values

The mathematical scripts used in computing the fuzzy running costs are displayed below:

```
import math

#***************** These are all functions *****************#

# This function generates probabilistic coefficients of the Negative Binomial distribution #
def triangle(n):
   if n == 0:
      return []
   elif n == 1:
      return [[1]]
   else:
      new_row = [1]
      result = triangle(n-1)
      last_row = result[-1]
      for i in range(len(last_row)-1):
         new_row.append(last_row[i] + last_row[i+1])
      new_row += [1]
      result.append(new_row)
   return result
```

```python
# This function sums up the probabilities of each row to facilitate the normalisation into standard probability values between 0 and 1 #

def summation(row):
    sum = 0
    for r in range(0, len(row)):
        sum = sum + row[r]
    return sum



# This function normalises the probability values between 0 and 1 #

def Normalize(Pascal):
    NormTriang = []
    for n in range(1, len(Pascal)):
        row = []
        for r in range(0, len(Pascal[n])):
            numerator = Pascal[n][r]
            denominator = summation(Pascal[n])
            val = numerator / denominator
            row.append(val)
        NormTriang.append(row)

    return NormTriang

# This function positions the probability values in order to correspond with the future cost equivalents #

def RowToColumn(Array):
    RowToCol = []
    for j in range(0, len(Array[0])):
        list = []
        for i in range(0, len(Array)):
            list.append(Array[i][j])
        RowToCol.append(list)
    return RowToCol



# This function achieves the formulation of a square matrix by inserting zeros into empty columns and rows in order to allow matrix aggregation #

def InsertZero(Array):
    for i in range(0, len(Array)):
        b = 2
        for j in range(0, len(Array[i])):
            Array[i].insert(b*j, 0)
        Array[i].append(0)

    for i in range(0, len(Array)):
        b = i + 1
        for k in range(0, len(Array)-b):
            Array[i].append(0)
            Array[i].insert(0, 0)
    return Array
```

```
# This function aggregates the new matrix developed by combining the future cost values into a fuzzy relation #

def NewMatrix(A):
    A = RowToColumn(A)

    new_mat = []
    for p in range(0, len(A)):
        row = []
        for q in range(0, len(A)):
            i = A[p]
            j = A[q]

            num_R = 0.0
            for k in range(0, len(A[0])):
                val = (i[k] * j[k])
                num_R = num_R + val


            sum_1 = 0.0
            sum_2 = 0.0
            for k in range(0, len(A[0])):
                val1 = (i[k] * i[k])
                val2 = (j[k] * j[k])

                sum_1 = sum_1 + val1
                sum_2 = sum_2 + val2

            den_R = math.sqrt(sum_1 * sum_2)
            entry_R = num_R / (den_R + 0.0000000000001)

            row.append(entry_R)
        new_mat.append(row)
    return new_mat



# This function limits the decimal point of normalised probability coefficients into a rounded string #

def Float_to_roudedString(R_1):
    for i in range(0, len(R_1)):
        for j in range(0, len(R_1[i])):
            R_1[i][j] = ("%.6f" % R_1[i][j])
    return R_1




# This function computes the progressive future costs over the expected life based on the revocability rate #

def Binomial(size, A, d):
    Pascal = triangle(size)

    for i in range(0, len(Pascal)):
        for j in range(0, len(Pascal[i])):
            Pascal[i][j] = Pascal[i][j] / Pascal[i][j]
```

```
    upper = A * math.pow(1 + d, 2)
    lower = A / math.pow(1 + d, 2)

    mat = [[A]]
    for j in range(1, len(Pascal)):
        list = []
        upper = A * math.pow(1 + d, j)
        lower = A / math.pow(1 + d, j)
        list.append(lower)
        list.append(upper)
        mat.append(list)

    for i in range(2, len(mat)):
        for j in range(0, len(mat[i-2])):
            mat[i].insert(j+1, mat[i-2][j])

    mat = InsertZero(mat)
    mat = RowToColumn(mat)

    return mat




# This function converts the array of future cost events into a square matrix #


def getVector(Mat, z):
    vector = []
    for j in range(0, len(Mat[0])):
        val = 0
        for i in range(0, len(Mat)):
            val = val + Mat[i][j]
        value1 = val/(j + 1)
        vector.append(value1)

    for j in range(0, len(vector)):
        new_val = vector[j] / math.pow(1 + z, j)
        vector[j] = new_val


    return vector


# This function generates a continuum of fuzzy cumulative future cost values for the matrix #

def inset_1(Array):
    list = []
    for i in range(0, len(Array[0])):
        list.append(0)
    Array.insert(0, list)
    Array[0][int((len(Array[0]) - 1) / 2)] = 1
    return Array




# This function generates the fuzzy lower, fuzzy mean and fuzzy cumulative future cost values #
```

```
def Full_new_gen(R_1):
    list2 = []
    for i in range(0, len(R_1)):
        val = 0
        for j in range(0, len(R_1[i])):
            val = val + R_1[i][j] * vector[j]
        val = val * 2
        list2.append(val)
    return list2

#****************** End of Functions *******************#


#---Input parameters----#
A = 32, 000
d = 0.01
z = 0.03

# A =  Initial Cost Value
# d =  Construction Price Index (rise or fall of cashflow values)
# z =  Discount Rate

ArrayLenght = 31

#----------------------#


BinMat = Binomial(ArrayLenght, A, d)
vector = getVector(BinMat, z)
print "New generation vector"
print vector

print " "
print "P V"
BinMat = Float_to_roudedString(BinMat)
for i in range(0, len(BinMat)):
    print BinMat[i]



Pascal = triangle(ArrayLenght)
Array = Normalize(Pascal)
Array = InsertZero(Array)
Array = inset_1(Array)
Array = RowToColumn(Array)

R_1 = NewMatrix(Array)


del Array[0]
del Array[-1]

print " "
print "Binomial Correct Triangle"
Array = Float_to_roudedString(Array)
for i in range(0, len(Array)):
    print Array[i]
```

```
print " "
print "Full-new-generation"
vector_fullNew = Full_new_gen(R_1)
print vector_fullNew

val = 0
for i in range(0, len(vector_fullNew)):
    val = val + vector_fullNew[i]
average = val / len(vector_fullNew)
lowest = min(vector_fullNew)
highest = max(vector_fullNew)

print " "
print "Final Fuzzy Full-new-generation"
vec_three = [lowest, average, highest]
print vec_three

print " "
print "New Matrix"
R_1 = Float_to_roudedString(R_1)
for i in range(0, len(R_1)):
    print R_1[i]
```

STEP F – Compute Fuzzy New-Generation Whole-life Cost Estimate

The mathematical equation proposed, is based on the identified whole-life cost variables, and is expressed as:

$$Fuzzy\ NWLC_{retrofit} = C_i + C_d + \begin{cases} \sum_{t=d_i}^{T} \frac{F_{L,m}}{(1+r)^t} \\ \sum_{t=d_i}^{T} \frac{F_{M,m}}{(1+r)^t} \\ \sum_{t=d_i}^{T} \frac{F_{U,m}}{(1+r)^t} \end{cases} + \begin{cases} \sum_{t=d_i}^{T} \frac{F_{L,u}}{(1+r)^t} \\ \sum_{t=d_i}^{T} \frac{F_{M,u}}{(1+r)^t} \\ \sum_{t=d_i}^{T} \frac{F_{U,u}}{(1+r)^t} \end{cases} \qquad Eqn\ 5.1.4$$

$C_i = Initial\ or\ Installation\ Cost\ of\ Building\ Retrofit\ Option$

$C_d = Cost\ of\ disruption\ of\ the\ Building\ Retrofit\ Option$

$F_{L,m} = Fuzzy\ Lower\ of\ maintenance\ cost\ over\ building\ retrofit\ life$

$F_{M,m} = Fuzzy\ Mean\ of\ maintenance\ cost\ over\ building\ retrofit\ life$

$F_{U,m} = Fuzzy\ Upper\ of\ maintenance\ cost\ over\ building\ retrofit\ life$

$F_{L,u} = Fuzzy\ Lower\ of\ utilities\ (Energy\ and\ Gas)\ cost\ over\ building\ retrofit\ life$

$F_{M,u} = Fuzzy\ Mean\ of\ utilities\ (Energy\ and\ Gas)\ cost\ over\ building\ retrofit\ life$

$F_{U,u} = Fuzzy\ Upper\ of\ utilities\ (Energy\ and\ Gas)\ cost\ over\ building\ retrofit\ life$

$d_i = period\ in\ the\ building\ life, when\ retrofit\ installation\ is\ implemented$

$r = declining\ discount\ rate\ over\ the\ building\ retrofit\ life$

$T = Estimated\ Building\ retrofit\ life, in\ years$

STEP G – Ranking of Whole-life Cost Estimates of Retrofit Options

The computations from Step F, will provide three whole-life cost estimates for each retrofit option, corresponding to the Fuzzy lower, Fuzzy mean and Fuzzy upper New-Generation Whole-life Cost values. The respective whole-life cost estimates for the retrofit options under consideration will be collated under the appropriate categories, sorted and ranked based on the numerical order of preference, where the lowest whole-life cost estimate is considered the most preferred, and the highest whole-life cost estimate is considered the least preferred.

STEP H – Compare rankings of whole-life costing techniques

The ordinal ranked values of the Standard Whole-life Cost (WLC) estimate, New-Generation Whole-life Cost (NWLC) estimate, Fuzzy Lower New-Generation Whole-life Cost estimate (FL-NWLC), Fuzzy Mean New-Generation Whole-life cost estimate (FM-NWLC), and Fuzzy Upper New-Generation Whole-life Cost (FU-NWLC) estimate, will be compared. The Spearman's rank correlation test, will then be used, to statistically analyse the ranked data, for each whole-life cost estimate. The measures provided in the Spearman's correlation coefficients, of the respective models, will be tested for statistical significance, in order to assess decision-outcomes, based on the use of respective models. The comparison will be made, with regards, to the estimated number of years, discount rates, and effect of revocability and disruption. The effects of each assumption on the whole-life cost model, will be assessed by varying different scenarios, as discussed under Section 4.3.1 Scenario Analysis.

STEP I – Decide on Optimal Retrofit Configuration

Based on the interpretations of the respective Spearman Correlation test, the optimal retrofit configuration, can be inferred, and this will be specific for the case study projects under consideration. The choice of the optimal retrofit configuration, will be based on the value that, overall, minimises the whole-life costs. The most desirable scenario, is to identify a single retrofit configuration, that has a clear advantage over all the other alternatives. However, if there is a tie, it might be necessary to re-examine the assumptions, and identify factors that contribute to the ambiguity in the decision. Also, other techniques could be suggested, to resolve such situational ambiguities. Considering the many assumptions in whole-life cost procedures, such situations of tied ranks, based on equivalent cost estimates, are rather unusual. In the current work, none of the whole-life cost estimates in the retrofit projects tied.

STEP J – Output Whole-life Cost decision

The output decision on the retrofit building configuration based on the whole-life cost estimate, will involve clear identification of the retrofit option, preferred over the others. This identification and output of the preferred retrofit option, is contingent upon the assumptions adopted in the models. The output whole-life cost decision is based on cost value alone. Retrofit configurations could however, constitute a multi-objective decision problem, if other desirable factors are included, and tested for.

5.4 Summary

This chapter summarizes the major developmental work in this thesis, and reports on the Fuzzy New-Generation Whole-life cost model. The conceptual scope and principle of the Fuzzy New-Generation Whole-life Cost model has been explained. The chapter presents the mathematical formulae of the Fuzzy New-Generation Whole-life Cost model as well as the software program, used in computing the Fuzzy New-Generation Whole-life Costing model. This chapter also provides a process flow-chart that itemises, the procedural step to implementing the Fuzzy New-Generation whole-life costing model, in office retrofit buildings.

Chapter 6 Case Study Description

6.1 Introduction

This chapter provides a concise description of the Case Study projects, used in this work. It commences with an account of the buildings' history, and then goes on, to provide details of the buildings' characteristics. The information relevant to the whole-life costing exercise is analysed and stated. The information obtained from the case studies, are then used to compute the whole-life cost estimates of retrofit options in the projects.

6.2 Case Study 1 – SPACE Building Project

The SPACE building was first constructed, as a 2-storey primary school during the 1930's. It attained the status of a listed building in 2000, and was acquired by Castle Rock Edinvar Housing Association, in 2002. As the building is Grade II listed, all proposed interventions must take cognisance of the historic fabric, and must be acceptable to the Planning Department and Historic Scotland. The building has been re-modelled into a multi-tenanted office building, whose occupants consist mostly of social enterprises and community charities.

The SPACE retrofitting project, utilised two innovative and complementary technologies – ThermalShield^{TM} (a Building Fabric Retrofit Solution to reduce energy loss), and EnergyFusion^{TM} (an Energy Management service used to reduce energy consumption). The retrofit work was completed in year 2013.

6.2.1 Building Description:

The building has a narrow, elongated plan in three segments (a central block and two wings), as shown in Figure 6.1, and is brick-built, with cavity walls, a pitched roof on a steel and timber structure, and single-glazed vertical sliding sash windows, with multiple panes. The building has an expansive front elevation and has good occupancy levels. The owners of the building consider the building to be commercially viable, and are of the opinion, that the retrofit work has contributed to the building's desirability to business organisations.

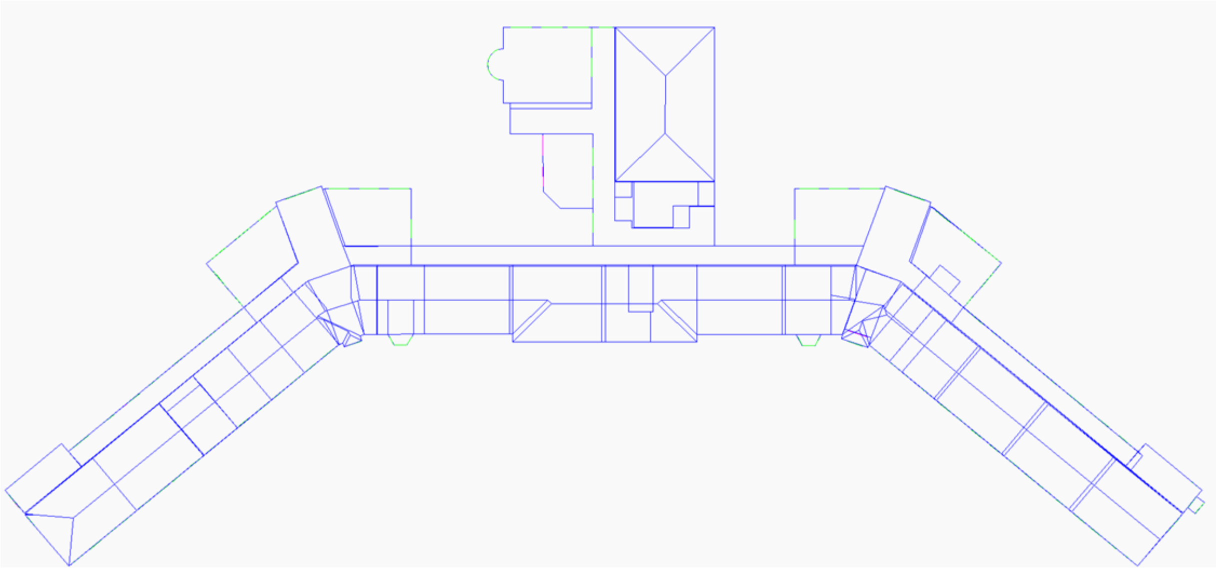


Figure 6-1   Plan Showing the Main Building of the SPACE project

More general information on the SPACE building are stated:

- **Geographic location**

  The SPACE Project is located on 11 Harewood Road, Edinburgh. It is located on Latitude – 55.935333N, and Longitude – 3.131437W.

- **Building Type**

  The building employs a mixture of construction forms, with both solid and cavity rendered brick walls, suspended timber and concrete floors, pitched slate roofs and flat felted roofs.

- **Size**

  The building is approximately 1800 square meters of Net Lettable Area

- **Age**

  The building has its origins in the 1930's, and is currently over 80 years old.

- **Occupancy Schedule**
  The building is typically occupied from Monday to Friday, 9am until 6pm, or 8am until 5pm, depending on the preferred operating hours of respective tenants.

6.2.2 Purpose and Description of the Retrofitting Work in the SPACE project

In 2002, Edinburgh Council, included the then, Craigmillar primary school building, as part of a Public-Private Partnership (PPP) Programme, as a result of dwindling pupil numbers. The Craigmillar primary school, was therefore put up for sale. The original intention was to demolish the building, and erect a new structure. However, pressure was mounted from the local community, on the presence of some precious murals in the existing building, and this led to the building being listed as a Grade II historic building. The new owners – Castle Rock Edinvar, had to rethink, on the possible use of the building, which could tie-in with a housing development project, and this led to the emergence, and retrofitting of a multi-tenanted office complex.

Considering the varied background of stakeholders involved in the SPACE project, the intention of Castle Rock Edinvar, was to reduce heat losses and improve on the energy-efficiency of the building, in the most minimally disruptive approach as possible. To this end, a comprehensive investigation was conducted that yielded a number of robust details, products and methodologies, for delivering cost-effective, practical, sensitive, and high performing treatments for solid wall properties, most of which can be installed whilst a good degree of occupancy of the building, can be maintained. The SPACE building utilised two key commercial retrofit packages – ThermalShield^{TM}, and EnergyFusion^{TM}. More on these commercial solutions are discussed.

6.2.2.1 ThermalShield^{TM}

ThermalShield^{TM} is an innovative commercial solution, that is currently been promoted to improve fabric performance in buildings. There are tens of manufacturers and installers, across the United Kingdom. ThermalShield^{TM} aims to minimise energy loss through the building fabric (Thomson, 2012), using a host of insulation measures. ThermalShield^{TM} is essentially a portfolio of insulation packages, including additional loft insulation, insulated internal linings for walls, purpose-designed secondary glazing for existing sash windows, incorporated 'sun-guard' glass for reduction in solar gains, insulation of spandrel panels beneath windows, and shutter boxes beside them (when required), and insulation of suspended ground floors. ThermalShield^{TM} is considered as having significant potential, in older buildings, with listed status, or in conservation areas. ThermalShield^{TM} has a reasonable high technology readiness (6 of 10), and has been fully demonstrated in actual system applications, with over 100 completed projects (Stott, 2012).

Prior to the retrofitting work, the windows along the listed front façade were single glazed timber, sash and case windows. The elemental build-up of the south wall consisted of 500mm precast concrete lintel, 75mm unventilated air gap, 50mm mineral wall insulation, 12.5mm plasterboard on 50mm metal framing. The elemental build-up of the north wall consisted of 25mm roughcast external render, 90mm solid brickwork, 110mm cavity, 110mm brick, 50mm unventilated air gap, 50mm metal stud framing finished internally with 12.5mm plasterboard. The area below the window was built-up of 25mm roughcast external render, 230mm solid brick work, 50mm mineral wall insulation, 170mm unventilated air gap, 12.5mm internal lining.

In operational terms, ThermalShield^{TM} focuses on the upgrading of existing building elements, with innovative use of building materials, rather than blanket removal and replacement. This often involves different improvement to specific aspects of the building fabric. In the SPACE project, it was proposed that the South wall will be enhanced through addition of 75mm of hemp insulation, to the air gap between the concrete lintel and the mineral-wool. This extra insulation with lapped insulation to the joints, is intended to reduce air-leakage pathways, and improve the junctions' vulnerability to thermal bridging. The wall below the window will be reinforced with 170mm of bead insulation, blown into the gap between mineral wool and plasterboard. The North wall will be reinforced with 110mm of bead insulation, pumped into the cavity between the brick leaf. In addition to these, hemp insulation was installed to the cavity behind the plasterboard, and to the overhead joists, to form a continuous insulating layer, in an attempt to mitigate cold bridging.

6.2.2.2 EnergyFusion^{TM}

EnergyFusion^{TM} offers a completely novel and powerful approach, to addressing the issue of building controls. It moves on from smart metering, which tends to indicate usage profile only, to providing a fully automatic, intelligent, and target-driven approach, to the management and reduction of energy within buildings. EnergyFusion^{TM} is essentially an energy demand regulator, and works through reducing and controlling energy demand, within the user-environment, in relation to supply signals. EnergyFusion^{TM} monitors occupancy via infra-red sensors, monitors internal conditions such as temperature, relative-humidity, Carbondioxide concentration, and daylight levels. The system also monitors the use of building services, and records associated energy-uses. EnergyFusion^{TM} interphases building systems to adjust control settings, or turn systems off when appropriate, and provides an interface for remote monitoring of the building. The EnergyFusion^{TM} system is however, a new approach to advanced building control, and its potentials are yet to be fully tested on a wide-scale for commercial office buildings. EnergyFusion^{TM} is beneficial in providing a promising and strategic approach, to building control management, in addition to energy consumption reduction.

EnergyFusion^{TM} has a technology readiness of 7 out of 10, and there are claims regarding its potentials to achieve about 30% savings in lighting and heating requirements (Stott, 2012). EnergyFusion^{TM} employs a unique algorithm which establishes energy targets, and aids the management of energy-use. This self-monitoring potential of real-time, closed-loop, control of energy performance, as well as usage-recording, provides a powerful and intelligent demand response, to building management. In a previous trial, the EnergyFusion^{TM} system was installed in a commercial office building, focusing on the communal areas for 12 months managing lighting only. Over this time period, it demonstrated savings in lighting energy of over 60%, against a pre-installation measured baseline (Stott, 2012).

In operational terms, EnergyFusion^{TM} is an energy management and building control system, that can be used to manage the lighting and heating services. It supports wired and wireless infrastructure. EnergyFusion^{TM} measures the energy consumed by devices and groups of devices, stores the data, and employs a predictive approach to making intelligent control decisions, in order to automatically reduce and optimise energy-use, within buildings.

The EnergyFusion^{TM} is however, still a patented technology (patent No: GB2461292) and hence, the exact working mechanism cannot be discussed in details. Another central feature of EnergyFusion^{TM} is that, it has an occupancy mode, where some locations in the building can be accessed in terms of occupancy biodata (informed by Infra-red and other sensors). The system could then take "executive level" decision with respect to occupancy rights. For instance, if a user arrives after closing hours, it will recognise their profile, and turn on only the lighting, routinely accessed by the individual. This could have benefits for security purposes

The SPACE project team consisted of local building consultancies, academic groups, in-house experts, and energy-efficiency organisations. The intention was to gather a team that possess the necessary skills and experiences, to deliver a successful project, and identify wider benefits from the project. An energy simulation model of the SPACE building, was developed using the IES <VE> software. The front elevation of the energy simulation model is shown in Figure 6-1, revealing the buildings' expansive front coverage, and a relatively high length-breadth ratio.

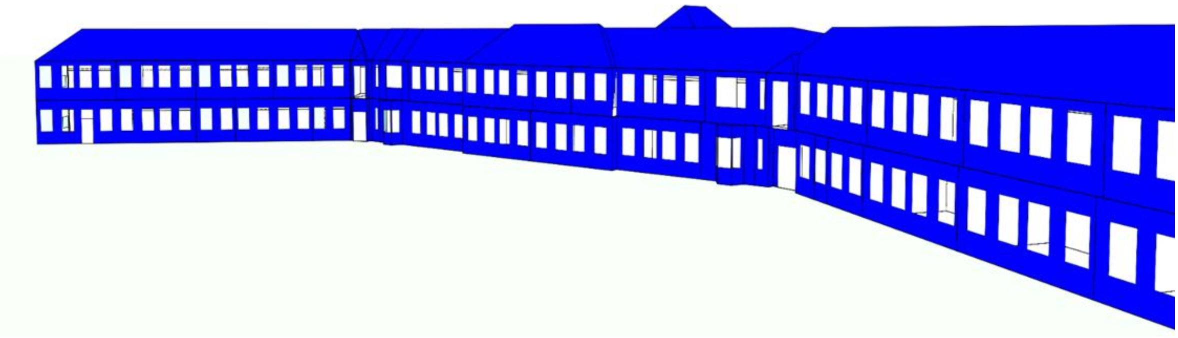


Figure 6-2 Elevation view of the SPACE project

Table 6:1 Predicted and Actual Energy Use of the SPACE building

Energy Source	Actual	Base Model	% Difference
Electricity	190,300	189,200	99%
Natural Gas	803,100	811,000	101%
Total	**993,400**	**1,000,200**	

Five runs of the IES<VE> model was considered by the project team. This consisted of:

1. The 'base case'- the building in its current condition, with no improvements.
2. The building with low cost energy measures (LCEMs) installed.
3. The building with low cost energy measures (LCEMs) and the ThermalShield^{TM} (TS) measures.
4. The building with low cost energy measures (LCEMs) and the EnergyFusion^{TM} (EF) Management Services.
5. The building with low cost energy measures (LCEMs), ThermalShield^{TM} (TS) measures and EnergyFusion^{TM} (EF) Management System.

Table 6:2 Predicted Energy Use by the IES<VE> model of the SPACE building

Run	Description	Gas (KWh/yr.)	Electricity (KWh/yr.)	Total (KWh/yr.)	Savings (%)
1	Base Case (BCP 1)	811,000	189,200	1,000,200	-
2	LCEMs only (BCP 2)	775,000	189,200	964,200	4%
3	LCEMs + TS (BCP 3)	362,200	192,300	554,500	45%
4	LCEMs + EF (BCP 4)	674,500	173,300	847,800	15%
5	LCEMs + TS + EF (BCP 5)	318,100	175,400	493,500	51%

6.2.3 Cost Information

The cost information on the SPACE project have been broken down into distinct categories - Initial cost and Future cost elements, in order to aid the computation of whole-life cost estimates (Ashworth & Perera, 2013). The components of each of these cost categories are discussed:

6.2.3.1 Initial (Installation) Cost

The Initial cost, basically pertains to the Installation and Acquisition Cost of the retrofit option, and generally includes labour, materials, professional fees and associated charges (Kirkham, 2014). The Initial cost of BCPs, in the SPACE building project is reported in Table 6:3.

Table 6:3 Capital Cost of BCPs in the SPACE project

Run	Description of Retrofit	Capital Cost (£)
BCP 1	Base Case	0
BCP 2	LCEMs only	40,000
BCP 3	LCEMs + TS	219,000
BCP 4	LCEMs + EF	289,000
BCP 5	LCEMs + TS + EF	580,000
BCP 6	LCEMs + TS + EF + CHP	1,080,000
BCP 7	LCEMs + TS + EF + Wind	763,000
BCP 8	LCEMs + TS + EF + Mechanical Ventilation	680,000
BCP 9	LCEMs + TS + EF + PV-Amorphous	780,000
BCP 10	LCEMs + TS + EF + PV-Monocrystalline	780,000

6.2.3.2 Future (Utilities) Cost

The building is supplied with Natural Gas and Electricity, and also has a roof-mounted solar photovoltaic (PV) installation. The electricity consumption levels could vary in different years, but in the 12-month period for the year, 2011 – 2012, the building used up £993,300kWh/yr. of delivered energy. Table 6.4 shows the breakdown of energy-use by fuel type, and the associated costs. The unit cost of electricity, is estimated as 11.28 pence per kilowatt-hour, and the unit cost of gas is 2.88 pence per kilowatt-hour. The respective cost of electricity and gas, is shown:

Table 6:4 Breakdown of Energy use by fuel type and associated cost

	kWh/yr	kWh/m^{2}yr	Cost
Electricity	190,300	56	£21,500
Natural Gas	803,000	236	£23,200
Total	**993,300**	**292**	**£44,700**

The baseline cost of £44,700, was the actual cost based on metre recordings, as shown in Table 6:4. An approximate energy cost of £45,000 was obtained using the IES<VE> model, as shown in Table 6:5. These values are relatively close, and are accurate to about 99%, which suggest an acceptable predictability of the energy simulation model, developed using the IES <VE> software.

Table 6:5 Electricity and Gas Cost values as estimated by the IES<VE> software

Runs	Electricity Cost (£)	Gas Cost (£)	Total Cost (£)
BCP 1	21,700	23,300	45,000
BCP 2	21,700	22,300	44,000
BCP 3	21,700	19,700	41,400
BCP 4	19,500	9,400	28,900
BCP 5	19,700	9,500	29,200
BCP 6	19,500	9,500	29,000
BCP 7	4,900	9,500	14,400
BCP 8	6,000	9,400	15,400
BCP 9	5,200	9,500	14,700
BCP 10	5,000	9,500	14,500

6.2.3.2 Future (Maintenance and Operation) Cost

The Annual Maintenance and Operation cost of the SPACE project, is obtained from the owners of the SPACE building. The maintenance and operation cost is considered same for the Building Configuration Permutations considered, as this case retrofit project, mainly impacts on energy-efficiency. The annual maintenance and operation costs in the SPACE building, as provided by the owners, is displayed in Table 6:6:

Table 6:6 Annual Maintenance and Operation cost in the SPACE Building

Components	**Annual Average Cost**
Alarm	£200
Cleaning	£22,000
Window Cleaning	£3,200
Insurance	£6,500
Lift Consultancy	£200
Lift Line	£200
Lift Insurance	£200
Lift Maintenance	£800
Reception	£27,000
Waste disposal	£1,900
Hygiene Compliance	£1,600
Water Rates	£14,300
Security	£5,800
Recycling	£1,600
Repairs	£8200
Drinking Water provision	£500
Grounds Maintenance/Caretaking	£7,000
Postage Uplift	£800
Total	**£102,000**

6.2.4 Disruption Analysis of Retrofit Options in the SPACE Project

The owners of the SPACE project were keen to minimise the disruption to profit-earning activities, in the course of retrofitting the SPACE project. Being a commercial outfit, minimising the cost of disruption was desired, as business tenants tend to lose significant income, and perhaps reputation, should the retrofitting initiative take place, over an extended duration. This intention was re-echoed in the interviews with members of the project team. Spider diagrams can be used to graphically depict the level of disruptiveness of respective technologies, in the SPACE building, as seen in Figure 6-3 and Figure 6-4, for BCP 3 and BCP 8 for the SPACE building project respectively. In Figure 6-3, the retrofit interventions commences with fabric measures including draught-proofing, ground-floor insulation, internal wall-lining, cavity wall insulation, roof insulation, and treatment of cold spots. It also includes some use of heating controls. The spider diagram in Figure 6-3 reveals the disruptiveness of the retrofit technologies. The greater the perimeter of the retrofit package, the more disruptive the retrofit option. The approach to evaluating the cost of disruption is reported in Appendix A-1.

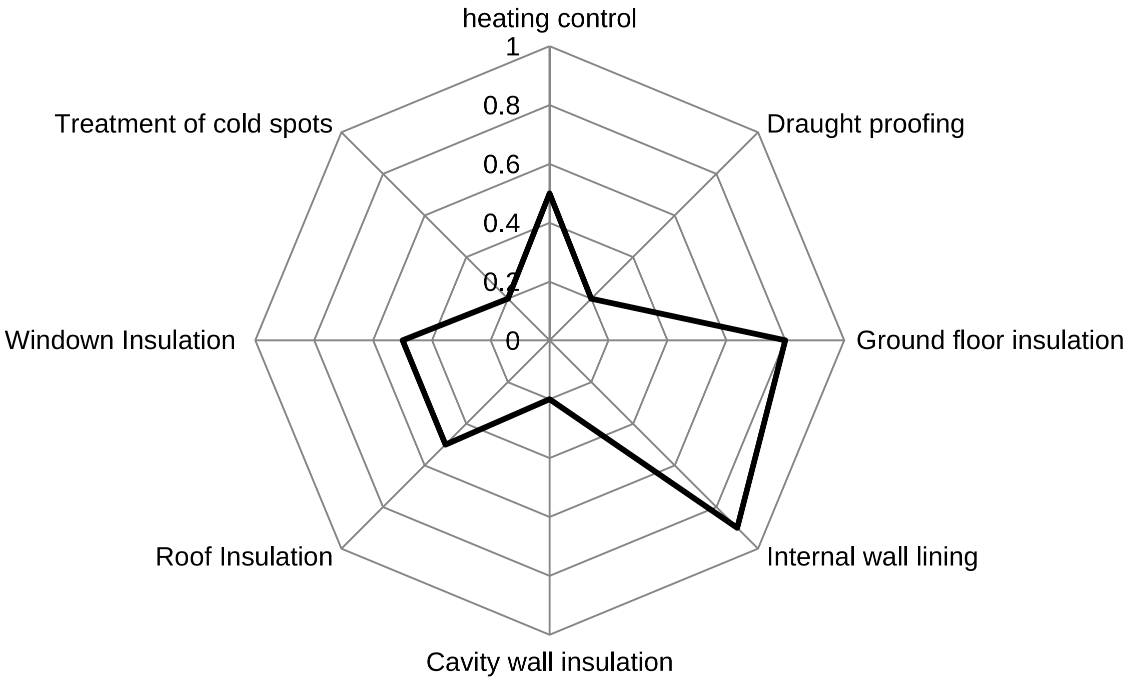


Figure 6-3 BCP 3 (SPACE PROJECT)

In Figure 6-4, the retrofit intervention for BCP 8, is represented using a Spider diagram. The number of retrofit interventions in BCP 8, are more than those used in BCP 3. A rule-of-thumb in evaluating the disruption is that, the higher the perimeter in the spider diagram, the greater the potential cost of disruption incurred, in implementing the retrofit intervention. It is therefore desirable for building owners, and occupiers to seek for a portfolio of retrofit intervention, that is minimally disruptive. It can also be seen from Table 6:7, that the cost of disruption in BCP 8, is relatively greater, than that of BCP 3. The spider diagrams for the rest of the building configuration permutations in the SPACE building project is reported upon in the Appendix A-2.

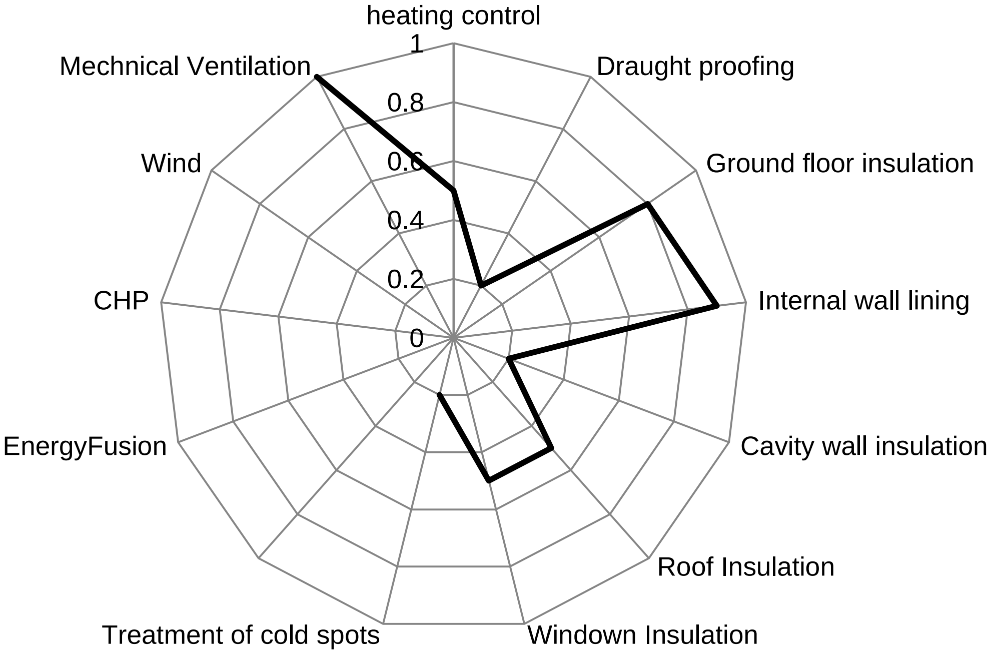


Figure 6-4 BCP 8 (SPACE PROJECT)

6.2.5 Estimated Cost of Disruption in the SPACE project

The estimated cost of disruption in the SPACE project, has been computed using fuzzy logic, aided by the Factor Chart analysis template described in Figure 5-2. The procedures for computing the cost of disruption, has been explained in Chapter 5. For BCP 1, the base case does not have any cost of disruption, whereas BCP 2 to

BCP 10, have estimated costs of disruption. The estimated cost, of disruption for each of the BCPs, in the SPACE project is shown in Table 6:7:

Table 6:7 Estimated Cost of Disruption in the SPACE Building Project

Run	Fuzzy Lower (£)	Fuzzy Mean (£)	Fuzzy Upper (£)
BCP 1	0	0	0
BCP 2	3,300	4,800	5,700
BCP 3	3,500	15,500	24,000
BCP 4	3,300	9,500	14,300
BCP 5	3,500	24,700	39,300
BCP 6	3,500	24,700	39,300
BCP 7	4,600	27,500	43,600
BCP 8	5,700	30,000	50,000
BCP 9	4,600	27,500	43,600
BCP 10	4,600	27,500	43,600

6.3 Case Study 2 – Medium-sized (MS) Masonry Building Project

The Cost data on the MS Masonry Office Building Project, is based on the work of Hendricken *et al.,*(2012), a project supported by Energy Efficiency Hub (EEH) in the United States. Published data, collected on the MS office retrofit building project included the Capital cost, Annual maintenance cost, Annual utility cost, and the retrofit technologies implemented. 22 BCPs resulted from the published data obtained and a whole-life cost analysis, was conducted on the MS project.

6.3.1 Building Description

The MS Masonry office Building is located in Philadelphia, PA, United States. The building meets the ASHRAE 90.1 – 1989 building requirement. This also suggests the building is over twenty years old. It is a 3-storey building, and has approximately 5,600m^2 of Net Lettable Area.

The building is designed to have 20% single glazing, and roof-top packaged air-conditioning. The building's roof insulation has an R-value of 15. The roof is covered in asphalt membrane, with solar absorptance value of 0.9. The exterior wall construction (from outside layer to inside layer), consists of 1 inch of stucco, 8 inch of concrete, R-6 continuous insulation, and ½ inch gypsum wallboard. Other relevant attributes of the MS Office building are summarised below, in Table 6:8:

Table 6:8 Baseline Characteristics of the MS Project

	Variable	Value
1	Occupant Density	0.0538 person/square metre
2	Ventilation Requirement	26.5 CFM/person
3	Lighting Power Density	16.4 watts / square metre
4	Internal Small Plug Loads	10.76 watts/ square metre
5	Elevator Consumption	32,000 watts
6	Exterior Lighting	18,000 watts
7	Envelop Infiltration rate	2.4 CFM/square metre

The baseline MS masonry office building, is considered relatively energy-inefficient, in the Greater Philadelphia Innovation Cluster (GPIC) region, in terms of both envelope and equipment, but are assumed to be commissioned, or running with good control algorithms, and balanced systems. The baseline mechanical system of the MS Masonry office building, of interest, has the following mechanical configuration, shown in Table 6:9:

Table 6:9 Baseline Mechanical Information on the MS Project

	Mechanical Systems	Specification
1.	System	3 Constant-air-volume(CAV), Air-handling units (AHU)
2.	Main Cooling Coil	Direct expansion, Coefficient-of-Performance (COP 3)
3.	Main Heat Coil	Hot water coil system
4.	Zone Reheat	Hot water from central boiler, or a natural gas furnace.
5.	Heat Plant	Natural gas boiler with hot water coil system
6.	Heat Efficiency	70% Annual Fuel Efficiency Utilisation (AFUE)

6.3.2 Description and Purpose of the Retrofitting Work in the MS project

The primary purpose of the retrofit work, is to make the building more energy-efficient. The building is modelled using the EnergyPlus software. EnergyPlus provides an assessment of the energy performance, based on different retrofit initiatives as shown in Table 6:10

The simulation parameters included Infiltration, Windows-to-wall ratio, Roof thermal properties, Wall Thermal properties, Window U-value, Window Solar Heat Gain, Occupant Density, Lighting Density, Equipment Density, Minimum Outdoor air volume, Heat, Ventilation and Air-Conditioning (HVAC) equipment properties, and HVAC Energy-input ratio.

The 22 BCPs were developed from the MS building baseline, using the EnergyPlus modelling software. The specific energy-efficiency measures, considered in the retrofitting of the MS masonry office building project, is shown in Table 6:10.

Table 6:10 Energy Efficiency Measures in the MS Project modelled using EnergyPlus Software (Where x, means available)

Runs	Temperature Reset Strategy	T-5 Lighting Upgrade	LED light upgrade and exterior LED	High Efficiency elevator Upgrade	Double pane window Upgrade	White Roof Upgrade	Insulated Roof Upgrade	Insulated Wall Upgrade	High Efficiency Boiler	High Efficiency Cooling	Variable-Air-Volume Upgrade	Ground Source Heat Pump	High Efficiency Central chiller	Ice Tank thermal storage	Photovoltaics	Smart Grid Control
BCP 1																
BCP 2																
BCP 3																
BCP 4	x	x														
BCP 5	x		x	x												
BCP 6	x	x		x	x											
BCP 7	x		x	x	x											
BCP 8	x	x							x	x						
BCP 9	x	x		x	x				x	x						
BCP 10	x		x	x	x				x	x						
BCP 11									x	x	x					
BCP 12			x	x					x	x	x					
BCP 13		x		x	x				x	x	x					
BCP 14			x	x	x				x	x	x					
BCP 15									x		x		x			
BCP 16		x							x		x		x			
BCP 17			x	x					x		x		x			
BCP 18		x		x	x				x		x		x			
BCP 19			x	x	x				x		x		x			
BCP 20			x	x	x	x			x		x		x	x		
BCP 21		x		x	x		x	x	x		x		x		x	x
BCP 22			x	x	x							x			x	x

6.3.3 Cost Information

The Cost data obtained on the Initial cost, Maintenance cost, and the Utilities cost for the MS masonry office building project, is displayed in Table 6:11. The cost information on the MS project, have been broken down into the Capital cost and the Future cost elements. The Future cost elements compose of the Energy and Gas costs, and the Maintenance cost, and is directly analogous with the Cost Components considered in the SPACE project.

Table 6:11 Characteristics of the Selected Building Configuration Permutations in the MS project

Runs	**Capital Cost ($ US)**	**Annual Maintenance Cost ($)**	**Annual Electrical Use (Kwh)**	**Annual Gas Use (Kwh)**	**Annual Electrical Energy Cost ($)**	**Annual Gas Energy Cost ($)**	**Total Annual Utilities Cost ($)**
BCP 1	612,000	8,800	934,000	199,000	81,000	7,400	88,400
BCP 2	795,000	4,200	843,000	199,000	73,100	7,400	80,500
BCP 3	577,000	16,000	1,001,000	166,000	86,800	6,100	92,900
BCP 4	1,101,500	8,800	780,500	226,200	67,700	8,400	76,100
BCP 5	1,285,000	4,200	661,000	226,200	57,300	8,400	65,700
BCP 6	1,288,000	8,800	715,000	227,800	62,000	8,400	70,400
BCP 7	1,468,000	4,200	537,500	278,000	47,000	10,300	57,300
BCP 8	1,150,000	8,800	811,000	122,000	70,300	4,500	74,800
BCP 9	1,335,000	8,800	673,500	191,000	58,400	7,100	65,500
BCP 10	1,518,000	4,200	554,000	191,000	48,000	7,100	55,100
BCP 11	1,170,500	16,000	847,000	139,000	73,500	5,100	78,600
BCP 12	1,362,000	4,200	627,000	139,000	54,400	5,100	59,500
BCP 13	1,366,000	8,800	614,000	114,000	53,200	4,200	57,400
BCP 14	1,549,000	4,200	523,000	114,000	45,300	4,200	49,500
BCP 15	1,276,000	17,700	826,000	139,000	71,600	5,200	76,800
BCP 16	1,285,000	10,400	696,000	139,000	60,300	5,200	65,500
BCP 17	1,468,000	5,800	606,000	139,000	52,500	5,200	57,700
BCP 18	1,510,000	10,400	601,000	135,000	52,200	5,000	57,200
BCP 19	1,693,000	5,800	552,000	135,000	47,900	5,000	52,900
BCP 20	1,805,000	5,800	593,000	110,500	51,500	4,000	55,500
BCP 21	3,420,000	10,400	455,000	98,500	39,500	3,600	43,100
BCP 22	4,485,000	4,200	445,000	44,300	38,600	1,600	40,200

6.3.4 Disruption Analysis of Retrofit Options in the MS Project

The implication of disruption, was not given attention in the implementation of the MS Office retrofit building project. However, information on the retrofit technologies has been collected to estimate the possible cost of disruption for varying retrofit options. The procedure to evaluating the cost of disruption follows the procedures articulated in Section 5.3 Procedural implementation of the Fuzzy New-Generation Whole-life Costing Technique. Using the disruption measures of retrofit initiatives, provided by Gleeson *et al.,* (2011), the cost of disruption is estimated using fuzzy logic, and in accordance with the Factor Chart analysis described in Figure 5-2.

Figure 6-5 presents the spider diagrams of the disruption analysis for BCP 4, which principally consists of LCEMs, and changing the lighting, and the temperature reset features. It should be noted that BCP 1 to BCP 4, are considered as having non-disruptive cost implications. The disruption analysis provides an indication of the degree of disruption, based on the retrofit technologies used. The greater the perimeter of the BCP retrofit disruption measure on the Spider diagram, the higher the estimated disruption cost in the retrofit initiative.

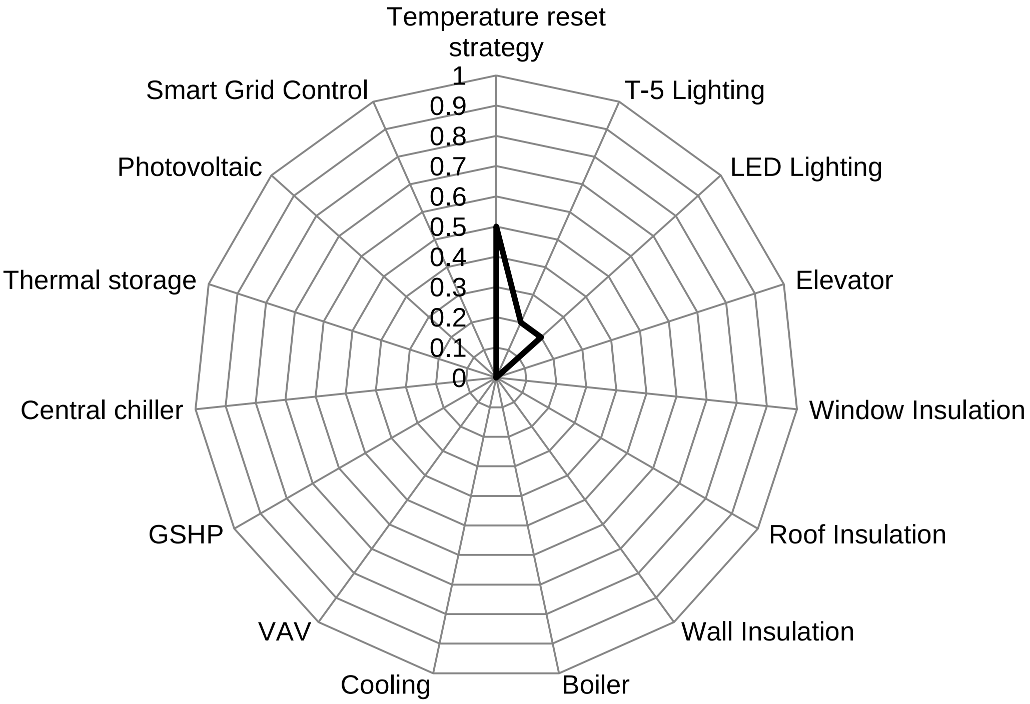


Figure 6-5 BCP-4 in MS Project

Figure 6-6 presents the spider diagram for BCP 21. The individual retrofit technologies consists of a broad range of fabric measures, energy and efficient appliances, and smart technologies. The implementation follows the Factor Chart Analysis described in Figure 5-3. Based on the rule-of-thumb, the retrofit technologies in BCP 21 are considered more disruptive, than those used in BCP 4. The spider diagrams for the remaining sixteen BCPs in the MS project are reported upon in the Appendix A-3.

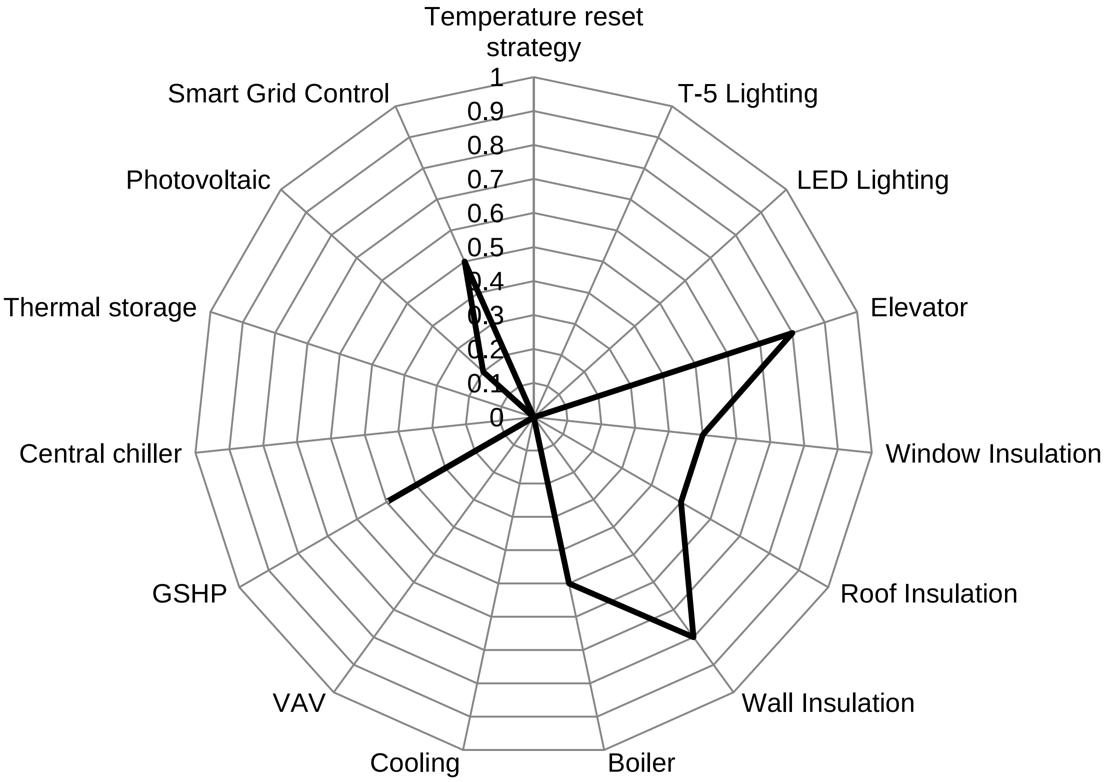


Figure 6-6 BCP-21 in MS Project

6.3.5 Estimated Cost of Disruption in the MS project

Table 6:12 shows the estimated cost of disruption in the MS project, based on the fuzzy logic approach of evaluating the implications of disruption, for respective retrofit technologies. Table 6:12, reports on the cost of disruption in the MS project is estimated to range between $6,200 and $55,000

Table 6:12 Estimated Cost of Disruption in the MS Project

Run	Fuzzy Lower ($)	Fuzzy Mean ($)	Fuzzy Upper ($)
BCP 1	0	0	0
BCP 2	0	0	0
BCP 3	0	0	0
BCP 4	0	0	0
BCP 5	6,200	15,500	25,000
BCP 6	8,200	18,000	28,000
BCP 7	8,200	18,000	28,000
BCP 8	1,900	2,900	3,300
BCP 9	8,200	18,000	28,000
BCP 10	8,200	18,000	28,000
BCP 11	1,900	2,900	3,300
BCP 12	8,200	18,500	28,000
BCP 13	10,000	21,000	31,500
BCP 14	10,000	21,000	31,500
BCP 15	1,900	2,900	3,300
BCP 16	1,900	2,900	3,300
BCP 17	8,200	18,500	28,000
BCP 18	10,000	21,000	31,500
BCP 19	10,000	21,000	31,500
BCP 20	10,000	21,000	31,500
BCP 21	24,600	41,000	55,000
BCP 22	12,000	24,000	35,000

6.4 Summary

This chapter provides information on the retrofit case study projects selected, and the data extracted from the building prototypes developed. Energy simulation models constructed in both case studies, are appraised. The cost of disruption is evaluated using Fuzzy logic techniques, in conjunction with the Factor Chart analysis. The Initial capital cost, Electricity and Gas cost, Maintenance and Operational cost data, in respective case study projects, are reported upon, and these data are used in computing, and analysing the whole-life cost estimates in subsequent chapters.

Chapter 7 Presentation of Results

7.1 Introduction

This chapter reports on the whole-life cost estimates, computed based on identified retrofit options, in the case study projects considered. In the SPACE Project, 10 BCPs were evaluated based on the different whole-life cost models over a period of 20 years, 40 years and 60 years. Also, in the MS project, 22 BCPs were evaluated over a 20-year, 40-year and 60-year estimated life. The whole-life cost estimates were evaluated based on the scenarios – “Discounting and Revocability only”, and “Discounting, Disruption, and Revocability”. This chapter also provides some descriptive statistics on the whole-life cost estimates of BCPs considered in the case study projects – SPACE and MS.

7.2 Whole-life Cost Estimates of Options in the SPACE Project

In the SPACE office building project, 10 BCPs were evaluated based on the different whole-life cost models, over a period of 20 years, 40 years, and 60 years. The time-value of money, was adjusted for, based on the declining discount rate schedule, suggested by the HM-Treasury (2013), which corresponds to 3.5% over a period of 1 – 30 years, 3% over a period of 31 – 75 years, and following on to 1%, over a period greater than 300 years.

7.2.1 Whole-life Cost Values based on Discounting and Revocability scenario

Table 7:1 shows the whole-life cost estimate of various building configuration permutations (BCPs) considered in the SPACE project. The evaluation of the whole-life cost values for each of the retrofit runs, considered the Initial costs, maintenance and operating costs, and utilities (that is, electricity and gas) costs over the building’s life. This were evaluated based on the declining discount rate schedule specified by HM-Treasury (2013). The applicable discount rate, over a 20-year estimated life based on the schedule specified by the HM-Treasury, is a constant annual rate of 3.5%. The New-Generation Whole-life Cost (NWLC) Model, and the Fuzzy New-

Generation Whole-life Cost Model, adopted a revocability rate of 10%, - which implies a proportionate increase or decrease in the Future cost values in succeeding years. This revocability rate is consistent with the work of Ellingham and Fawcett (2006) - the first documented work, where revocability is implied, as a relevant consideration in whole-life costing scenarios.

The Standard Whole-life Costing (WLC) technique, does not have an established mechanism, to accommodate revocability, and hence, no consideration of such is included in its cost estimates. However, revocability is appraised in the NWLC model, and the Fuzzy-New Generation whole-life cost model. Figure 7-1 depicts the whole-life cost model, for all the BCPs considered in the SPACE project. Over a 20-year horizon, the whole-life cost estimate could range between £2.1million and £3.6million. On average, BCP 6 however, appears the least cost-effective option over a 20-year life, while BCP 1 is the most cost-effective. It can therefore, be noted that cost savings over a time-horizon of 20-years, is unlikely to be a key driver, for investors interested in retrofit projects. This is because the benefits of whole-life costing of retrofit options in the SPACE office building are inconspicuous, considering the relatively short, building appraisal life.

Over the 20-year period however, the Standard deviation observed between the whole-life cost estimates, in the SPACE project reported in Table 7:1, are quite comparable, and all range between £250,000 and £300,000.

Table 7:1 Whole-life Cost Estimates over a 20-year Period in SPACE project

Runs	**WLC (£)**	**NWLC (£)**	**FL-NWLC (£)**	**FM-NWLC (£)**	**FU-NWLC (£)**
BCP 1	2,090,000	2,178,000	1,523,000	2,045,000	2,210,000
BCP 2	2,111,000	2,201,000	1,549,000	2,067,000	2,231,000
BCP 3	2,254,000	2,343,000	1,699,000	2,205,000	2,366,000
BCP 4	2,450,000	2,540,000	1,833,000	2,354,000	2,521,000
BCP 5	2,745,000	2,840,000	2,128,000	2,651,000	2,817,000
BCP 6	3,501,000	3,607,000	2,804,000	3,384,000	3,570,000
BCP 7	3,074,000	3,175,000	2,385,000	2,923,000	3,096,000
BCP 8	2,663,000	2,750,000	2,077,000	2,543,000	2,692,000
BCP 9	2,880,000	2,972,000	2,256,000	2,748,000	2,905,000
BCP 10	2,877,000	2,969,000	2,254,000	2,745,000	2,902,000

It follows, that the range of the Standard deviation of whole-life cost estimates, is a maximum of £50,000, for the BCPs under consideration. This suggests that the average difference between whole-life cost estimates of respective retrofit options, is only about half the annual cost of utilities, in the first year of operation. These cost difference is also only about, a quarter of the annual future costs, for the first year of operation, which can be considered relatively meagre in influencing decision-outcomes. Figure 7.1 displays the whole-life cost estimates of respective BCPs in the SPACE project, and suggests that BCP 6 represents the highest whole-life cost, amongst the possible options.

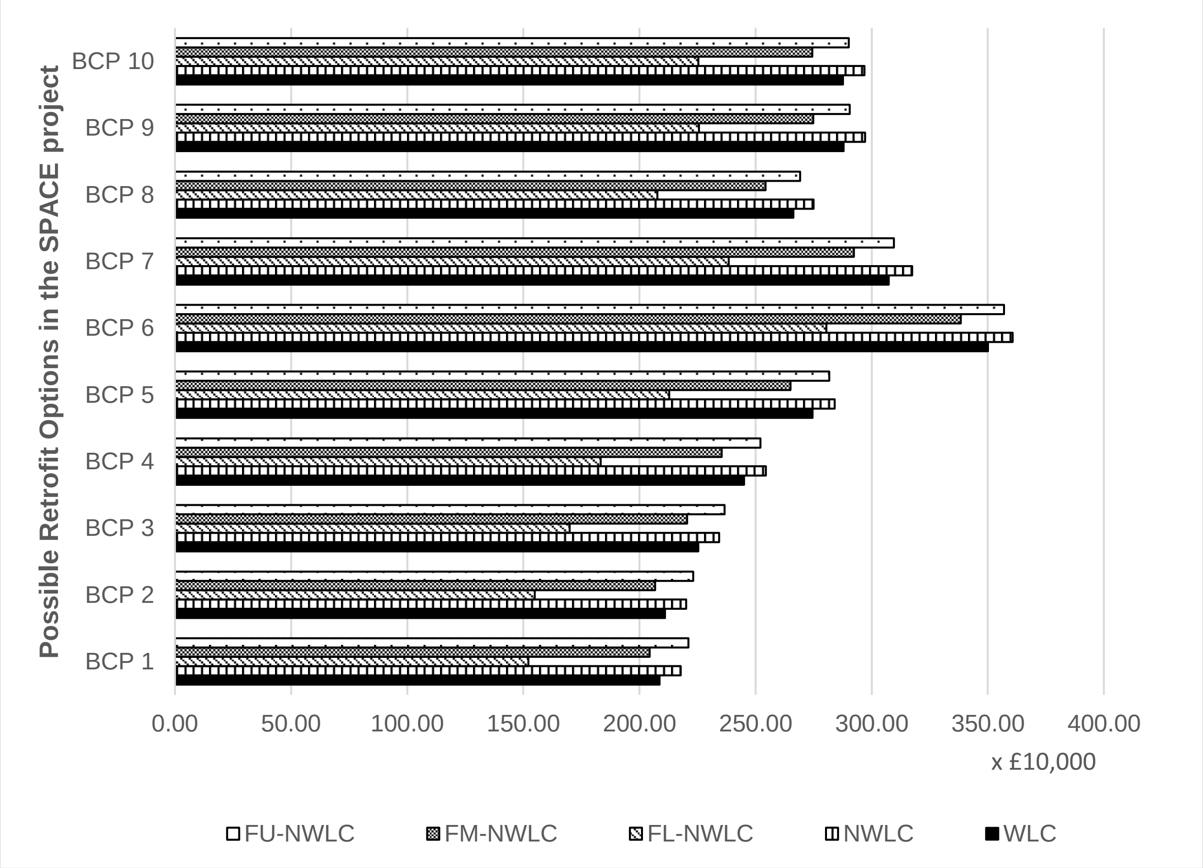


Figure 7-1   Whole-life Cost Estimates over a 20-year Period in SPACE project

Table 7:2 shows the whole-life cost estimates in the SPACE project, over a 40-year period, for the 10 BCPs considered. Over the estimated period, the declining discount rate schedule, is adopted which translates into assuming a discount rate of 3.5%, over the 1 – 30 year period, and the discount rate of 3.0%, over the 31 – 40 year period. This discount rate specification follows the guidance provided by HM-Treasury (2013). A revocability rate of 10%, is also adopted, over the period. Over a 40-year horizon, the whole-life cost estimate of BCPs considered in the SPACE project, could range between £3.1million and £5.6million. The Standard deviation of the whole-life cost estimates of the BCPs, over an estimated 40-year life, as reported in Table 7:2, ranges between £500,000 and £670,000. Although cost savings are relatively higher than the 20-year period, they are unlikely to alter decision-outcomes. It also follows that the range of the Standard deviations is around £170,000, over a 40-year period.

Table 7:2 Whole-life Cost Estimates over a 40-year Period in SPACE project

Runs	**WLC (£)**	**NWLC (£)**	**FL-NWLC (£)**	**FM-NWLC (£)**	**FU-NWLC (£)**
BCP 1	3,146,000	3,471,000	2,580,000	4,147,000	4,418,000
BCP 2	3,162,000	3,485,000	2,592,000	4,139,000	4,407,000
BCP 3	3,287,000	3,604,000	2,708,000	4,211,000	4,471,000
BCP 4	3,548,000	3,884,000	2,773,000	4,215,000	4,467,000
BCP 5	3,846,000	4,183,000	3,072,000	4,520,000	4,772,000
BCP 6	4,731,000	5,109,000	3,827,000	5,408,000	5,683,000
BCP 7	4,247,000	4,607,000	3,245,000	4,619,000	4,860,000
BCP 8	3,670,000	3,979,000	2,842,000	4,052,000	4,263,000
BCP 9	3,947,000	4,274,000	3,052,000	4,317,000	4,538,000
BCP 10	3,942,000	4,269,000	3,047,000	4,308,000	4,529,000

Figure 7-2 depicts the whole-life cost estimates of respective BCPs in the SPACE project, and suggests that BCP 6 represents the least cost-effective retrofit option. There is however, inexactness, as to the most cost-effective option, over the 40-year period, based on the results, from the different whole-life cost models – Standard, New-Generation, and Fuzzy New-Generation, Whole-life cost models. This suggests that the benefits of whole-life costing are becoming more conspicuous over the 40-year life period.

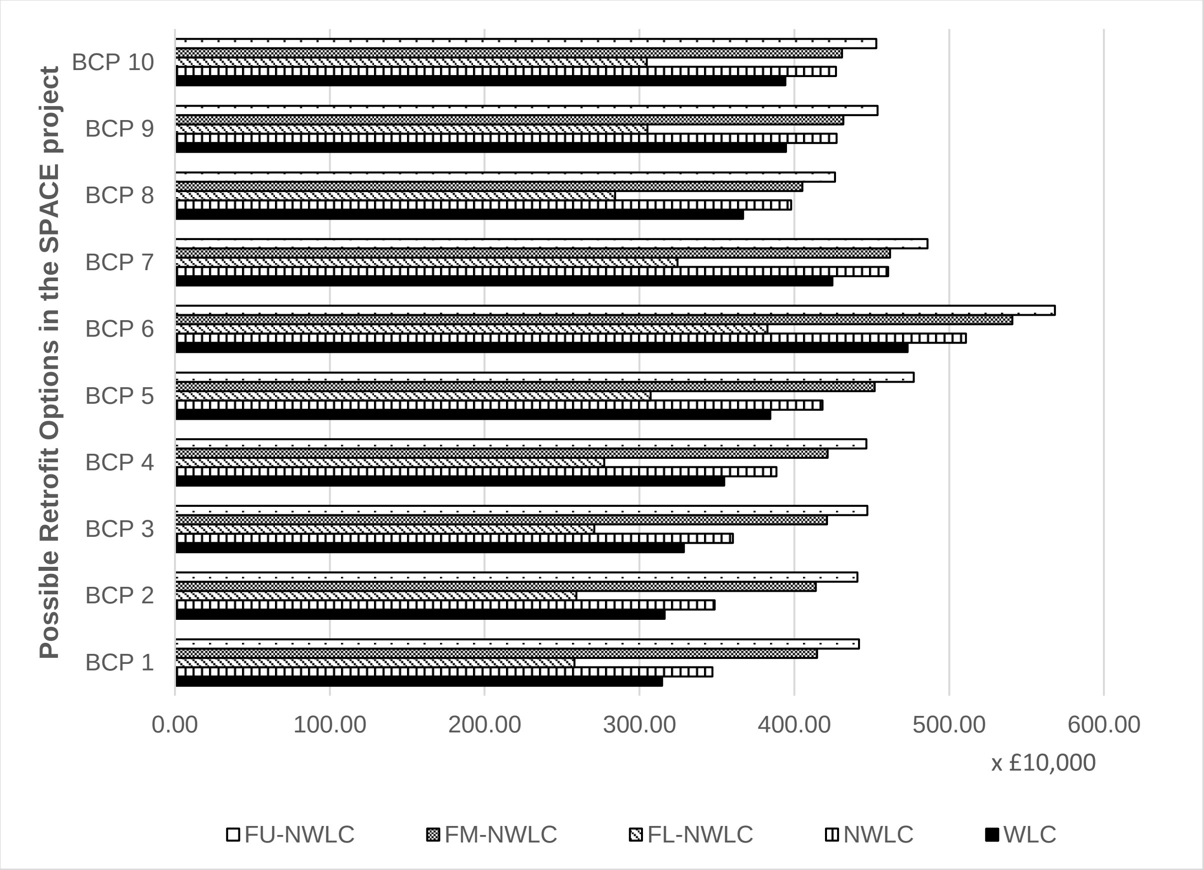


Figure 7-2 Whole-life Cost Estimates over a 40-year Period in SPACE project

Table 7:3 shows the whole-life cost estimates, over a 60-year period, for the 10 BCPs considered in the SPACE project. Over the estimated period, the declining discount rate schedule, is adopted, which translates into using a discount rate of 3.5%, over the 1 – 30 year period, and the discount rate of 3.0% over the 31 – 60 year period, following on from the guidance, provided by the HM-Treasury (2013). The revocability rate of 10%, is used, over the period under consideration. Over a 60-year horizon, the whole-life cost estimates, could range between £3.7million and £8.3million, with BCP 6 still constituting the least cost-effective office retrofit option, for all of the whole-life cost techniques. The Standard deviation of the 60-year, whole-life cost estimates of BCPs in the SPACE project, ranges between £900,000 and £1,800,000. The deviation is reasonably large, and implies that there is a potential for £900,000 difference in the whole-life cost estimates depending on the model used in estimation. The 60-year life provides a convincing context for whole-life cost analysis, and it can be expected that decision-makers in the SPACE project will be interested in the whole-life cost comparison of options, over the 60-year period, in order to make more informed choices on retrofit options.

Table 7:3 Whole-life Cost Estimates over a 60-year Period in SPACE project

Runs	WLC (£)	NWLC (£)	FL-NWLC (£)	FM-NWLC (£)	FU-NWLC (£)
BCP 1	3,726,000	4,310,000	3,996,000	7,385,000	7,892,000
BCP 2	3,737,000	4,317,000	3,979,000	7,310,000	7,808,000
BCP 3	3,852,000	4,422,000	4,030,000	7,230,000	7,708,000
BCP 4	4,147,000	4,752,000	3,821,000	6,601,000	7,016,000
BCP 5	4,447,000	5,053,000	4,129,000	6,925,000	7,342,000
BCP 6	5,403,000	6,081,000	4,920,000	7,892,000	8,334,000
BCP 7	4,889,000	5,535,000	3,977,000	6,271,000	6,611,000
BCP 8	4,221,000	4,776,000	3,541,000	5,634,000	5,944,000
BCP 9	4,530,000	5,118,000	3,754,000	5,903,000	6,222,000
BCP 10	4,525,000	5,112,000	3,743,000	5,883,000	6,200,000

Figure 7-3 shows the whole-life cost estimates of 10 BCPs, in the SPACE project, and it is unclear, as to which of the BCPs, is more cost-effective, as there is much more closeness in the whole-life cost values, from different models. This implies that a 60-year horizon provides a useful time horizon, to conduct whole-life cost analysis in the SPACE office retrofit building project.

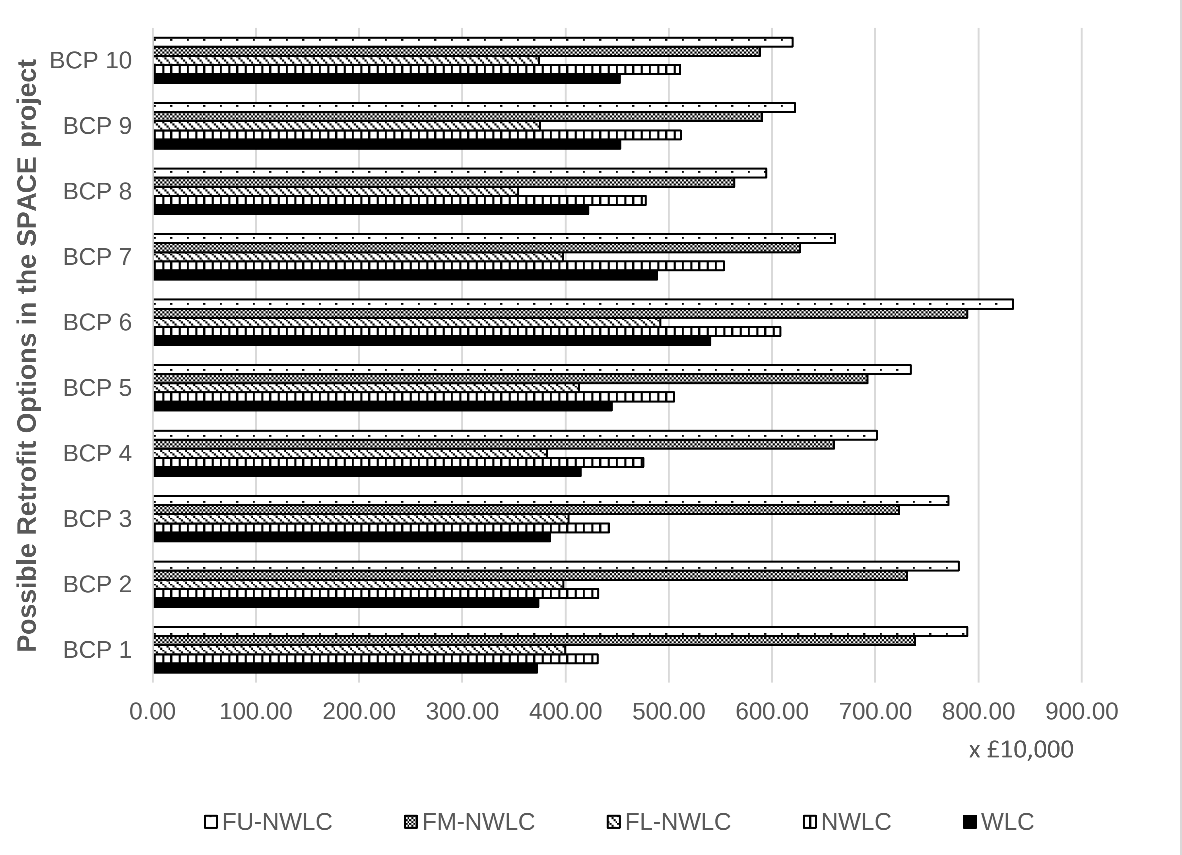


Figure 7-3 Whole-life Cost Estimates over a 60-year Period in SPACE project

7.2.2 Whole-life Cost values based on Discounting, Disruption and Revocability Scenario

Table 7:4 shows the whole-life cost estimate, over the 20-year period, for the 10 BCPs considered in the SPACE project. The added cost of disruption have been evaluated using the fuzzy logic approach, reported upon in Section 5.3, and individually detailed, in the Appendix A-1. The cost of disruption is exempt from the Standard Whole-life Costing approach, as well as in the New-Generation Whole-life Costing approach. It is only in the Fuzzy New-Generation Whole-life Costing approach, that the cost of disruption is evaluated. This distinction is necessary in order to appraise the insights of the new model, over the existing ones.

The declining discount rate schedule, provided by the HM-Treasury (2013) is applied for discounting purposes, and the revocability rate of 10%, is used in all the period under consideration. In this scenario, the Standard Whole-life costing (WLC) estimate of BCPs, still range between £2.1 million and £3.6 million. This similarity in cost estimates despite changing scenarios, suggests, the limited effects of disruption over this time period, and in the SPACE project. The cost of disruption in this case study, tend not be sufficiently large enough, to significantly influence decisions made in office retrofit building projects. This assertion is however, subject to the estimated value of the cost of disruption. It will be helpful for future work, to examine the cost of disruption in larger samples of office retrofit building projects, as well as in other commercial building typologies, to better understand the economic effects of disruption in retrofit scenarios.

Table 7:4 Whole-life Cost Estimates over a 20-year Period, with the added Cost of Disruption in the SPACE Project

Runs	**WLC (£)**	**NWLC (£)**	**FL-NWLC (£)**	**FM-NWLC (£)**	**FU-NWLC (£)**
BCP 1	2,087,000	2,178,000	1,522,000	2,045,000	2,210,000
BCP 2	2,111,000	2,201,000	1,553,000	2,072,000	2,237,000
BCP 3	2,254,000	2,343,000	1,702,000	2,221,000	2,390,000
BCP 4	2,450,000	2,545,000	1,837,000	2,364,000	2,535,000
BCP 5	2,746,000	2,840,000	2,132,000	2,675,000	2,857,000
BCP 6	3,501,000	3,607,000	2,808,000	3,409,000	3,609,000
BCP 7	3,074,000	3,175,000	2,389,000	2,951,000	3,140,000
BCP 8	2,663,000	2,750,000	2,083,000	2,573,000	2,741,000
BCP 9	2,880,000	2,972,000	2,261,000	2,775,000	2,949,000
BCP 10	2,877,000	2,969,000	2,259,000	2,772,000	2,946,000

The results in Table 7:4, provides an indication of the disparity between existing whole-life cost models, and the fuzzy models. The fuzzy models suggests that the combined costs of disruption and revocability, has potential to increase the total whole-life cost estimate in the SPACE project by up to 4%, over a 20-year estimated life range. The Standard Deviation of the whole-life cost estimates of BCPs in the SPACE project, over a 20-year life, ranges between £250,000 and £300,000. It also follows that the range of around £50,000, remains true for retrofit options in the SPACE project, over the 20-year horizon. It is also noticeable that the cumulative effects of revocability and disruption, are unlikely to significantly influence decisions, made on office retrofit building projects, over a 20-year estimated life. Figure 7-4 shows the whole-life cost estimates of BCPs in the SPACE project, over a 20-year estimated life. From Figure 7-4, it is noticeable that BCP 6, has the highest whole-life cost estimate, over the 20-year horizon, and is therefore, unlikely, that this building configuration will appeal to decision-makers on the SPACE project, on a whole-life cost basis.

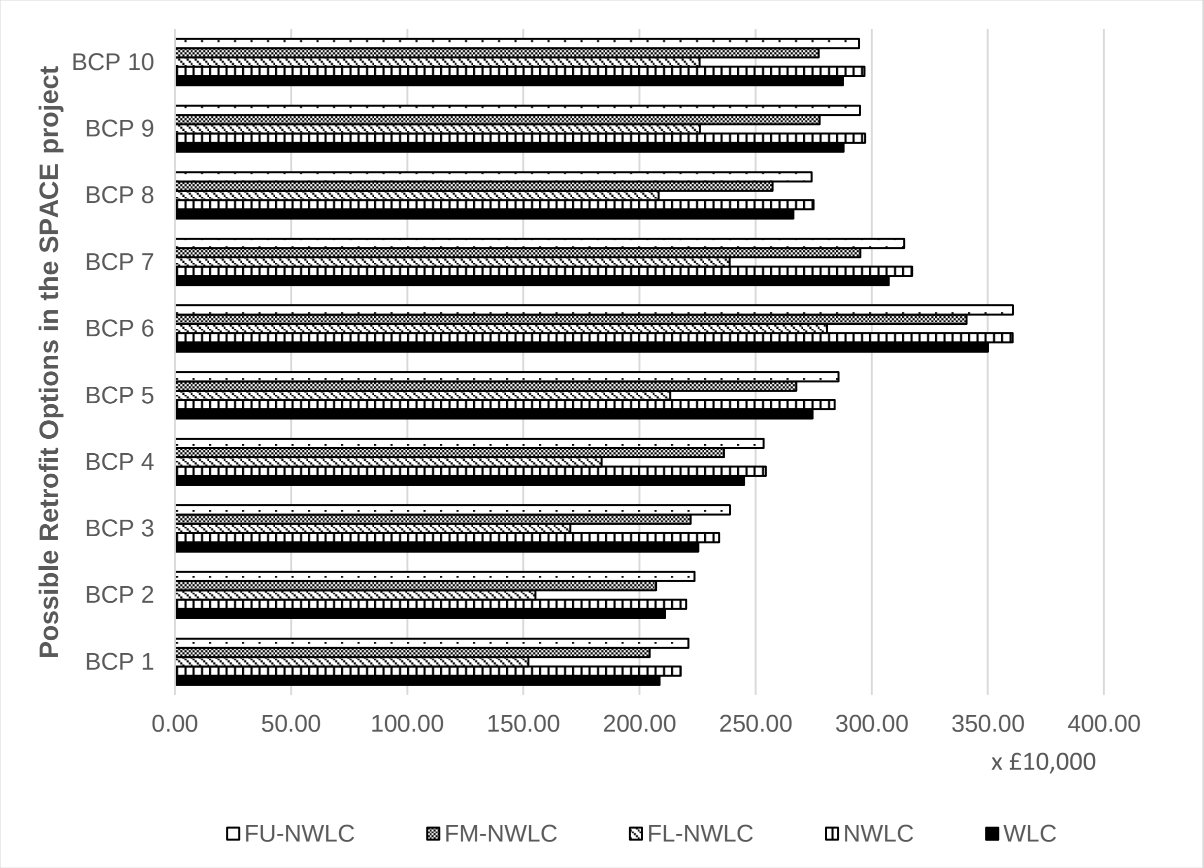


Figure 7-4 Whole-life Cost Estimates over a 20-year Period, with the added cost of Disruption), in SPACE Project

Table 7:5 reports on the whole-life cost estimates of BCPs in the SPACE project, over the 40-year period. The Standard deviation ranges between £500,000 and £660,000. These values provide indications that, there is a tendency that the cost of disruption will have more significant impacts, regarding decisions on office retrofit projects, in the SPACE project.

Table 7:5 Whole-life Cost Estimates over a 40-year Period with the added cost of Disruption, in SPACE project

Runs	WLC (£)	NWLC (£)	FL-NWLC (£)	FM-NWLC (£)	FU-NWLC (£)
BCP 1	3,147,000	3,472,000	2,580,000	4,147,000	4,418,000
BCP 2	3,162,000	3,485,000	2,595,000	4,144,000	4,413,000
BCP 3	3,287,000	3,604,000	2,711,000	4,226,000	4,495,000
BCP 4	3,548,000	3,884,000	2,777,000	4,225,000	4,481,000
BCP 5	3,846,000	4,183,000	3,076,000	4,545,000	4,812,000
BCP 6	4,731,000	5,109,000	3,831,000	5,432,000	5,722,000
BCP 7	4,247,000	4,607,000	3,250,000	4,646,000	4,903,000
BCP 8	3,670,000	3,979,000	2,848,000	4,082,000	4,313,000
BCP 9	3,947,000	4,274,000	3,057,000	4,344,000	4,582,000
BCP 10	3,942,000	4,269,000	3,052,000	4,336,000	4,573,000

Table 7:5 report on the whole-life cost estimates of existing whole-life costing models, and the newly developed Fuzzy New-Generation Whole-life cost model. The Fuzzy model suggests that, the combined cost of disruption and revocability, has potential to increase the whole-life cost estimate in the SPACE project, by up to 20%, over a 40-year estimated life range.

Figure 7-5 shows the whole-life cost estimates of BCPs over a 40-year period. BCP 6 demonstrates potential of least whole-life cost-effectiveness, based on the fuzzy model, but other BCPs are catching up with regards to whole-life costs. It is however, not definitive, as to which BCP constitute the most economical BCP over this period.

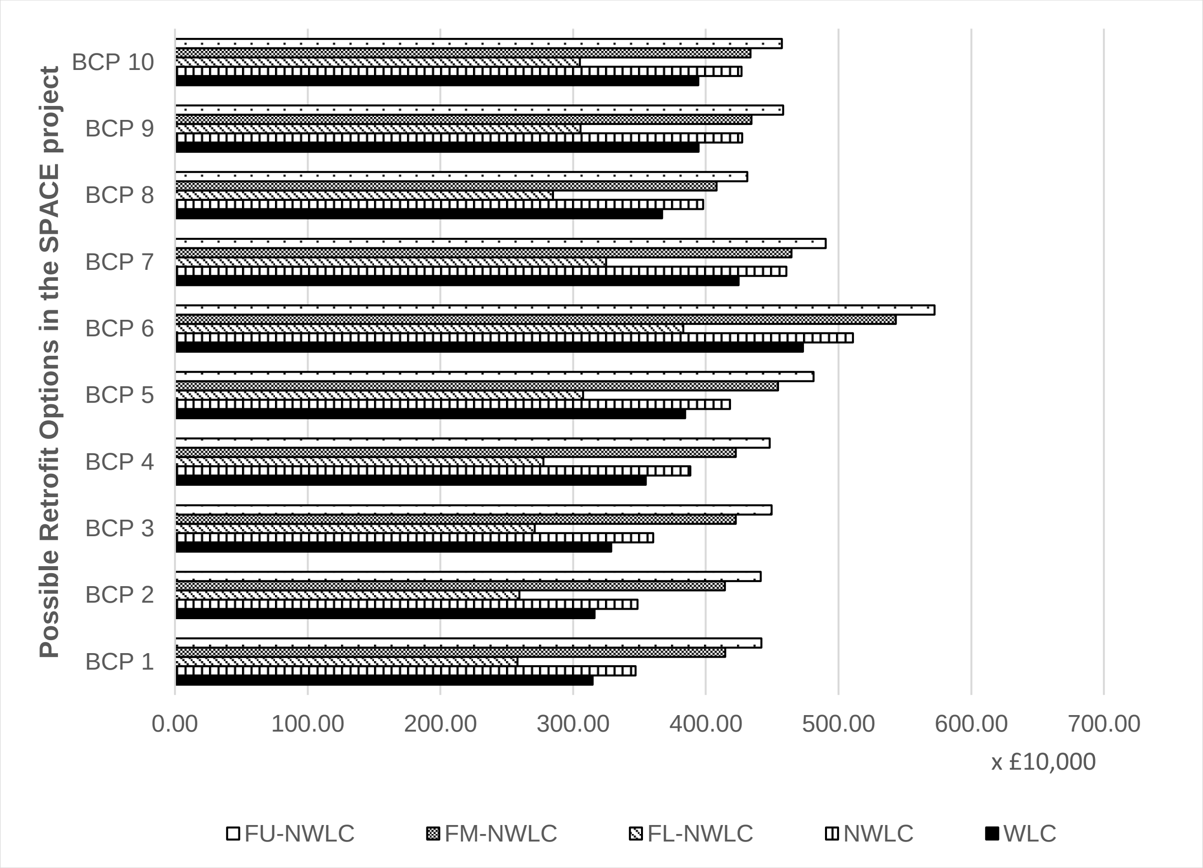


Figure 7-5 Whole-life Cost Estimates over a 40-year Period, with the added Cost of Disruption, in the SPACE Project

Table 7:6 provides the whole-life cost estimates of BCPs in the SPACE project, over a 60-year period, with the included the cost of disruption. The evaluation of the whole-life cost is based on the declining discount rate schedule, specified by HM-Treasury (2013), which is 3.5% over the 30-year period, and 3% over the 31-year to

60-year period. The Standard deviation of BCPs range between £900,000 and £1,800,000. This period of horizon arguably provide a reasonable and convincing context, for conducting whole-life costing analysis, on the SPACE office retrofit building project.

Table 7:6 Whole-life Cost Estimates over a 60-year Period, with the added cost of Disruption, in the SPACE project

Runs	WLC	NWLC	FL-NWLC	FM-NWLC	FU-NWLC
BCP 1	3,726,000	4,310,000	3,997,000	7,385,000	7,892,000
BCP 2	3,737,000	4,317,000	3,983,000	7,315,000	7,814,000
BCP 3	3,852,000	4,422,000	4,033,000	7,246,000	7,733,000
BCP 4	4,148,000	4,753,000	3,825,000	6,611,000	7,030,000
BCP 5	4,447,000	5,053,000	4,132,000	6,950,000	7,381,000
BCP 6	5,404,000	6,081,000	4,923,000	7,917,000	8,374,000
BCP 7	4,889,000	5,535,000	3,981,000	6,298,000	6,655,000
BCP 8	4,221,000	4,776,000	3,547,000	5,664,000	5,994,000
BCP 9	4,530,000	5,118,000	3,758,000	5,931,000	6,266,000
BCP 10	4,525,000	5,112,000	3,748,000	5,910,000	6,244,000

The results in Table 7:6 also provide the whole-life cost estimates of retrofit options in the SPACE project, over a 60-year period, with the added cost of disruption. The numerical difference between existing whole-life cost models, and the fuzzy models, over an estimated 60-year period is relatively significant. The results suggest that, the added cost of disruption and revocability, has potential to increase the whole-life cost estimate in the SPACE project by up to 38% over a 60-year estimated life range.

Figure 7-6 provides the whole-life cost values for BCPs in the SPACE project, over a 60-year estimated life. BCP 6 stands out as the least cost-effective retrofit option, in the SPACE project, on a whole-life basis. However, there is the possibility that the effects of the cost of disruption are reasonably diminished, as the whole-life cost estimates of BCPs, become more comparable, and equal in values.

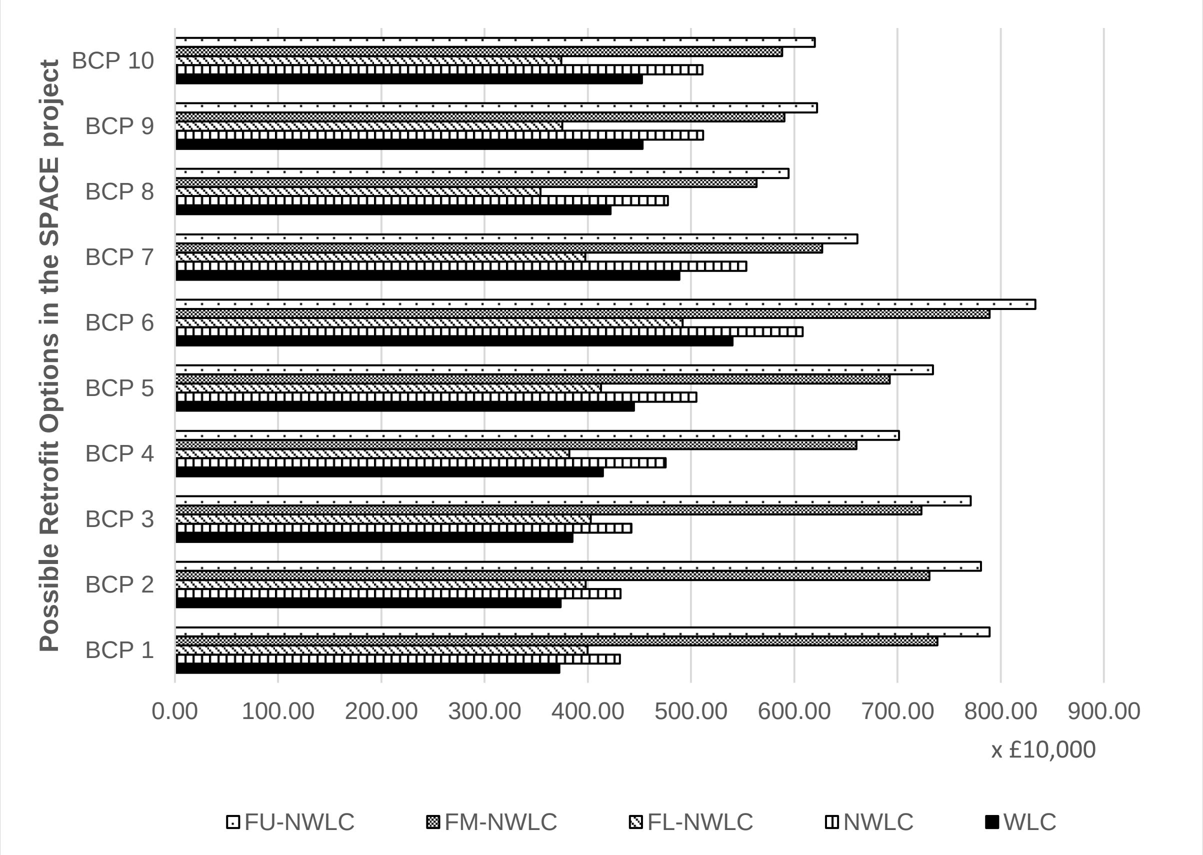


Figure 7-6 Whole-life Cost Estimates over a 60-year Period, with the added Cost of Disruption, in the SPACE project

7.3 Whole-life Cost Estimates of Options in the MS Project

In the MS office building project, 22 BCPs were evaluated based on the different whole-life cost models, over a period of 20 years, 40 years and 60 years. The time-value of money, was adjusted for, based on the declining discount rate schedule suggested by the HM-Treasury (2013), which corresponds to 3.5% over a period of 1 – 30 years, 3% over a period of 31 – 75 years, and following on to 1%, over a period greater than 300 years.

7.3.1 Whole-life Cost Values based on Discounting and Revocability scenario

Table 7:7 shows the whole-life cost estimates of the various BCPs considered in the MS project. The evaluation of the whole-life cost values of the BCPs considered the initial costs, maintenance and operating costs, and utilities (electricity and gas) costs. This were evaluated based on the declining discount rate schedule, specified by HM-Treasury (2013), which is 3.5% over the 20-year period. The New-Generation whole-life costing model, and the newly developed Fuzzy New-Generation Whole-life cost model adopted a revocability rate of 10%, - which implies a possible increase or decrease in the future costs, in succeeding years. This is consistent with assumptions in the SPACE project, and in previous work by Ellingham and Fawcett (2006).

In the Standard Whole-life Costing (WLC), revocability is not recognised in its framework (Kishk, 2005; Ellingham and Fawcett, 2006). However, revocability is implied in the New-Generation whole-life cost (NWLC) model, and the Fuzzy New-Generation Whole-life Costing model. This distinction in the model parameters in the different genres of whole-life cost models, provide a scope for appraising the effects of revocability and disruption, in the whole-life costing framework.

Table 7:7 Whole-life Cost Estimates over a 20-year Period in the MS Project

Runs	**WLC ($)**	**NWLC ($)**	**FL-NWLC ($)**	**FM-NWLC ($)**	**FU-NWLC ($)**
BCP 1	3,240,000	3,297,000	2,586,000	3,257,000	3,473,000
BCP 2	2,575,000	2,624,000	2,166,000	2,642,000	2,794,000
BCP 3	4,472,000	4,535,000	3,439,000	4,393,000	4,704,000
BCP 4	3,564,000	3,613,000	2,939,000	3,561,000	3,762,000
BCP 5	2,863,000	2,904,000	2,491,000	2,908,000	3,041,000
BCP 6	3,673,000	3,719,000	3,063,000	3,661,000	3,855,000
BCP 7	2,927,000	2,962,000	2,577,000	2,958,000	3,080,000
BCP 8	3,595,000	3,644,000	2,974,000	3,591,000	3,790,000
BCP 9	3,653,000	3,696,000	3,055,000	3,634,000	3,822,000
BCP 10	2,953,000	2,987,000	2,607,000	2,981,000	3,101,000
BCP 11	4,871,000	4,925,000	3,873,000	4,770,000	5,062,000
BCP 12	2,857,000	2,894,000	2,501,000	2,892,000	3,017,000
BCP 13	3,575,000	3,613,000	2,997,000	3,543,000	3,720,000
BCP 14	2,908,000	2,939,000	3,147,000	3,661,000	3,829,000
BCP 15	5,213,000	5,267,000	4,140,000	5,086,000	5,396,000
BCP 16	3,865,000	3,908,000	3,187,000	3,823,000	4,030,000
BCP 17	3,199,000	3,235,000	2,767,000	3,208,000	3,351,000
BCP 18	3,976,000	4,014,000	3,319,000	3,921,000	4,117,000
BCP 19	3,358,000	3,392,000	2,939,000	3,361,000	3,497,000
BCP 20	3,506,000	3,541,000	3,079,000	3,512,000	3,651,000
BCP 21	5,695,000	5,726,000	5,073,000	5,619,000	5,797,000
BCP 22	5,717,000	5,743,000	5,409,000	5,722,000	5,823,000

Figure 7-7 depicts the whole-life cost estimates for BCPs, considered in the MS Office retrofit project. Over a 20-year horizon, the whole-life cost estimate could range between $2.1million and $5.8 million. BCP 21 and BCP 22 however, appears to be the least cost-effective option, while BCP 2 seems the most cost-effective. The Standard deviation of the whole-life cost estimates of BCPs, over a 20-year period, ranges from $140,000 to $450,000. Although, this range is much higher than those observed in the SPACE project, and the BCPs, are more in number. It is perceived that whole-life cost savings, over a time-horizon of 20-years, is unlikely to be a key driver, for investors embarking on a retrofit work in this project.

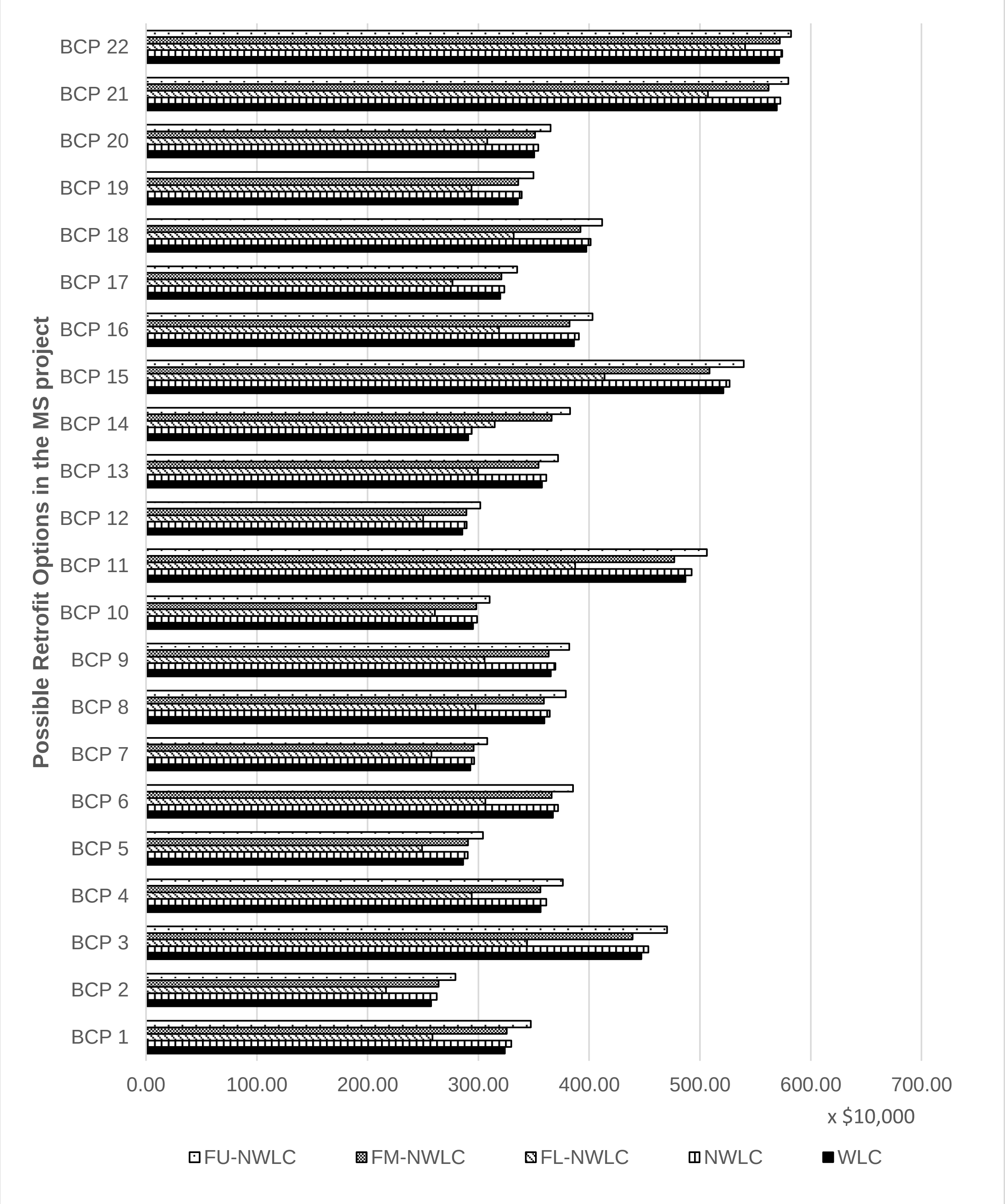


Figure 7-7 Whole-life Cost Estimates over a 20-year Period in the MS Project

Table 7:8 shows the whole-life cost estimates, over a 40-year period, for the 22 BCPs considered in the MS project. Over the estimated period, the declining discount rate schedule, is adopted to adjust for the time-value of money, which translates into using a discount rate of 3.5%, over the 1 – 30 year period, and the discount rate of 3.0% over the 31 – 40 year period. The revocability rate of 10% is applied over the period under consideration. Over a 40-year horizon, the whole-life cost estimate in the MS project range between $3.1 million and $5.6 million. The Standard deviation of whole-life cost estimates of BCPs ranges between $360,000 and $990,000.

Figure 7-8 depicts the whole-life cost estimates of respective BCPs in the MS project, and shows that BCP 15 has the highest whole-life cost. There is however, an inexactness as to the most cost effective option, over the 40-year period. This implies that whole-life costing, over the 40-year period will provide a good context to assess office retrofit building options. Also, further analysis could be required, to assess the predictions of whole-life cost estimates and the eventual whole-life cost outcomes.

Table 7:8 Whole-life Cost Estimates over a 40-year Period in the MS Project

Runs	**WLC ($)**	**NWLC ($)**	**FL-NWLC ($)**	**FM-NWLC ($)**	**FU-NWLC ($)**
BCP 1	4,452,000	4,678,000	3,738,000	5,568,000	5,893,000
BCP 2	3,395,000	3,577,000	3,076,000	4,474,000	4,716,000
BCP 3	6,268,000	6,547,000	4,906,000	7,328,000	7,768,000
BCP 4	4,699,000	4,900,000	3,976,000	5,640,000	5,937,000
BCP 5	3,591,000	3,745,000	3,263,000	4,459,000	4,668,000
BCP 6	4,772,000	4,963,000	4,047,000	5,633,000	5,917,000
BCP 7	3,600,000	3,736,000	3,266,000	4,342,000	4,531,000
BCP 8	4,723,000	4,922,000	3,999,000	5,646,000	5,940,000
BCP 9	4,722,000	4,903,000	3,993,000	5,513,000	5,785,000
BCP 10	3,614,000	3,747,000	3,279,000	4,332,000	4,516,000
BCP 11	6,577,000	6,829,000	5,207,000	7,434,000	7,841,000
BCP 12	3,546,000	3,687,000	3,214,000	4,326,000	4,520,000
BCP 13	4,593,000	4,759,000	3,859,000	5,269,000	5,523,000
BCP 14	3,535,000	3,657,000	3,196,000	4,173,000	4,345,000
BCP 15	7,028,000	7,286,000	5,516,000	7,833,000	8,258,000
BCP 16	5,054,000	5,245,000	4,184,000	5,819,000	6,114,000
BCP 17	3,997,000	4,144,000	3,522,000	4,724,000	4,937,000
BCP 18	5,112,000	5,287,000	4,237,000	5,758,000	6,034,000
BCP 19	4,126,000	4,265,000	3,649,000	4,786,000	4,988,000
BCP 20	4,290,000	4,433,000	3,814,000	4,987,000	5,195,000
BCP 21	6,744,000	6,892,000	5,860,000	7,190,000	7,434,000
BCP 22	6,286,000	6,390,000	5,941,000	6,791,000	6,942,000

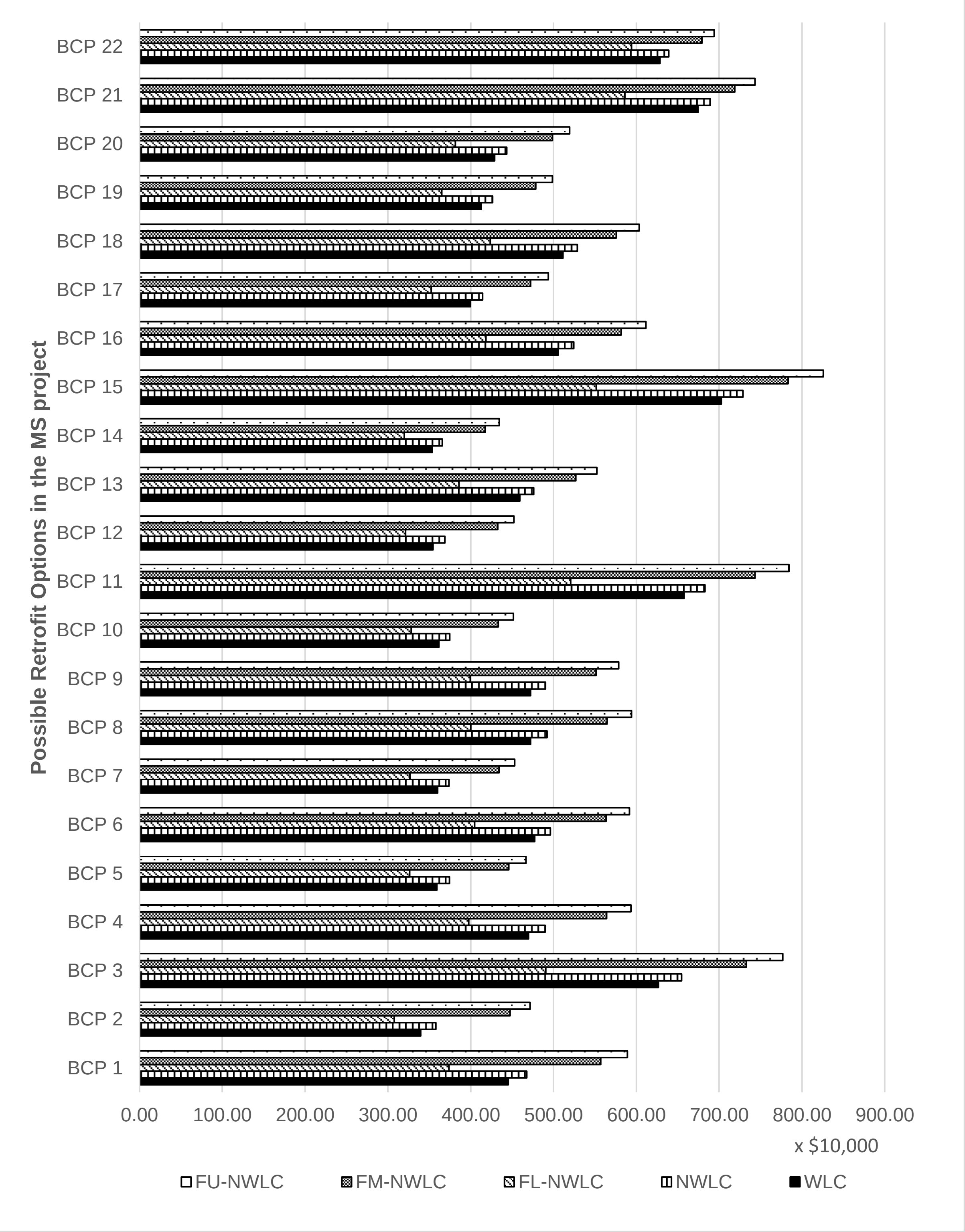


Figure 7-8 Whole-life Cost Estimates over a 40-year Period in MS Project

Table 7:9 presents the whole-life cost estimates, over a 60-year period, for the 22 BCPs considered in the MS project. Over the estimated period, the declining discount rate schedule, is adopted to adjust for the time-value of money, which translates into using a discount rate of 3.5%, over the 1 – 30 year period, and the discount rate of 3.0%, over the 31 – 60 year period. The revocability rate of 10% is used, over the period under consideration. Over a 60-year horizon, whole-life cost estimates could range between $3.8 million and $12 million. The Standard deviation of the whole-life cost estimates is between $925,000 and $2.2 million. This is arguably a large range, and deviations, are much larger than, over the 20-year and 40-year estimated life. This large disparity in whole-life cost values of retrofit options, in the MS project provide a convincing context for the conduct of whole-life costing. Figure 7-9 shows the whole-life cost estimates of BCPs in the MS project, and it is unclear, as to which of the BCPs constitutes the most cost-effective, as there is much more proximity in the whole-life cost values, especially as seen, in BCP 3 and BCP 15, from different models. This implies that a 60-year horizon provides a reasonable time horizon to conduct whole-life cost analysis in retrofit scenarios in office buildings.

Table 7:9 Whole-life Cost Estimates over a 60-year Period in the MS Project

Runs	**WLC ($)**	**NWLC ($)**	**FL-NWLC ($)**	**FM-NWLC ($)**	**FU-NWLC ($)**
BCP 1	5,053,000	5,458,000	5,280,000	9,091,000	9,653,000
BCP 2	3,802,000	4,123,000	4,415,000	7,541,000	7,992,000
BCP 3	7,158,000	7,672,000	6,652,000	11,295,000	12,000,000
BCP 4	5,261,000	5,626,000	5,326,000	8,719,000	9,224,000
BCP 5	3,952,000	4,224,000	4,369,000	6,992,000	7,372,000
BCP 6	5,318,000	5,663,000	5,308,000	8,508,000	8,985,000
BCP 7	3,933,000	4,176,000	4,234,000	6,557,000	6,896,000
BCP 8	5,282,000	5,642,000	5,330,000	8,681,000	9,180,000
BCP 9	5,252,000	5,581,000	5,177,000	8,210,000	8,664,000
BCP 10	3,942,000	4,179,000	4,220,000	6,482,000	6,812,000
BCP 11	7,423,000	7,889,000	6,728,000	10,884,000	11,522,000
BCP 12	3,887,000	4,139,000	4,223,000	6,635,000	6,986,000
BCP 13	5,098,000	5,400,000	4,916,000	7,675,000	8,091,000
BCP 14	3,846,000	4,064,000	4,049,000	6,123,000	6,427,000
BCP 15	7,928,000	8,408,000	7,036,000	11,277,000	11,932,000
BCP 16	5,644,000	5,993,000	5,397,000	8,577,000	9,058,000
BCP 17	4,392,000	4,658,000	4,531,000	7,028,000	7,397,000
BCP 18	5,676,000	5,998,000	5,319,000	8,214,000	8,655,000
BCP 19	4,507,000	4,757,000	4,583,000	6,916,000	7,262,000
BCP 20	4,679,000	4,937,000	4,789,000	7,212,000	7,570,000
BCP 21	7,264,000	7,539,000	6,721,000	9,138,000	9,513,000
BCP 22	6,567,000	6,755,000	6,648,000	8,404,000	8,664,000

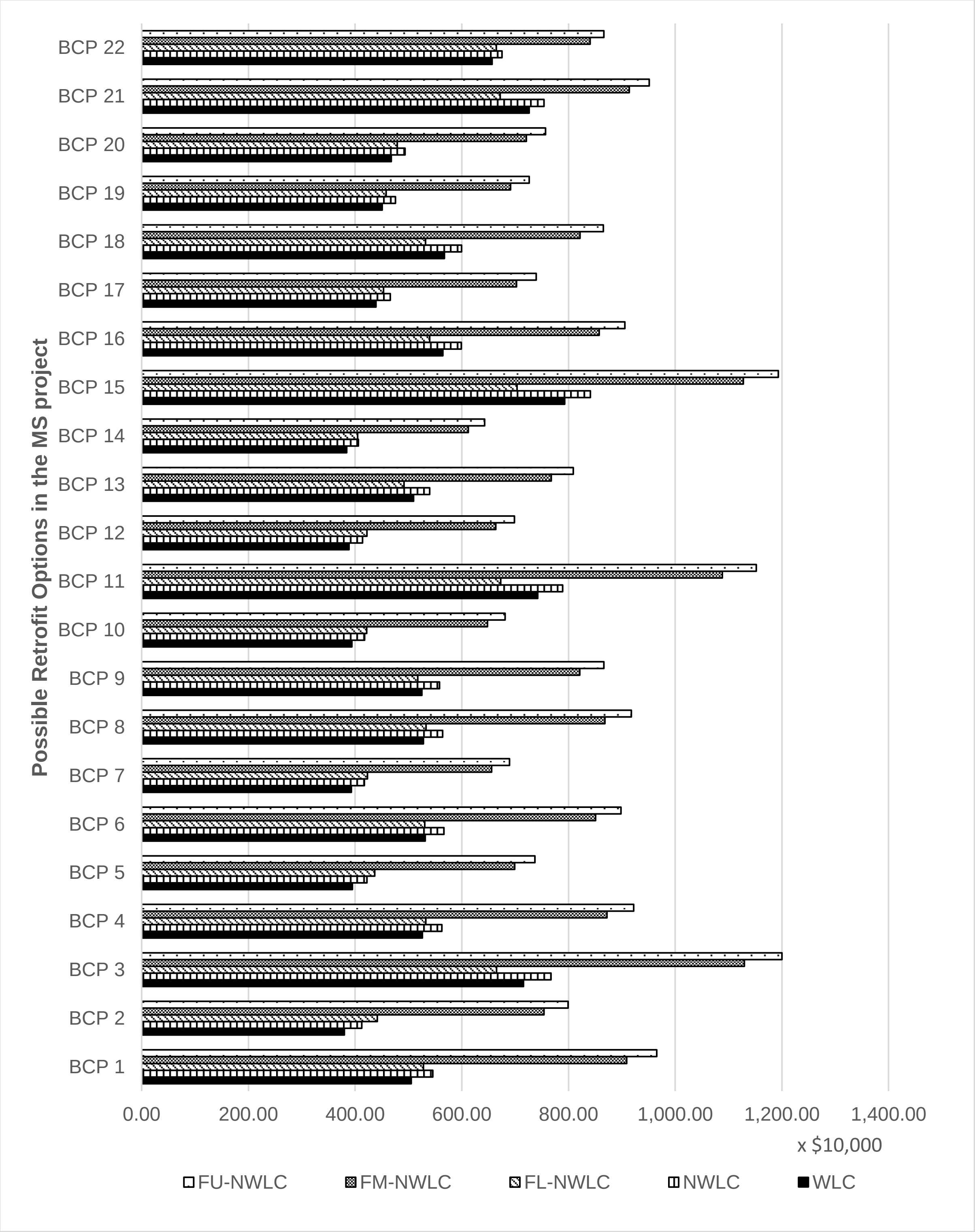


Figure 7-9 Whole-life Cost Estimates over a 60-year Period in the MS Project

7.3.2 Whole-life Cost values based on Discounting, Disruption and Revocability Scenario

Table 7:10 shows the whole-life cost estimates, over a 20-year period for the 22 BCPs considered in the MS project. Over the estimated period, the declining discount rate schedule is adopted, which translates into using a discount rate of 3.5%, over the 1 – 20 year period. Over the 20-year horizon, the whole-life cost estimate of retrofit options under this scenario could range between $2.5 million and $5.8 million.

Table 7:10 Whole-life Cost Estimates over a 20-year Period, with added Cost of Disruption in the MS Project

Runs	WLC ($)	NWLC ($)	FL-NWLC ($)	FM-NWLC ($)	FU-NWLC ($)
BCP 1	3,240,000	3,297,000	2,592,000	3,272,000	3,498,000
BCP 2	2,575,000	2,624,000	2,174,000	2,661,000	2,822,000
BCP 3	4,472,000	4,535,000	3,447,000	4,411,000	4,732,000
BCP 4	3,564,000	3,613,000	2,941,000	3,564,000	3,765,000
BCP 5	2,863,000	2,904,000	2,500,000	2,926,000	3,069,000
BCP 6	3,673,000	3,719,000	3,071,000	3,680,000	3,883,000
BCP 7	2,927,000	2,962,000	2,579,000	2,960,000	3,083,000
BCP 8	3,595,000	3,644,000	2,982,000	3,609,000	3,818,000
BCP 9	3,653,000	3,696,000	3,065,000	3,655,000	3,853,000
BCP 10	2,953,000	2,987,000	2,617,000	3,002,000	3,132,000
BCP 11	4,871,000	4,925,000	3,875,000	4,772,000	5,066,000
BCP 12	2,857,000	2,894,000	2,502,000	2,894,000	3,020,000
BCP 13	3,575,000	3,613,000	3,005,000	3,561,000	3,748,000
BCP 14	2,908,000	2,939,000	3,157,000	3,683,000	3,860,000
BCP 15	5,213,000	5,267,000	4,150,000	5,107,000	5,427,000
BCP 16	3,865,000	3,908,000	3,197,000	3,844,000	4,061,000
BCP 17	3,199,000	3,235,000	2,792,000	3,249,000	3,405,000
BCP 18	3,976,000	4,014,000	3,331,000	3,945,000	4,152,000
BCP 19	3,358,000	3,392,000	2,592,000	3,272,000	3,498,000
BCP 20	3,506,000	3,541,000	2,174,000	2,660,000	2,822,000
BCP 21	5,695,000	5,726,000	3,447,000	4,411,000	4,732,000
BCP 22	5,717,000	5,743,000	2,941,000	3,564,000	3,765,000

The results in Table 7:10 provide an indication of the average disparity between existing whole-life cost models and the fuzzy model. The fuzzy model suggests the added cost of disruption and revocability has potential to increase the whole-life cost estimate in the MS project by only up to 2%, over a 20-year estimated life.

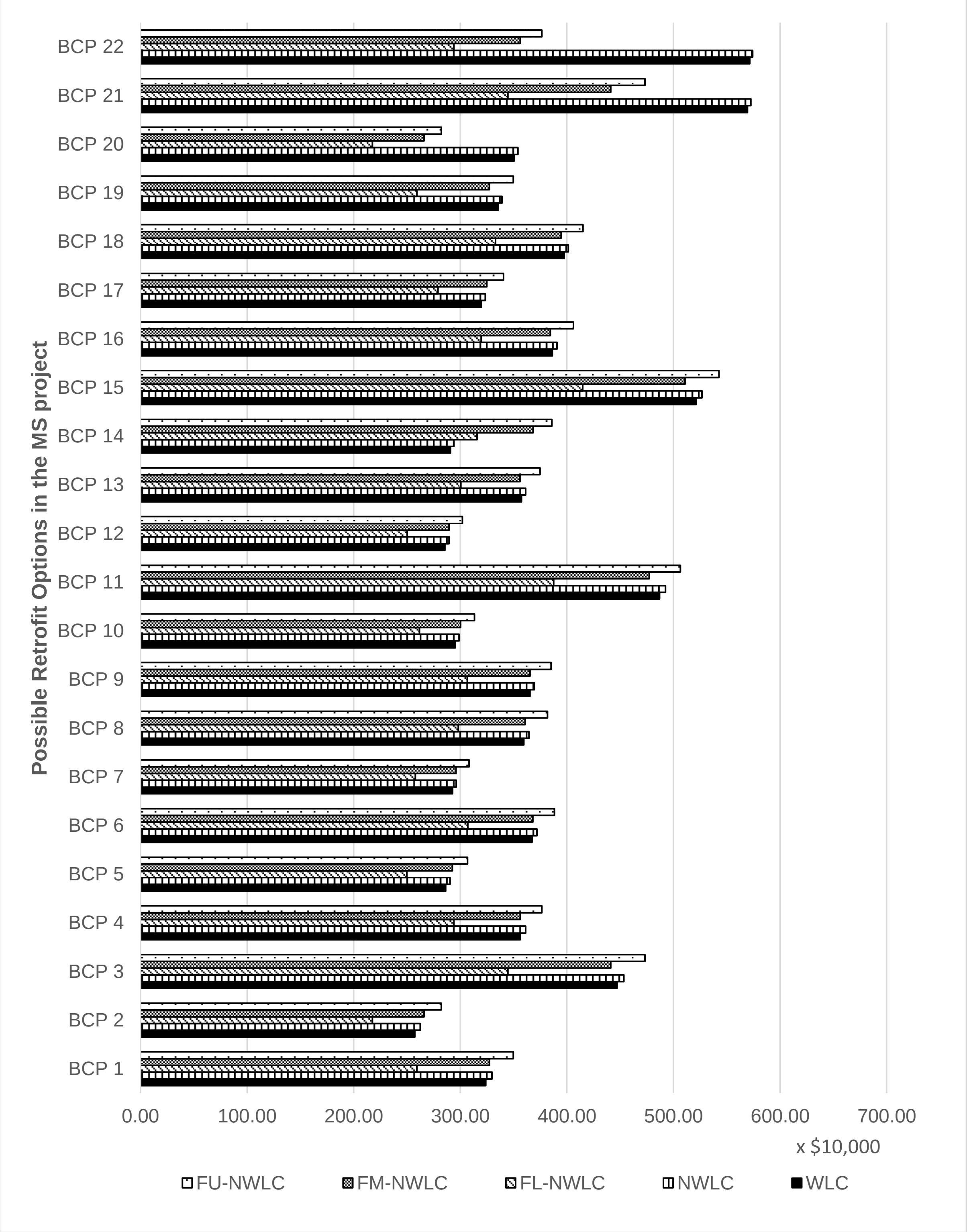


Figure 7-10 Whole-life Cost Estimates over a 20-year Period, with added Cost of Disruption in the MS Project

Table 7:11 shows the whole-life cost estimates, over a 40-year period, for the 22 BCPs considered in the MS project. Over the estimated period, the declining discount rate schedule is adopted, which translates into adopting a discount rate of 3.5% over the 1 – 30 year period, and a discount rate of 3% over the 31 – 40 year period. Over a 40-year horizon, the whole-life cost estimate of retrofit options, could range between $3.3 million and $8.3 million.

Table 7:11 Whole-life Cost Estimates over a 40-year Period, with added Cost of Disruption, in the MS project.

Runs	**WLC ($)**	**NWLC ($)**	**FL-NWLC ($)**	**FM-NWLC ($)**	**FU-NWLC ($)**
BCP 1	4,452,000	4,678,000	3,744,000	5,584,000	5,918,000
BCP 2	3,395,000	3,577,000	3,084,000	4,492,000	4,744,000
BCP 3	6,268,000	6,547,000	4,915,000	7,347,000	7,796,000
BCP 4	4,699,000	4,900,000	3,978,000	5,643,000	5,940,000
BCP 5	3,591,000	3,745,000	3,271,000	4,477,000	4,696,000
BCP 6	4,772,000	4,963,000	4,055,000	5,651,000	5,945,000
BCP 7	3,600,000	3,736,000	3,268,000	4,345,000	4,534,000
BCP 8	4,723,000	4,922,000	4,008,000	5,665,000	5,968,000
BCP 9	4,722,000	4,903,000	4,003,000	5,534,000	5,817,000
BCP 10	3,614,000	3,747,000	3,289,000	4,353,000	4,548,000
BCP 11	6,577,000	6,829,000	5,209,000	7,437,000	7,844,000
BCP 12	3,546,000	3,687,000	3,215,000	4,329,000	4,524,000
BCP 13	4,593,000	4,759,000	3,867,000	5,287,000	5,551,000
BCP 14	3,535,000	3,657,000	3,206,000	4,194,000	4,376,000
BCP 15	7,028,000	7,286,000	5,526,000	7,854,000	8,290,000
BCP 16	5,054,000	5,245,000	4,194,000	5,840,000	6,146,000
BCP 17	3,997,000	4,144,000	3,547,000	4,765,000	4,992,000
BCP 18	5,112,000	5,287,000	4,249,000	5,782,000	6,069,000
BCP 19	4,126,000	4,265,000	3,744,000	5,584,000	5,918,000
BCP 20	4,290,000	4,433,000	3,084,000	4,492,000	4,744,000
BCP 21	6,744,000	6,892,000	4,915,000	7,347,000	7,796,000
BCP 22	6,286,000	6,390,000	3,978,000	5,643,000	5,940,000

The results in Table 7:11, also provide an indication on the average difference between existing whole-life cost models, and the fuzzy models. The fuzzy model suggests that, the added cost of disruption and revocability, has potential to increase the whole-life cost estimate in the MS project by up to 19%, over a 40-year estimated life range.

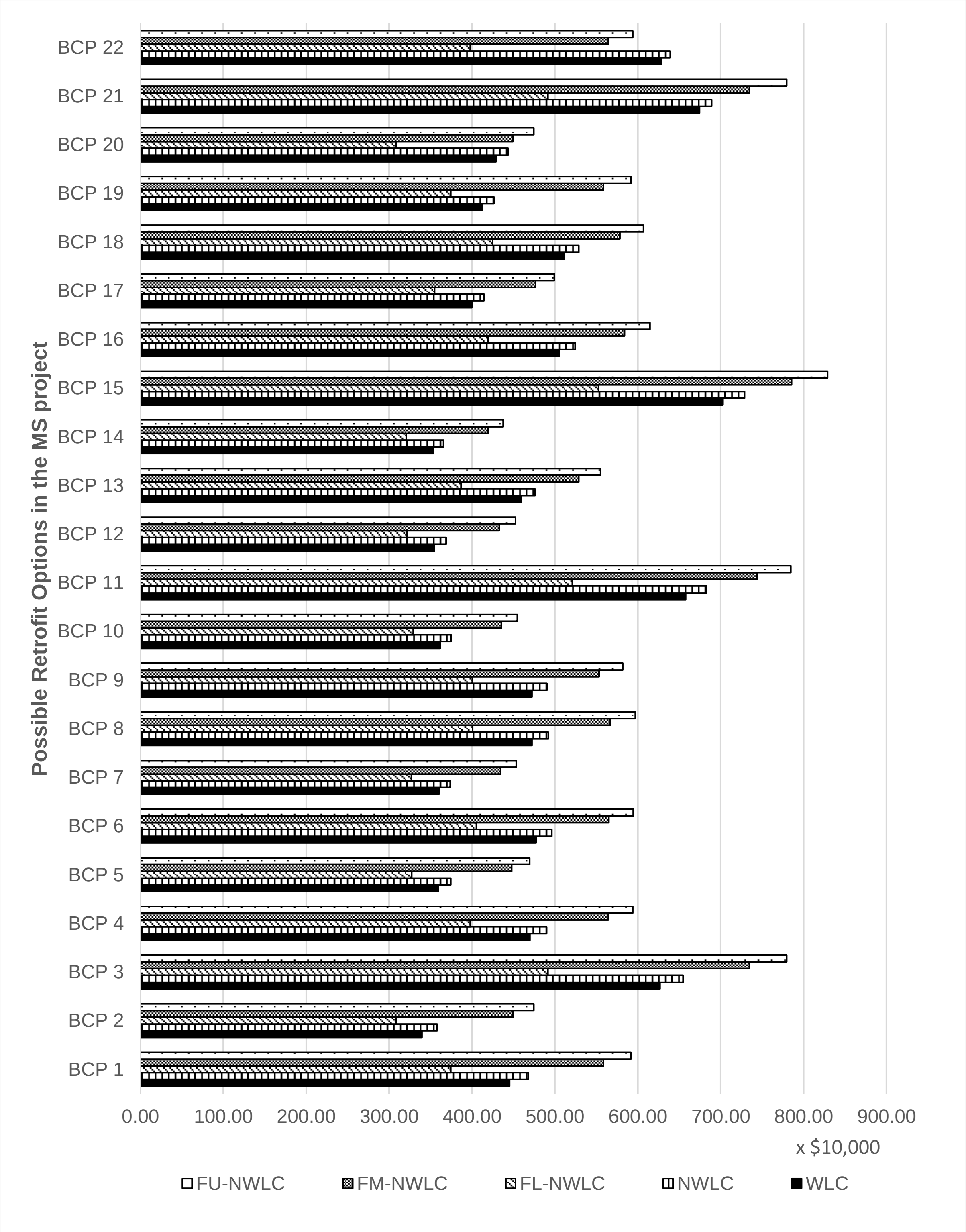


Figure 7-11 Whole-life Cost Estimates over a 40-year Period, with added cost of Disruption, in the MS project.

Table 7:11 shows the whole-life cost estimates, over a 60-year period, for the 22 BCPs considered in the MS project. Over the estimated period, the declining discount rate schedule is adopted, which translates into using a discount rate of 3.5%, over the 1 – 30 year period, and a discount rate of 3%, over the 31 – 60 year period. Over a 60-year horizon, the whole-life cost estimate of retrofit options, could range between $3.8 million and $12 million.

Table 7:12 Whole-life Cost Estimates over a 60-year Period, with added cost of disruption, in the MS Project

Runs	WLC ($)	NWLC ($)	FL-NWLC ($)	FM-NWLC ($)	FU-NWLC ($)
BCP 1	5,053,000	5,458,000	5,286,000	9,106,000	9,678,000
BCP 2	3,802,000	4,123,000	4,423,000	7,560,000	8,020,000
BCP 3	7,158,000	7,672,000	6,660,000	11,313,000	12,029,000
BCP 4	5,261,000	5,626,000	5,328,000	8,722,000	9,227,000
BCP 5	3,952,000	4,224,000	4,377,000	7,010,000	7,400,000
BCP 6	5,318,000	5,663,000	5,316,000	8,526,000	9,014,000
BCP 7	3,933,000	4,176,000	4,236,000	6,560,000	6,899,000
BCP 8	5,282,000	5,642,000	5,338,000	8,699,000	9,208,000
BCP 9	5,252,000	5,581,000	5,187,000	8,231,000	8,695,000
BCP 10	3,942,000	4,179,000	4,230,000	6,503,000	6,844,000
BCP 11	7,423,000	7,889,000	6,730,000	10,887,000	11,525,000
BCP 12	3,887,000	4,139,000	4,225,000	6,638,000	6,990,000
BCP 13	5,098,000	5,400,000	4,924,000	7,693,000	8,119,000
BCP 14	3,846,000	4,064,000	4,059,000	6,144,000	6,458,000
BCP 15	7,928,000	8,408,000	7,046,000	11,298,000	11,964,000
BCP 16	5,644,000	5,993,000	5,407,000	8,599,000	9,090,000
BCP 17	4,392,000	4,658,000	4,556,000	7,069,000	7,451,000
BCP 18	5,676,000	5,998,000	5,330,000	8,238,000	8,690,000
BCP 19	4,507,000	4,757,000	5,286,000	9,106,000	9,678,000
BCP 20	4,679,000	4,937,000	4,423,000	7,560,000	8,020,000
BCP 21	7,264,000	7,539,000	6,660,000	11,313,000	12,029,000
BCP 22	6,567,000	6,755,000	5,328,000	8,722,000	9,227,000

The results in Table 7:12, also provide an indication of the average difference between the existing whole-life cost models, and the fuzzy model. The fuzzy model suggests, the added cost of disruption and revocability, has potential to increase the whole-life cost estimate in the MS project, by up to 41% over a 60-year estimated life. Figure 7-12 also reveals that BCP 3, BCP 15 and BCP 21, show potentials of constituting the least cost-effective whole-life value among the retrofit options considered, which demonstrates the potential for increased comparability of options, over the 60-year estimated life.

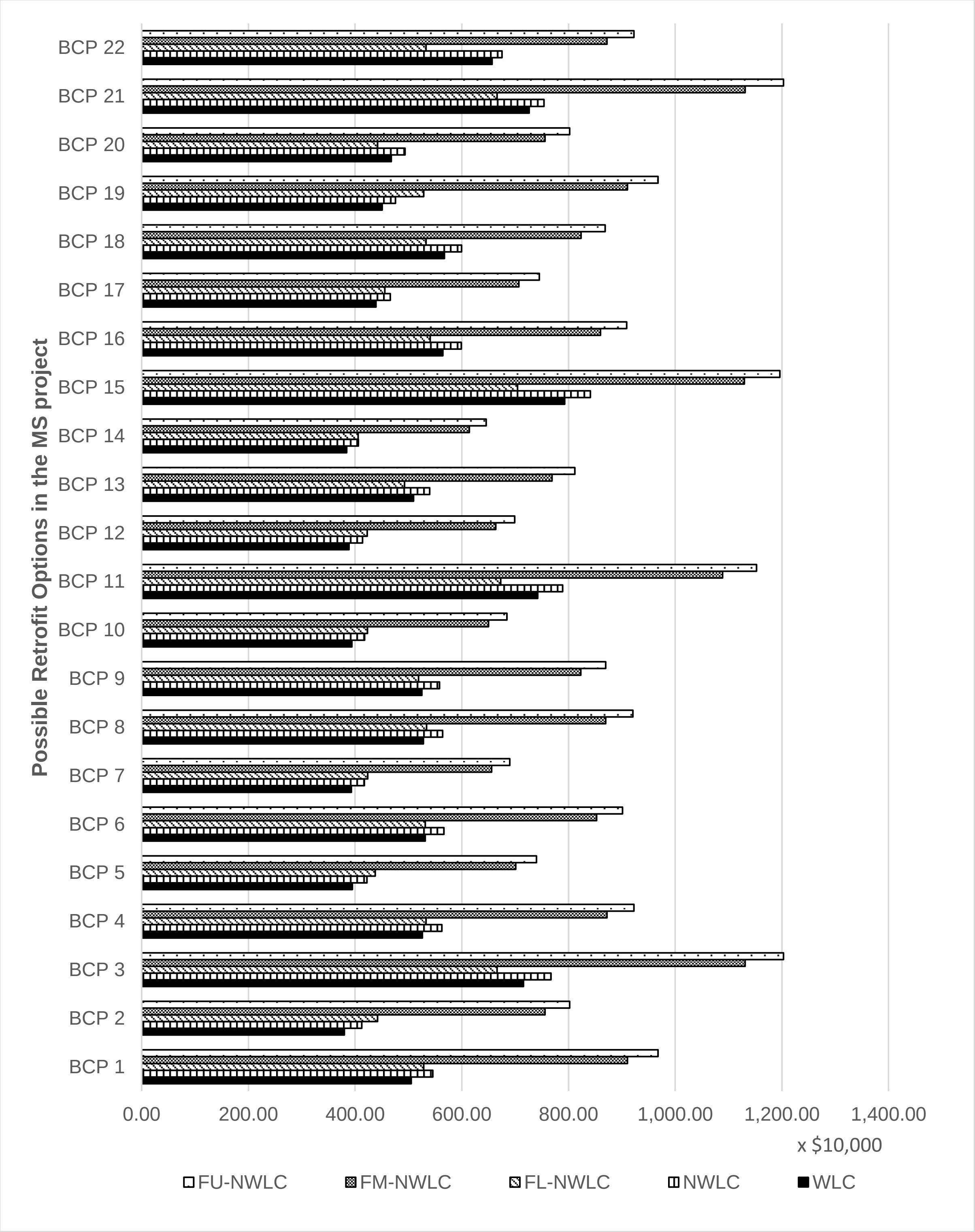


Figure 7-12 Whole-life Cost Estimates over a 60-year Period, with added Cost of Disruption, in the MS Project

7.4 Ranking in SPACE project (Discounting and Revocability)

Table 7:13 shows the rank ordering of the whole-life cost estimates reported in Table 7:1, in the SPACE project, over a 20-year period. The rank ordering over the 20-year period are identical, irrespective of the whole-life cost model used. One possible explanation for this, is that, the ‘Initial capital’ cost weighs significantly higher than the ‘Future’ costs, as previously argued by Tietz (1987). Hence, the 20-year horizon may not provide a convincing context, for the conduct of whole-life costing in the SPACE office retrofit building project.

Also, over a 20-year period, the business case for whole-life costing is not significantly clear. In Table 7:13, BCP 1 - the base case, representing the “no retrofitting scenario” is shown, as the most preferred option, and suggests the economic desirability of the *status-quo*, over the 20-year estimated period. The situation is expected to be altered, should there be changes that significantly minimise the Initial capital cost and significantly increases the ‘Future’ costs, over the life of the building.

Table 7:13 Whole-life Cost rank-ordering, over a 20-year Period in SPACE project

	WLC	NWLC	FL-NWLC	FM-NWLC	FU-NWLC
Increasing Order of Preference ↑	BCP 1	BCP 1	BCP 1	BCP 1	BCP 1
	BCP 2	BCP 2	BCP 2	BCP 2	BCP 2
	BCP 3	BCP 3	BCP 3	BCP 3	BCP 3
	BCP 4	BCP 4	BCP 4	BCP 4	BCP 4
	BCP 8	BCP 8	BCP 8	BCP 8	BCP 8
	BCP 5	BCP 5	BCP 5	BCP 5	BCP 5
	BCP 10	BCP 10	BCP 10	BCP 10	BCP 10
	BCP 9	BCP 9	BCP 9	BCP 9	BCP 9
	BCP 7	BCP 7	BCP 7	BCP 7	BCP 7
	BCP 6	BCP 6	BCP 6	BCP 6	BCP 6

Table 7:14 shows the rankings of whole-life cost estimates, reported in Table 7:2, in the SPACE project, over a 40-year period. The rank orderings of BCPs, over the 40-year period, are relatively identical, especially for the WLC, NWLC and FL-NWLC models. However, there are few changes regarding the FM-NWLC and FU-NWLC models. Both FM-NWLC and FU-NWLC models, consider the best three rankings to be BCP 8, BCP 2 and BCP 1 respectively. While, the best three rankings according to the WLC, NWLC and FL-NWLC are BCP 1, BCP 2 and BCP 3 respectively.

The context for whole-life costing is however, evident, over the 40-year estimated life. Given the results from the rankings, it can be argued that the fuzzy models provide a broad range of values, and there are indications, that the fuzzy models provide viable alternatives to the existing models. There may however, be scope for examining the ‘critical’ estimated life, in office retrofit building projects, over which, whole-life cost analysis will be imperative. This will be a useful line of inquiry in future research work.

Table 7:14 Whole-life Cost rank-ordering over a 40-year Period in SPACE project

	WLC	NWLC	FL-NWLC	FM-NWLC	FU-NWLC
Increasing Order of Preference ↑	BCP 1	BCP 1	BCP 1	BCP 8	BCP 8
	BCP 2	BCP 2	BCP 2	BCP 2	BCP 2
	BCP 3	BCP 3	BCP 3	BCP 1	BCP 1
	BCP 4	BCP 4	BCP 4	BCP 3	BCP 4
	BCP 8	BCP 8	BCP 8	BCP 4	BCP 3
	BCP 5	BCP 5	BCP 10	BCP 10	BCP 10
	BCP10	BCP 10	BCP 9	BCP 9	BCP 9
	BCP 9	BCP 9	BCP 5	BCP 5	BCP 5
	BCP 7	BCP 7	BCP 7	BCP 7	BCP 7
	BCP 6	BCP 6	BCP 6	BCP 6	BCP 6

Table 7:15 shows the rank ordering of whole-life cost estimates, reported in Table 7:3 in the SPACE project, over a 60-year period. The rankings, over the 60-year period, retains some similarities with the ranking, over the 40-year period, but also highlights a number of differences. Specifically, the rank orderings of BCPs in the SPACE project based on the WLC and NWLC, remains largely identical, over the estimated periods considered. This could imply that there are minimal ranking disparities between the WLC and NWLC model, in the conduct of whole-life costing of office retrofit building projects, as the rank ordering are identical. It will be useful to assess more case study projects, to test this hypothesis. A vital observation in the SPACE project however, is that, over the 40- year period, the FL-NWLC model produces the same results as the FM-NWLC and the FU-NWLC. This could suggest that the fuzzy model better captures future cost uncertainties, and responds more dynamically, than the WLC, and the NWLC model. There are however, obvious similarities across all the models. Perhaps the most obvious is that all the models, seem to suggest that BCP 6 is the least desirable, on the basis of its high whole-life

cost value. Over the 60-year period, the context for whole-life costing remains clearly evident in the SPACE project.

Also, although BCP 8 remains the most preferred option, based on the FL-NWLC model, over the 60-year estimated life, BCP 10 and BCP 9, have however, replaced BCPs 2 and BCPs 1, in terms of economic desirability. This could actually make a case for long-term consideration of retrofit solutions. The use of fuzzy models, in evaluating revocability and disruption, have shown potentials in the SPACE project, to highlight new insights, that could sway, and influence the overall decision-choices of building owners. This could effectively impact on the quality of decisions-made, in office retrofit building scenarios.

Table 7:15 Whole-life Cost rank-ordering over a 60-year Period in SPACE project

	WLC	NWLC	FL-NWLC	FM-NWLC	FU-NWLC
Increasing Order of Preference ↑	BCP 1	BCP 1	BCP 8	BCP 8	BCP 8
	BCP 2	BCP 2	BCP 10	BCP 10	BCP 10
	BCP 3	BCP 3	BCP 9	BCP 9	BCP 9
	BCP 4	BCP 4	BCP 4	BCP 7	BCP 7
	BCP 8	BCP 8	BCP 7	BCP 4	BCP 4
	BCP 5	BCP 5	BCP 2	BCP 5	BCP 5
	BCP 10	BCP 10	BCP 1	BCP 3	BCP 3
	BCP 9	BCP 9	BCP 3	BCP 2	BCP 2
	BCP 7	BCP 7	BCP 5	BCP 1	BCP 1
	BCP 6	BCP 6	BCP 6	BCP 6	BCP 6

In the SPACE project, only 5 options (BCP 1 to BCP 5) were originally considered. The decision was however, not based on whole-life cost considerations. Rather decisions were based on the least ‘Future’ cost achievable in the options considered. There is scare evidence that the project owners in the SPACE project prioritised whole-life cost considerations, in selecting the preferred retrofit project option. This work highlights the benefits whole-life cost modelling would have demonstrated in fulfilling their project objectives.

It could be beneficial to examine the application of whole-life cost modelling in projects, which have an estimated life, beyond the 60-year horizon. The principal deterrence however, is the heightened complexities, and difficulties in predicting future cost events, as well as the performance of building elements at this stage. The effects of obsolescence also appears to peak after this stage and replacement or overhauling the entire building components could be required (Goh & Sun, 2015).

7.5 Ranking in SPACE project (Discounting, Disruption and Revocability)

Table 7:16 shows the rankings of the whole-life cost estimates reported in Table 7:4, in the SPACE project, over a 20-year period. Over this period, the cost of disruption added to the initial cost, only marginally increases the ratio of the Initial cost relative to the Future costs, and expectedly does not alter the rankings of the whole-life cost estimates in the SPACE project. It is therefore deducible that the inclusion of the cost of disruption in the SPACE project could have limited benefits in the whole-life cost analysis, over the 20-year estimated life period.

Table 7:16 Whole-life Cost (including Disruption) rank-ordering over a 20-year Period in SPACE project

	WLC	**NWLC**	**FL-NWLC**	**FM-NWLC**	**FU-NWLC**
Increasing Order of Preference ↑	BCP 1	BCP 1	BCP 1	BCP 1	BCP 1
	BCP 2	BCP 2	BCP 2	BCP 2	BCP 2
	BCP 3	BCP 3	BCP 3	BCP 3	BCP 3
	BCP 4	BCP 4	BCP 4	BCP 4	BCP 4
	BCP 8	BCP 8	BCP 8	BCP 8	BCP 8
	BCP 5	BCP 5	BCP 5	BCP 5	BCP 5
	BCP 10	BCP 10	BCP 10	BCP 10	BCP 10
	BCP 9	BCP 9	BCP 9	BCP 9	BCP 9
	BCP 7	BCP 7	BCP 7	BCP 7	BCP 7
	BCP 6	BCP 6	BCP 6	BCP 6	BCP 6

Table 7:17 shows the rank ordering of the whole-life cost estimates reported in Table 7:5, in the SPACE project, over a 40-year period. The contributions from the cost of disruption, is perhaps not substantial enough to alter the rankings of BCPs, over the 40-year period. In terms of the ranking, one observable difference in rank ordering, is seen in FM-NWLC, where there is a preference switch between BCP 3 and BCP 4, which was in 4th and 5th positions respectively in *Table 7:14*. BCP 3 and BCP 4 are in alternate positions in Table 7:17. This observation suggests that the cost of disruption is not as highly influential in the whole-life costing of the SPACE project, but still have some effects on decision outcomes. It will however, be helpful to further evaluate the cost of disruption, in more samples of office retrofit building projects, in order to assess its place in whole-life cost evaluation.

Table 7:17 Whole-life Cost (including Disruption) rank-ordering over a 40-year Period in SPACE project

	WLC	NWLC	FL-NWLC	FM-NWLC	FU-NWLC
Increasing Order of Preference ↑	BCP 1	BCP 1	BCP 1	BCP 8	BCP 8
	BCP 2	BCP 2	BCP 2	BCP 2	BCP 2
	BCP 3	BCP 3	BCP 3	BCP 1	BCP 1
	BCP 4	BCP 4	BCP 4	BCP 4	BCP 4
	BCP 8	BCP 8	BCP 8	BCP 3	BCP 3
	BCP 5	BCP 5	BCP 10	BCP 10	BCP 10
	BCP 10	BCP 10	BCP 9	BCP 9	BCP 9
	BCP 9	BCP 9	BCP 5	BCP 5	BCP 5
	BCP 7	BCP 7	BCP 7	BCP 7	BCP 7
	BCP 6	BCP 6	BCP 6	BCP 6	BCP 6

Table 7:18 shows the rankings in the whole-life cost estimates in Table 7:6 in the SPACE project, over a 60-year period. The effects of the cost of disruption is less evident, than in the 20-year and 40-year period, as ranking preferences are the same as in Table 7:15. Hence, in the SPACE project, the effects of the cost of disruption are relatively insignificant, over the 60-year period. One reason for this, is that the cost of disruption is computed as a component of the initial costs, and its effect in whole-life costing analysis, becomes less influential, as the building life extends into the future.

Table 7:18 Whole-life Cost (including Disruption) rank-ordering over a 60-year Period in SPACE project

	WLC	NWLC	FL-NWLC	FM-NWLC	FU-NWLC
Increasing Order of Preference ↑	BCP 1	BCP 1	BCP 8	BCP 8	BCP 8
	BCP 2	BCP 2	BCP 10	BCP 10	BCP 10
	BCP 3	BCP 3	BCP 9	BCP 9	BCP 9
	BCP 4	BCP 4	BCP 4	BCP 7	BCP 7
	BCP 8	BCP 8	BCP 7	BCP 4	BCP 4
	BCP 5	BCP 5	BCP 2	BCP 5	BCP 5
	BCP 10	BCP 10	BCP 1	BCP 3	BCP 3
	BCP 9	BCP 9	BCP 3	BCP 2	BCP 2
	BCP 7	BCP 7	BCP 5	BCP 1	BCP 1
	BCP 6	BCP 6	BCP 6	BCP 6	BCP 6

7.6 Ranking in MS Project (Discounting and Revocability)

Table 7:19 shows the rankings of the whole-life cost estimates in Table 7:7, in the MS project, over a 20-year period. Over the 20-year estimated life period, the WLC and NWLC models, have identical rank orderings for the BCPs considered. Although identical trends are observed in the rank orderings of the WLC and the Fuzzy models, the ranking preference has some slight differences. Specifically, the three preferred BCPs, in the WLC, NWLC, FM-NWLC and FU-NWLC models are BCP’s 2, 12 and 5 respectively. The ranking of BCPs in the FL-NWLC model, is slightly different from the WLC and NWLC model, as BCP 5 replaces BCP 12, as the second most-preferred option. The most-preferred BCP in the rankings of all the WLC models is BCP 2.

This suggests that over a 20-year period, the business case for whole-life costing in the MS project, is not convincing. The findings are also consistent with the SPACE project. It could therefore be hypothesized that whole-life costing analysis tend to have limited benefits, over the 20-year period, in the SPACE retrofit project. BCP 2 is ranked as the most-preferred alternative, in all the whole-life cost models considered, and consists of minimal retrofit measures, which is similar to the base case. Equally, it is proposed that the effects of revocability and disruption, are rather less influential, as there are limited potentials to alter decision preferences of building investors in the MS project. Based on the results, whole-life cost analysis are unlikely to significantly impact decision-outcomes, in the MS project, as rank-ordering of BCPs, are identical.

Table 7:19 Whole-life Cost rank-ordering over a 20-year Period in MS project

	WLC	NWLC	FL-NWLC	FM-NWLC	FU-NWLC
↑ Increasing Order of Preference	BCP 2	BCP 2	BCP 2	BCP 2	BCP 2
	BCP 12	BCP 12	BCP 5	BCP 12	BCP 12
	BCP 5	BCP 5	BCP 12	BCP 5	BCP 5
	BCP 14	BCP 14	BCP 7	BCP 7	BCP 7
	BCP 7	BCP 7	BCP 1	BCP 10	BCP 10
	BCP 10	BCP 10	BCP 10	BCP 17	BCP 17
	BCP 17	BCP 17	BCP 17	BCP 1	BCP 1
	BCP 1	BCP 1	BCP 19	BCP 19	BCP 19
	BCP 19	BCP 19	BCP 4	BCP 20	BCP 20
	BCP 20	BCP 20	BCP 8	BCP 13	BCP 13
	BCP 4	BCP 4	BCP 13	BCP 4	BCP 4
	BCP 13	BCP 13	BCP 9	BCP 8	BCP 8
	BCP 8	BCP 8	BCP 6	BCP 9	BCP 9
	BCP 9	BCP 9	BCP 20	BCP 6	BCP 14
	BCP 6	BCP 6	BCP 14	BCP 14	BCP 6
	BCP 16	BCP 16	BCP 16	BCP 16	BCP 16
	BCP 18	BCP 18	BCP 18	BCP 18	BCP 18
	BCP 3	BCP 3	BCP 3	BCP 3	BCP 3
	BCP 11	BCP 11	BCP 11	BCP 11	BCP 11
	BCP 15	BCP 15	BCP 15	BCP 15	BCP 15
	BCP 21	BCP 21	BCP 21	BCP 21	BCP 21
	BCP 22	BCP 22	BCP 22	BCP 22	BCP 22

Table 7:20 show the rankings of whole-life cost estimates in Table 7:8, in the MS project. Over the 40-year estimated period, the rankings of BCPs in the MS project, based on the WLC and NWLC models, are identical, and the three most preferred options are BCP 2, BCP14 and BCP12 respectively. The rankings of BCPs for the FL-NWLC, is slightly different, as BCP 14 is the second most-preferred option on a whole-life cost basis, while BCP 12 comes after it. However, the rankings of BCPs considered in the MS project, using FM-NWLC and FU-NWLC models, reveal that BCP 14, BCP 12 and BCP 10, are the three most-preferred options, on a whole-life cost basis. There is a slight difference in the rankings of the FM-NWLC and FU-NWLC models. BCP 12 comes before BCP 10 in the FM-NWLC model, while BCP 10 comes before BCP 12, in the FU-NWLC model. It is however, clear that there are identical rankings in the whole-life cost models.

Table 7:20 Whole-life Cost rank-ordering over a 40-year Period in MS project

	WLC	**NWLC**	**FL-NWLC**	**FM-NWLC**	**FU-NWLC**
↑ **Increasing Order of Preference**	BCP 2	BCP 2	BCP 2	BCP 14	BCP 14
	BCP 14	BCP 14	BCP 14	BCP 12	BCP 10
	BCP 12	BCP 12	BCP 12	BCP 10	BCP 12
	BCP 5	BCP 7	BCP 5	BCP 7	BCP 7
	BCP 7	BCP 5	BCP 7	BCP 5	BCP 5
	BCP 10	BCP 10	BCP 10	BCP 2	BCP 2
	BCP 17	BCP 17	BCP 17	BCP 17	BCP 17
	BCP 19	BCP 19	BCP 19	BCP 19	BCP 19
	BCP 20	BCP 20	BCP 1	BCP 20	BCP 20
	BCP 1	BCP 1	BCP 20	BCP 13	BCP 13
	BCP 13	BCP 13	BCP 13	BCP 9	BCP 9
	BCP 4	BCP 4	BCP 4	BCP 1	BCP 1
	BCP 9	BCP 9	BCP 9	BCP 6	BCP 6
	BCP 8	BCP 8	BCP 8	BCP 4	BCP 4
	BCP 6	BCP 6	BCP 6	BCP 8	BCP 8
	BCP 16	BCP 16	BCP 16	BCP 18	BCP 18
	BCP 18	BCP 18	BCP 18	BCP 16	BCP 16
	BCP 3	BCP 22	BCP 3	BCP 22	BCP 22
	BCP 22	BCP 3	BCP 11	BCP 21	BCP 21
	BCP 11	BCP 11	BCP 15	BCP 3	BCP 3
	BCP 21	BCP 21	BCP 21	BCP 11	BCP 11
	BCP 15	BCP 15	BCP 22	BCP 15	BCP 15

Table 7:21 shows the rankings of the whole-life cost estimates, in Table 7:9, in the MS project, over a 60-year period. Over the 60-year period, the expected preferences of decision-makers in the MS project, over the 60-year period, based on the WLC and NWLC models, are BCP 2, BCP 14 and BCP 12. There is however, a slight difference in both rankings as BCP 14 replaces BCP 2, as the more preferred option. The rankings of the FM-NWLC and FU-NWLC models, remains identical. The rankings of the FL-NWLC model, however, have unique similarities with the rankings of the existing WLC and NWLC model, at some level, and also with the FM-NWLC and FU-NWLC models, at another level. BCP 14 and BCP 10, are the preferred options in the MS Project respectively, over the 60-year period, according to the fuzzy models. This ranking order, is consistent with the analysis over the 40-year period. However, the option ranked third is BCP 12 in the FL-NWLC model, which is identical with the WLC and NWLC models. The option ranked third, in the FM-NWLC and the FU-NWLC model, is BCP 7. The economic desirability of the options are not contrasting, and more analysis will be carried out in the next chapter to assess the

ranking correlation of paired models, in the case study projects examined. The differences observed, could rule out certain options in the decision-making process of the MS retrofit building.

Table 7:21 Whole-life Cost rank-ordering over a 60-year Period in MS project

	WLC	NWLC	FL-NWLC	FM-NWLC	FU-NWLC
↑ **Increasing Order of Preference**	BCP 2	BCP 14	BCP 14	BCP 14	BCP 14
	BCP 14	BCP 2	BCP 10	BCP 10	BCP 10
	BCP 12	BCP 12	BCP 12	BCP 7	BCP 7
	BCP 7	BCP 7	BCP 7	BCP 12	BCP 12
	BCP 10	BCP 10	BCP 5	BCP 19	BCP 19
	BCP 5	BCP 5	BCP 2	BCP 5	BCP 5
	BCP 17	BCP 17	BCP 17	BCP 17	BCP 17
	BCP 19	BCP 19	BCP 19	BCP 20	BCP 20
	BCP 20	BCP 20	BCP 20	BCP 2	BCP 2
	BCP 1	BCP 13	BCP 13	BCP 13	BCP 13
	BCP 13	BCP 1	BCP 9	BCP 9	BCP 18
	BCP 9	BCP 9	BCP 1	BCP 18	BCP 22
	BCP 4	BCP 4	BCP 6	BCP 22	BCP 9
	BCP 8	BCP 8	BCP 18	BCP 6	BCP 6
	BCP 6	BCP 6	BCP 4	BCP 16	BCP 16
	BCP 16	BCP 16	BCP 8	BCP 8	BCP 8
	BCP 18	BCP 18	BCP 16	BCP 4	BCP 4
	BCP 22	BCP 22	BCP 22	BCP 1	BCP 21
	BCP 3	BCP 21	BCP 3	BCP 21	BCP 1
	BCP 21	BCP 3	BCP 21	BCP 11	BCP 11
	BCP 11	BCP 11	BCP 11	BCP 15	BCP 15
	BCP 15	BCP 15	BCP 15	BCP 3	BCP 3

7.7 Ranking in MS Project (Discounting, Disruption and Revocability)

Table 7:22 shows the rankings of the whole-life cost estimates, in Table 7:10, in the MS project, over a 20-year period, with added cost of disruption. In the 20-year period, the rankings of the WLC and NWLC models, in the MS project are identical. The rankings of the FM-NWLC model and the FU-NWLC model, are also identical. The similarity in rankings in the MS project, suggest that the fuzzy models are more responsive to the inclusion of additional cost variables, and to changes in the elemental cost components. The rank ordering in the existing WLC and NWLC models are identical with the rank ordering in Table 7:19, where the cost of disruption is not considered.

Table 7:22 Whole-life Cost (including Disruption) rank-ordering over a 20-year Period in MS project

Increasing Order of Preference	**WLC**	**NWLC**	**FL-NWLC**	**FM-NWLC**	**FU-NWLC**
	BCP 2	BCP 2	BCP 2	BCP 2	BCP 2
	BCP 12	BCP 12	BCP 20	BCP 20	BCP 20
	BCP 5	BCP 5	BCP 5	BCP 12	BCP 12
	BCP 14	BCP 14	BCP 12	BCP 5	BCP 5
	BCP 7	BCP 7	BCP 7	BCP 7	BCP 7
	BCP 10	BCP 10	BCP 1	BCP 10	BCP 10
	BCP 17	BCP 17	BCP 19	BCP 17	BCP 17
	BCP 1	BCP 1	BCP 10	BCP 1	BCP 1
	BCP 19	BCP 19	BCP 17	BCP 19	BCP 19
	BCP 20	BCP 20	BCP 4	BCP 13	BCP 13
	BCP 4	BCP 4	BCP 22	BCP 4	BCP 4
	BCP 13	BCP 13	BCP 8	BCP 22	BCP 22
	BCP 8	BCP 8	BCP 13	BCP 8	BCP 8
	BCP 9	BCP 9	BCP 9	BCP 9	BCP 9
	BCP 6	BCP 6	BCP 6	BCP 6	BCP 14
	BCP 16	BCP 16	BCP 14	BCP 14	BCP 6
	BCP 18	BCP 18	BCP 16	BCP 16	BCP 16
	BCP 3	BCP 3	BCP 18	BCP 18	BCP 18
	BCP 11	BCP 11	BCP 3	BCP 3	BCP 3
	BCP 15	BCP 15	BCP 21	BCP 21	BCP 21
	BCP 21	BCP 21	BCP 11	BCP 11	BCP 11
	BCP 22	BCP 22	BCP 15	BCP 15	BCP 15

Table 7:23, shows the rankings of whole-life cost estimates, in the MS project, over a 40-year period, with added cost of disruption. Over the 40-year period, the added cost of disruption, has some effect on the rankings in the Fuzzy New-Generation whole-life cost variants, but does not have as much effect, in the existing WLC and NWLC model.

It can be observed from Table 7:23, that the BCPs ranked second and third, in the FL-NWLC techniques, are BCP 20 and BCP 14 respectively, as opposed to BCP 14 and BCP 12, in the “Discounting and Revocability” scenario, where the cost effects of disruption are not included. This perhaps buttresses the sensitivity of fuzzy whole-life cost models, in accommodating the effects of cost elements, in its framework.

Table 7:23 Whole-life Cost (including Disruption) rank-ordering over a 40-year Period in MS project

	WLC	**NWLC**	**FL-NWLC**	**FM-NWLC**	**FU-NWLC**
Increasing Order of Preference ↑	BCP 2	BCP 2	BCP 2	BCP 14	BCP 14
	BCP 14	BCP 14	BCP 20	BCP 12	BCP 12
	BCP 12	BCP 12	BCP 14	BCP 7	BCP 7
	BCP 5	BCP 7	BCP 12	BCP 10	BCP 10
	BCP 7	BCP 5	BCP 7	BCP 5	BCP 5
	BCP 10	BCP 10	BCP 5	BCP 2	BCP 2
	BCP 17	BCP 17	BCP 10	BCP 20	BCP 20
	BCP 19	BCP 19	BCP 17	BCP17	BCP 17
	BCP 20	BCP 20	BCP 1	BCP 13	BCP 13
	BCP 1	BCP 1	BCP 19	BCP 9	BCP 9
	BCP 13	BCP 13	BCP 13	BCP 1	BCP 1
	BCP 4	BCP 4	BCP 4	BCP 19	BCP 19
	BCP 9	BCP 9	BCP 22	BCP 4	BCP 4
	BCP 8	BCP 8	BCP 9	BCP 22	BCP 22
	BCP 6	BCP 6	BCP 8	BCP 6	BCP 6
	BCP 16	BCP 16	BCP 6	BCP 8	BCP 8
	BCP 18	BCP 18	BCP 16	BCP 18	BCP 18
	BCP 3	BCP 22	BCP 18	BCP 16	BCP 16
	BCP 22	BCP 3	BCP 3	BCP 3	BCP 3
	BCP 11	BCP 11	BCP 21	BCP 21	BCP 21
	BCP 21	BCP 21	BCP 11	BCP 11	BCP 11
	BCP 15	BCP 15	BCP 15	BCP 15	BCP 15

Table 7:24 shows the rankings of the whole-life cost estimates, in Table 7:12, in the MS project, over a 60-year period. There are no significant changes in the rank ordering of existing WLC and NWLC models, but there are changes in the FL-NWLC model. There are also no noticeable changes in the rankings of the FM-NWLC model and the FU-NWLC model, in the MS project. This suggests that, over the 60-year estimated period, in the MS project, the effects of the cost of disruption are relatively inconspicuous in the rank ordering of retrofit options in the MS project. However, the fuzzy model captures marginal differences, in the rank ordering of the MS project.

Table 7:24 Whole-life Cost (including Disruption) rank-ordering over a 60-year Period in MS project

	WLC	**NWLC**	**FL-NWLC**	**FM-NWLC**	**FU-NWLC**
↑ **Increasing Order of Preference**	BCP 2	BCP 14	BCP 14	BCP 14	BCP 14
	BCP 14	BCP 2	BCP 12	BCP 10	BCP 10
	BCP 12	BCP 12	BCP 10	BCP 7	BCP 7
	BCP 7	BCP 7	BCP 7	BCP 12	BCP 12
	BCP 10	BCP 10	BCP 5	BCP 5	BCP 5
	BCP 5	BCP 5	BCP 2	BCP 17	BCP 17
	BCP 17	BCP 17	BCP 20	BCP 2	BCP 2
	BCP 19	BCP 19	BCP 17	BCP 20	BCP 20
	BCP 20	BCP 20	BCP 13	BCP 13	BCP 13
	BCP 1	BCP 13	BCP 9	BCP 9	BCP 18
	BCP 13	BCP 1	BCP 1	BCP 18	BCP 9
	BCP 9	BCP 9	BCP 19	BCP 6	BCP 6
	BCP 4	BCP 4	BCP 6	BCP 16	BCP 16
	BCP 8	BCP 8	BCP 4	BCP 8	BCP 8
	BCP 6	BCP 6	BCP 22	BCP 4	BCP 4
	BCP 16	BCP 16	BCP 18	BCP 22	BCP 22
	BCP 18	BCP 18	BCP 8	BCP 1	BCP 1
	BCP 22	BCP 22	BCP 16	BCP 19	BCP 19
	BCP 3	BCP 21	BCP 3	BCP 11	BCP 11
	BCP 21	BCP 3	BCP 21	BCP 15	BCP 15
	BCP 11	BCP 11	BCP 11	BCP 3	BCP 3
	BCP 15	BCP 15	BCP 15	BCP 21	BCP 21

7.8 Summary

This chapter reports on the results obtained in the SPACE and MS Projects. In this chapter, the whole-life cost is reported over a 20-year, 40-year and 60-year period. The first scenarios basically considers ‘Discounting and Revocability’. While the second scenario considers, ‘Discounting, Disruption, and Revocability’. The whole-life cost estimates, are ranked in their order of preference, where the lowest whole-life cost estimates, are most preferred, and the highest whole-life cost estimates are least preferred. This chapter leads to the analysis and interpretation using Sensitivity analysis, and the Spearman’s rank correlation test.

Chapter 8 Analysis and Interpretation of Results

8.1 Introduction

This chapter presents the analysis and interpretation of the results obtained, and reported upon in Chapter 6 and Chapter 7. It commences with estimating the potential cost added, by disruption and revocability, in the case study projects. The chapter reports on the Sensitivity analysis carried out in the SPACE and MS projects using discount rate values of 3%, 5%, 7%, and 9%. It also, analyses the results of the Spearman's rank correlation test, based on the declining discount rate schedule, in the in the SPACE and MS retrofit projects

8.2 Cost of Disruption in Office Retrofit Projects

From Table 8:1, it can be observed that the average cost of disruption, in the SPACE building project, based on the retrofit options considered, can lead to an additional cost of 2% - 12%, relative to the initial capital cost of the retrofit project. It should however, be noted that the average cost of disruption of retrofit options, considered in the SPACE project, range between 3 – 4% of the initial installation cost. It is however, unclear whether this cost is generalizable for other office retrofit projects. It can be expected that the cost of disruption, in Commercial Office buildings, will be higher than, those of residential buildings, of similar characteristics. There is however, scope for further research, regarding the evaluation of the cost of disruption, in different building typologies

Table 8:1 % Cost of Disruption to the Capital Cost in the SPACE project

BCPs	% Change in FL-NWLC	% Change in FM-NWLC	% Change in FU-NWLC	Average
1	0.0	0.0	0.0	0.0
2	8.2	12.1	14.1	11.5
3	1.6	7.1	11.0	6.5
4	1.1	3.3	4.9	3.1
5	0.6	4.3	6.8	3.9
6	0.3	2.3	3.6	2.1
7	0.6	3.6	5.7	3.3
8	0.8	4.4	7.2	4.2
9	0.6	3.5	5.6	3.2
10	0.6	3.5	5.6	3.2

It can also be seen from Table 8:1, that the cost of disruption for BCP 2, which consist principally of low cost energy measures (LCEM's), has a higher proportion of the cost of disruption, relative to other retrofit mechanisms - Energy Efficient Systems and Control Systems. It is therefore, inferred that insulation measures tend to be more disruptive, than energy-efficient systems. Although both measures are compliments, rather than substitutes, in the retrofitting of buildings.

From Table 8:2, the average cost of disruption, in the MS building project, can lead to an additional cost of 0.2% to 1.5%, relative to the initial capital cost. For majority of retrofit options considered, in the MS project, an average cost of disruption ranging from 1.2 – 1.5%, relative to the initial cost of installation, is more likely. It can be seen that these values, are comparatively smaller to the proportion seen in the SPACE project. This could be a result of the building characteristics, including building size, orientation, and scale of the retrofit work. It could also be a result of directed focus on Energy systems and Efficient appliances, rather than fabric measures. For instance, the SPACE project consists of just one storey, and retrofit options are examined in distinct packages. The MS project, on the other hand, tend to have more comparable disruption costs, consisting of three storeys, and is about three times the size of the SPACE project, in Net Lettable Area. Also, the MS project, considers retrofit technologies individually, rather than in packages, as observed in the SPACE project.

Table 8:2 % Cost of Disruption to the Capital Cost in the MS project

BCPs	% Change in FL-NWLC	% Change in FM-NWLC	% Change in FU-NWLC	Average
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.5	1.2	1.9	1.2
6	0.6	1.4	2.2	1.4
7	0.6	1.2	1.9	1.2
8	0.2	0.2	0.3	0.2
9	0.6	1.4	2.1	1.4
10	0.5	1.2	1.8	1.2
11	0.2	0.2	0.3	0.2
12	0.6	1.3	2.1	1.3
13	0.7	1.6	2.3	1.5
14	0.6	1.4	2.0	1.3
15	0.2	0.2	0.3	0.2
16	0.2	0.2	0.3	0.2
17	0.6	1.2	1.9	1.2
18	0.7	1.4	2.1	1.4
19	0.6	1.3	1.9	1.2
20	0.6	1.2	1.7	1.2
21	0.7	1.2	1.6	1.2
22	0.3	0.5	0.8	0.5

There is therefore, a possibility, for a lesser cost of disruption, relative to the initial cost of installation, in more extensive retrofit measures. One possible situation that can result from such occurrence, is that, the cost of disruption could tend to decline with, the increasing scale of the building retrofit project. The cost of disruption is considered, a one-off cost, expended in the course of implementing a retrofit solution. An understanding of the cost of disruption, could assist investors in scheduling retrofit initiatives, over the life of buildings. This could be beneficial for business organisations, which have seasonal operational peak periods.

8.3 Cost of Revocability in Office Retrofit Projects

This section discusses the cost of revocability, in respective case study projects. The cost of revocability in the retrofit case study projects, has been appraised using a constant revocability rate of 10%, in successive years. This convention is consistent with previous work on whole-life costing, conducted by Ellingham and Fawcett (2006).

The revocability rate of 10%, implies a proportionate increase or decrease, in the Future costs, of retrofit options, in successive years. The probabilities of Future cost estimates, has been apportioned using the Negative Binomial probability distribution. The bracketed cost values in Table 8:3 to Table 8:8, refer to ‘savings’, rather than ‘costs’, consistent with International Financial Reporting Standards (IFRS). In the case study projects examined – SPACE and MS, the cost of revocability, pertains to the Future Costs in buildings, and is computed, over an estimated life of 20 years, 40 years, and 60 years. The implication of the cost of revocability, is discussed in the SPACE and MS projects.

8.3.1 Cost of Revocability in SPACE Project

The cost of revocability in office retrofit projects, pertains to the potential for variability in the Future costs, and can be cumulatively appraised, over the estimated life of the projects. In the SPACE project, the estimated cost of revocability, over a 20-year life can range from 31 – 33%, of the overall future costs, as seen in Table 8:3. The differential range in the estimated cost of revocability in competing retrofit options, is only about 2%. The cost of revocability, over this period, is unlikely to significantly alter the decision-preferences of investors, as the relative difference in the proportion of the estimated revocability cost to the Standard Future cost, is relatively small. An awareness on the possibility for variability in future costs, could however, improve whole-life cost evaluation of office retrofit options.

Table 8:3 Cost of Revocability in the SPACE Project over the 20-year horizon

BCPs	Low Revocability Cost (£)	Upper Revocability Cost (£)	Range of Revocability Cost (£)	Proportion of Standard Future Costs
1	(418,000)	271,000	689,000	0.33
2	(416,000)	266,000	682,000	0.33
3	(412,000)	256,000	668,000	0.33
4	(464,000)	223,000	687,000	0.32
5	(465,000)	224,000	689,000	0.32
6	(527,000)	239,000	766,000	0.32
7	(526,000)	185,000	711,000	0.31
8	(446,000)	169,000	615,000	0.31
9	(476,000)	173,000	649,000	0.31
10	(475,000)	172,000	647,000	0.31

Over a 40-year period, the cost of revocability can range from 46 – 58%. In comparison to the 20-year period, it can be seen from Table 8:4, that the cost of revocability has increased, and the range of variability, is more significant, over the 40-year period. The estimated cost of revocability, is also subject to the discounting convention (Verbruggen, 2013), and hence, there is a relative decrease in the proportion of the cumulative Future cost, relative to the estimated life, of the retrofit option.

Table 8:4 Cost of Revocability in the SPACE project over the 40-year horizon

BCPs	**Low Revocability Cost (£)**	**Upper Revocability Cost (£)**	**Range of Revocability Cost (£)**	**Proportion of Standard Future Costs**
1	(567,000)	1,272,000	1,839,000	0.58
2	(531,000)	1,285,000	1,816,000	0.58
3	(360,000)	1,403,000	1,763,000	0.57
4	(486,000)	1,207,000	1,693,000	0.52
5	(194,000)	1,506,000	1,700,000	0.52
6	175,000	2,031,000	1,856,000	0.51
7	(239,000)	1,375,000	1,614,000	0.46
8	(148,000)	1,273,000	1,421,000	0.48
9	(115,000)	1,371,000	1,486,000	0.47
10	(116,000)	1,366,000	1,482,000	0.47

Over the 60-year period, as seen in Table 8:5, the cost of revocability ranges between 64% and 105%. Over the 60-year period, it is evident that there is a potential for the cost of revocability in the SPACE project, to surpass the sum total of the Standard Future costs. This observation buttresses, the need to pay more attention, to the cost of revocability, in whole-life costing scenarios.

Over the estimated periods – 20 years, 40 years, and 60 years, considered, in the SPACE project, it can be observed that BCP 1 – ("no retrofitting" scenario) reflects the highest overall cost proportion of revocability, 33%, 58% and 105% respectively over the 20-year, 40-year, and 60-year, period. This suggests, a potential for the whole-life cost of revocability, to be minimised, through the selection of efficient and optimal retrofit configuration. The evaluation of the cost of revocability, potentially provides a clear basis for justifying, and examining, the prospects of retrofit work in building scenarios.

Table 8:5 Cost of Revocability in the SPACE project, over the 60-year horizon

BCPs	Low Revocability Cost (£)	Upper Revocability Cost (£)	Range of Revocability Cost (£)	Proportion of Standard Future Costs
1	271,000	4,166,000	3,895,000	1.05
2	242,000	4,071,000	3,829,000	1.04
3	178,000	3,856,000	3,678,000	1.01
4	(326,000)	2,868,000	3,194,000	0.83
5	(318,000)	2,895,000	3,213,000	0.83
6	(484,000)	2,931,000	3,415,000	0.79
7	(912,000)	1,723,000	2,635,000	0.64
8	(680,000)	1,724,000	2,404,000	0.68
9	(776,000)	1,692,000	2,468,000	0.66
10	(781,000)	1,675,000	2,456,000	0.66

8.3.2 Cost of Revocability in MS Project

Table 8:6, shows the estimated cost of revocability, in the MS project, over the 20-year period. The range of the proportion of revocability cost, to the Standard Future cost, over the 20-year period, is between 32 – 35%, in the MS project. The proportion of revocability costs in the MS project, over a 20-year horizon, is comparable to that of the SPACE project, in which the proportion of revocability cost, ranged between 31 – 33%. This suggests that there is scope for generalising the results, of the proportion of revocability costs of BCPs, in office retrofit projects. It will however, be needful to involve more samples of office retrofit building projects. It could also be beneficial to conduct sensitivity analysis, on the revocability rates, in future work.

Table 8:6 Estimated Cost of Revocability in the MS Project, over the 20-year horizon

BCPs	Low Revocability Cost ($)	Upper Revocability Cost ($)	Range of Revocability Cost ($)	Proportion of Standard Future Costs
1	(461,000)	426,000	887,000	0.34
2	(277,000)	351,000	628,000	0.35
3	(747,000)	518,000	1,265,000	0.32
4	(443,000)	379,000	822,000	0.33
5	(256,000)	294,000	550,000	0.35
6	(435,000)	358,000	793,000	0.33
7	(243,000)	260,000	503,000	0.34
8	(441,000)	375,000	816,000	0.33
9	(427,000)	339,000	766,000	0.33
10	(240,000)	253,000	493,000	0.34
11	(726,000)	464,000	1,190,000	0.32
12	(247,000)	270,000	517,000	0.35
13	(416,000)	308,000	724,000	0.33
14	(339,000)	322,000	661,000	0.34
15	(784,000)	473,000	1,257,000	0.32
16	(488,000)	355,000	843,000	0.33
17	(304,000)	279,000	583,000	0.34
18	(476,000)	323,000	799,000	0.32
19	(297,000)	261,000	558,000	0.34
20	(301,000)	271,000	572,000	0.34
21	(455,000)	269,000	724,000	0.32
22	(218,000)	196,000	414,000	0.34

Table 8:7, shows the estimated cost of revocability, in the MS project, over the 40-year period. In the 40-year period, there is a progressive increase in the proportion of the cost of revocability to the Standard Future costs. The proportion of the cost of revocability, in the MS project, over the 40-year period, ranges between 47% - 63%. This range is consistent with the findings in the SPACE project, where the proportion of the cost of revocability to the Standard Future Cost, range between 46 – 58%, and hence, future work should pay attention to deducing the proportionate cost of revocability, in different building typologies.

Table 8:7 Estimated Cost of Revocability in the MS Project over the 40-year horizon

BCPs	Low Revocability Cost ($)	Upper Revocability Cost ($)	Range of Revocability Cost ($)	Proportion of Standard Future Costs
1	(521,000)	1,634,000	2,155,000	0.56
2	(188,000)	1,452,000	1,640,000	0.63
3	(1,075,000)	1,787,000	2,862,000	0.50
4	(541,000)	1,419,000	1,960,000	0.55
5	(212,000)	1,193,000	1,405,000	0.61
6	(551,000)	1,320,000	1,871,000	0.54
7	(227,000)	1,039,000	1,265,000	0.59
8	(543,000)	1,398,000	1,941,000	0.54
9	(559,000)	1,234,000	1,792,000	0.53
10	(230,000)	1,007,000	1,237,000	0.59
11	(1,098,000)	1,536,000	2,634,000	0.49
12	(222,000)	1,085,000	1,307,000	0.60
13	(572,000)	1,093,000	1,664,000	0.52
14	(239,000)	910,000	1,149,000	0.58
15	(1,222,000)	1,520,000	2,742,000	0.48
16	(680,000)	1,250,000	1,930,000	0.51
17	(347,000)	1,068,000	1,415,000	0.56
18	(694,000)	1,103,000	1,797,000	0.50
19	(355,000)	984,000	1,339,000	0.55
20	(350,000)	1,030,000	1,380,000	0.56
21	(717,000)	857,000	1,574,000	0.47
22	(254,000)	747,000	1,001,000	0.56

Table 8:8, shows the cost of revocability, over the 60-year period, in the MS project. Over the 60-year period, the proportion of the cost of revocability, in the MS project, ranges between 73% - 119%. This implies that, over a 60-year period, there is a potential that the cost of revocability, in the MS project, could surpass the nominal future costs of the building. This highlights the importance of the cost of revocability, and the importance of modelling for economic uncertainties, in the whole-life costing of building projects.

It is also noteworthy that the cost of revocability in the SPACE and MS projects, are comparable, in both projects. The effects of the cost of revocability, in both the SPACE and MS projects, reveal that, over the 60-year period, there is a clear potential for the cost implication of revocability to surpass the sum total of Standard Future costs in retrofit projects.

Table 8:8 Estimated Cost of Revocability in the MS Project over the 60-year horizon

BCPs	Low Revocability Cost ($)	Upper Revocability Cost ($)	Range of Revocability Cost ($)	Proportion of Standard Future Costs
1	420,000	4,794,000	4,373,000	0.98
2	744,000	4,321,000	3,577,000	1.19
3	(220,000)	5,129,000	5,349,000	0.81
4	246,000	4,144,000	3,898,000	0.94
5	535,000	3,537,000	3,002,000	1.13
6	165,000	3,843,000	3,678,000	0.91
7	408,000	3,070,000	2,662,000	1.08
8	228,000	4,078,000	3,850,000	0.93
9	95,000	3,583,000	3,487,000	0.89
10	383,000	2,976,000	2,593,000	1.07
11	(423,000)	4,371,000	4,794,000	0.77
12	445,000	3,209,000	2,764,000	1.09
13	(19,000	3,156,000	3,175,000	0.85
14	304,000	2,681,000	2,377,000	1.04
15	(602,000)	4,294,000	4,896,000	0.74
16	(57,000)	3,605,000	3,662,000	0.84
17	267,000	3,132,000	2,865,000	0.98
18	(176,000)	3,160,000	3,336,000	0.80
19	198,000	2,878,000	2,680,000	0.95
20	236,000	3,017,000	2,781,000	0.97
21	(376,000)	2,416,000	2,792,000	0.73
22	171,000	2,187,000	2,016,000	0.97

8.3.3 Impact on Whole-life Cost Evaluation

The inclusion of the cost of disruption, and the cost of revocability, have impacts on the total whole-life cost estimates, in retrofit projects. The evaluation and inclusion of these additional variables, in the whole-life costing framework, suggest a potential for underestimation, in the Standard Whole-life costing model. Table 8:9 presents, the percentage underestimation of whole-life costs of BCPs, in the SPACE project. It can be seen that, over a 20-year period, there is a potential for up to 2% underestimation of the whole-life costs of BCPs, in the SPACE project. The cost difference over the 20-year period is relatively small, and the benefits of including revocability and disruption, seem to be limited, over this period. It is also seen, that there is a potential for up to 21% underestimation, over a 40-year period, in the SPACE project, and up to 45% underestimation, over the 60-year period. Based on the evaluation of the MS and SPACE projects, it can be argued that Office retrofit projects with an expected life of 40-years or more, will benefit from, increased attention to the effects of revocability and disruption, in the whole-life cost modelling of building retrofits.

Table 8:9 Potential for Underestimation in the Whole-life Cost of the SPACE Project

BCPs	Percentage Underestimation over 20-year	Percentage Underestimation over 40-year	Percentage Underestimation over 60-year
1	1.5	21.4	45.4
2	1.6	21.0	44.8
3	2.0	19.8	42.8
4	(0.4)	13.3	32.4
5	0.6	13.1	31.5
6	0.0	10.7	27.4
7	(1.1)	6.0	16.8
8	(0.3)	7.7	20.3
9	(0.8)	6.7	18.3
10	(0.8)	6.6	18.1

Table 8:10 presents the percentage underestimation, in the whole-life costs of BCPs in the MS project. It can be seen that, over a 20-year period, there is a potential for up to 9% underestimation, in the whole-life costs of BCPs, in the MS projects. The range observed is much higher, than those observed in the SPACE project. The potential for underestimation is however, still in single-digit percentage figures, and is consistent, with the potential for underestimation, over the 20-year period, in the SPACE project. It is also be seen that, there is a potential for up to 30% underestimation, over a 40-year period, in the MS project, and up to 53% underestimation, over the 60-year period.

It is however, noticeable that there is a potential for the Fuzzy New-Generation whole-life cost model, to provide whole-life cost estimates, which are lesser in value, to the Standard Whole-life cost model. This can be seen in BCPs 4, 7, 8, 9, and 10, over the 20-year period, in the SPACE project. This also applies to BCPs 20, 21, and 22, over the 20-year estimated period, in the MS project. This implies that the inclusion of the cost of revocability and disruption, in the whole-life cost modelling framework, does not simply emphasize the prospects of underestimation, but also highlights the opportunities for savings. This approach acknowledges, the dual potentials of flexibility in whole-life cost modelling, such that, cost estimates have improved credibility, although, this could come, at the expense of precision, in whole-life cost estimates.

Table 8:10 Potential for Underestimation in the Whole-life Costing of the MS Project

BCPs	**Percentage Underestimation over 20-year**	**Percentage Underestimation over 40-year**	**Percentage Underestimation over 60-year**
1	7.4	24.8	47.8
2	8.8	28.4	52.6
3	5.5	19.6	40.5
4	5.4	20.9	43.0
5	6.7	23.5	46.6
6	5.4	19.7	41.0
7	5.1	20.6	43.0
8	5.8	20.9	42.6
9	5.2	18.8	39.6
10	5.7	20.5	42.4
11	3.8	16.2	35.6
12	5.4	21.6	44.4
13	4.6	17.3	37.2
14	4.7	19.2	40.5
15	4.0	15.2	33.7
16	4.9	17.8	37.9
17	6.1	19.9	41.1
18	4.3	15.8	34.7
19	4.00	30.3	53.4
20	(2.2)	9.6	41.7
21	(1.4)	13.5	39.6
22	(1.9)	(5.8)	28.8

8.4 Spearman’s rank correlation results in the SPACE Project

Table 8:11 to Table 8:14, provide a snapshot of correlation analyses, examined in the SPACE project. Spearman’s rank correlation analyses has been conducted on two case projects – SPACE and MS projects. Sensitivity analysis, is used to adjust discount rate assumptions, and the numbers of years, in order to test the effect of variable change, on the whole-life cost models. The Spearman’s rank correlation test, is a non-parametric test, used to assess the correlation of ordinal-ranked pairs, and provides a measure of the correlation of rankings, in respective whole-life costing techniques. The correlation measures, along the diagonal in Table 8:11 to Table 8:14, (top-left to bottom-right) are all unity, indicating perfect correlation between respective techniques. For example, in Table 8:11, the Spearman’s correlation coefficient between the Standard WLC and Fuzzy Mean NWLC, is 0.745. This implies that, the proportion of statistical variance between ranked pairs of BCPs, in the SPACE project, accounted for by the population membership, is about 75%. Equally, these implies, about 75% statistical similarity, in the correlation of ranked pairs. According to Cohen (1988), a correlation coefficient value of 0.745, is generally considered, a strong level of correlation.

The correlation coefficients, are considered at statistically significant P-values of 0.05 and 0.01 levels (2-tailed). The critical value of the Spearman’s rank correlation test, based on the number of rank samples , as specified in *Table 4:1*, by Hayslett (1988), is used to test the validity of the null and alternative hypothesis, in the case projects. Given that the primary purpose of whole-life costing, is to select among a number of competing options (Kishk, 2005), the Spearman’s correlation test, provides a useful means of assessing the economic desirability of BCPs, based on the ranks of whole-life cost estimates, in retrofit building projects. The correlation test also highlights the strategic benefit of utilising alternative whole-life cost models, in the appraisal of office retrofit options. The individual results of the Spearman correlation test, for different assumptions in the SPACE project, are reported upon in Appendix A-4. The summary of the hypothesis testing of the Spearman correlation analysis for the SPACE project, is presented in Table 8:15.

Table 8:11 Correlation coefficient at Discount Rate of 5%, over 40 years

	Correlation Coefficients				
Parameters	**WLC**	**NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
WLC	1.000**	1.000**	1.000**	0.745*	0.745*
NWLC		1.000**	1.000**	0.745*	0.745*
Fuzzy Lower NWLC			1.000**	0.745*	0.745*
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table 8:12 Correlation coefficient at Discount Rate of 3%, over 50 years

	Correlation Coefficients				
Parameters	**WLC**	**NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
WLC	1.000**	1.000**	0.285	- 0.673*	- 0.673*
NWLC		1.000**	0.285	- 0.673*	- 0.673*
Fuzzy Lower NWLC			1.000**	- 0.612	- 0.612
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table 8:13 Correlation coefficient at Discount Rate of 5% over 50 years

			Correlation Coefficients		
Parameters	**WLC**	**NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
WLC	1.000**	1.000**	0.697*	0.273	0.273
NWLC		1.000**	0.697*	0.273	0.273
Fuzzy Lower NWLC			1.000**	0.333	0.333
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table 8:14 Correlation coefficient at Discount Rate of 3% over 60 years

			Correlation Coefficients		
Parameters	**WLC**	**NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
WLC	1.000**	1.000**	- 0.697*	- 0.867**	- 0.867**
NWLC		1.000**	- 0.697*	- 0.867**	- 0.867**
Fuzzy Lower NWLC			1.000**	0.709*	0.709*
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table 8:15 Hypotheses Summaries on the Spearman's rank Correlation Analysis in the SPACE project

		WLC				**NWLC**				**Fuzzy Lower NWLC**				**Fuzzy Mean NWLC**				**Fuzzy Upper NWLC**			
	Discount Rate / **No's of Years**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**
WLC	20 yrs.					H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	30 yrs.					H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	40 yrs.					H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_0	H_A	H_A	H_A	H_0	H_A	H_A	H_A
	50 yrs.					H_A	H_A	H_A	H_A	H_0	H_A	H_A	H_A	H_0	H_0	H_A	H_A	H_0	H_0	H_A	H_A
	60 yrs.					H_A	H_A	H_A	H_A	H_0	H_A	H_A	H_A	H_0	H_0	H_A	H_A	H_0	H_0	H_A	H_A
NWLC	20 yrs.									H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	30 yrs.									H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	40 yrs.									H_A	H_A	H_A	H_A	H_0	H_A	H_A	H_A	H_0	H_A	H_A	H_A
	50 yrs.									H_0	H_A	H_A	H_A	H_0	H_0	H_A	H_A	H_0	H_0	H_A	H_A
	60 yrs.									H_0	H_A	H_A	H_A	H_0	H_0	H_A	H_A	H_0	H_0	H_A	H_A
Fuzzy Lower NWLC	20 yrs.													H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	30 yrs.													H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	40 yrs.													H_0	H_A	H_A	H_A	H_0	H_A	H_A	H_A
	50 yrs.													H_0	H_0	H_A	H_A	H_0	H_0	H_A	H_A
	60 yrs.													H_A	H_0	H_A	H_A	H_A	H_0	H_A	H_A
Fuzzy Mean NWLC	20 yrs.																	H_A	H_A	H_A	H_A
	30 yrs.																	H_A	H_A	H_A	H_A
	40 yrs.																	H_A	H_A	H_A	H_A
	50 yrs.																	H_A	H_A	H_A	H_A
	60 yrs.																	H_A	H_A	H_A	H_A
Fuzzy Upper NWLC	20 yrs.																				
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				

(Where H_A – Alternative Hypothesis, and H_0 – Null Hypotheses)

8.5 Interpretation of Correlation Analysis in SPACE project

It can be seen from Table 8:15, that in the SPACE project, over a 20-year, and 30-year period, the rank-ordering of whole-life costing models, are all significantly positively correlated, over the discount rate values – 3%, 5%, 7%, and 9% considered. This suggests that the cost differential in the initial and future costs, in retrofit options considered in the SPACE project, is unlikely to have far-reaching benefits, in the whole-life cost modelling of retrofit options, in the SPACE project.

It could also be the case that, initial costs of retrofit options, in the SPACE project, are relatively high, such that future cost contributions, in whole-life costing exercises, over the 20-year, and 30-year period, cannot meaningfully impact on the rank-ordering of options by different whole-life costing models. A related proposition could also be that, future costs, are less significant, such that initial cost contributions, tend to have a much larger influence in whole-life costing decisions. Foley (2012) had previously argued that, for most part of the 20th century, energy costs in buildings were relatively inexpensive, and hence investors were not interested in exploring, opportunity for savings, over the life of buildings.

Over a 40-year period, appreciable changes are noticeable, in the ranking correlations of whole-life costing models, in the SPACE project. However, these changes pertain more to the Fuzzy New-Generation whole-life costing model. At lower discount rate values of 3% and 5%, there are no significant correlations, in the rank ordering of the FM-NWLC, FU-NWLC models, and the existing WLC and NWLC, models. This implies that the scope for whole-life costing, tend to be more compelling, at lower discount rate values. There is however, potential need, to further assess the predictions of respective whole-life costing models, towards identifying model(s), which best capture the economic realities, in office retrofit building scenarios. This could involve actual collation of cost data, over the building life, especially for validation purposes.

Given the instructive proposals on declining discount rates, by the HM-Treasury (2013), the scope for whole-life cost modelling, over the 40-year period, become more imperative. The rank-ordering of the FL-NWLC model, and existing WLC and

NWLC models, are however, significantly correlated. This may not be unconnected, to the presumed low level of uncertainties, in these models.

It is however, observable that, over a 40-year period, and using higher discount rate values of 7% and 9%, the rank-ordering of the Fuzzy New-Generation whole-life costing model, and existing WLC and NWLC models, remain positively correlated.

Over a 50-year and 60-year period, the rank-ordering, of existing WLC and NWLC models, and the Fuzzy New-Generation whole-life costing model, in the SPACE projects, are not significantly correlated, at the 3% and 5% discount rate levels, but are significantly correlated at the 7% and 9% discount rate levels. It can however, be observed that, over the 50-year and 60-year period, the rank-ordering of the FL-NWLC model, are not significantly correlated, with existing WLC and NWLC models.

Specifically, over the 60-year period however, there are significant positive correlations in the rank-ordering, of the FL-NWLC model, and the FM-NWLC and FU-NWLC, models. This suggests, a potential for the FL-NWLC model, to better recognise cashflow uncertainties in its framework, than existing WLC and NWLC models.

In summary, in the SPACE project, it is noticeable that, there are significant correlations, in the rank-orderings of BCPs in the WLC and NWLC models, over the estimated periods considered, and at all discount rate values, examined. This suggests that rank-ordering by the NWLC model, might not necessarily aid the comparison of retrofit options, in the SPACE building project, as results are identical with the WLC model. This could also be partly responsible, for the low uptake of the NWLC model, in whole-life cost appraisal scenarios.

It should also be stated, that there are significant correlations, in the rankings of the FM-NWLC and FU-NWLC models, over the periods considered, and at the discount rate values examined. This suggests, the possibility of retaining only one of these models, in building retrofit investment scenarios. It will however, be necessary to undertake more studies before such hypothesis is upheld, and confirmed as valid.

8.6 Spearman's Rank Correlation results in the MS project

Table 8:16 to Table 8:18, report on selected Spearman's rank correlation analyses in the MS retrofit project. The whole-life costing exercise considered discount rate values of 3%, 5%, 7%, and 9%, and these are varied, over the 20-year, 40-year and 60-year period, in the MS retrofit project.

Table 8:16 Correlation coefficient at Discount Rate of 3% over 40 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
WLC	1.000**	0.309	0.763**	0.214	0.214
NWLC		1.000**	0.240	0.909**	0.909**
Fuzzy Lower NWLC			1.000**	0.294	0.294
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed)

Table 8:17 Correlation coefficient at Discount Rate of 3% over 50 years

	Correlation Coefficients				
Parameters	**WLC**	**NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
WLC	1.000**	0.462*	0.686**	0.354	0.462*
NWLC		1.000**	0.435*	0.293	1.000**
Fuzzy Lower NWLC			1.000**	0.309	0.435*
Fuzzy Mean NWLC				1.000**	0.293
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table 8:18 Correlation coefficient at Discount Rate of 3% over 60 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
WLC	1.000**	0.117	0.280	0.508*	0.118
NWLC		1.000**	0.385	0.377	0.809**
Fuzzy Lower NWLC			1.000**	0.303	0.315
Fuzzy Mean NWLC				1.000**	0.556**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table 8:16 to Table 8:18, displays the correlation coefficients, of respective whole-life cost models, over a 40-year, 50-year, and 60-year period, using a 3% discount rate value. The selected Spearman's rank correlation results, are displayed, as there are noticeable differences in the correlation coefficients of respective models. The remaining correlation analyses tables, in the MS project, are presented in Appendix A-5. Table 8:19 summarises the results of the Hypothesis-testing conducted on the MS retrofit project. The correlation coefficients, for the rest of the various sensitivity analyses scenarios, in the MS project, are presented in Appendix A-5. The results of the hypotheses tested in the MS project is discussed in Section 8.7, and compared with the SPACE project.

Table 8:19 Hypotheses Summaries on the Spearman's rank Correlation Analysis in the MS project

	Discount Rate / No's of Years	WLC				NWLC				Fuzzy Lower NWLC				Fuzzy Mean NWLC				Fuzzy Upper NWLC			
		3%	5%	7%	9%	3%	5%	7%	9%	3%	5%	7%	9%	3%	5%	7%	9%	3%	5%	7%	9%
WLC	20 yrs.					H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	30 yrs.					H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_0	H_A	H_A	H_A
	40 yrs.					H_0	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_0	H_A	H_A	H_A	H_0	H_A	H_A	H_A
	50 yrs.					H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_0	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	60 yrs.					H_0	H_A	H_A	H_A	H_0	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_0	H_A	H_A	H_A
NWLC	20 yrs.									H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	30 yrs.									H_A	H_A	H_A	H_A	H_0	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	40 yrs.									H_0	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	50 yrs.									H_A	H_0	H_A	H_A	H_0	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	60 yrs.									H_0	H_A	H_A	H_A	H_0	H_A	H_A	H_A	H_A	H_A	H_A	H_A
Fuzzy Lower NWLC	20 yrs.													H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	30 yrs.													H_A	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	40 yrs.													H_0	H_A	H_A	H_A	H_0	H_A	H_A	H_A
	50 yrs.													H_0	H_A	H_A	H_A	H_A	H_A	H_A	H_A
	60 yrs.													H_0	H_A	H_A	H_A	H_0	H_A	H_A	H_A
Fuzzy Mean NWLC	20 yrs.																	H_A	H_A	H_A	H_A
	30 yrs.																	H_A	H_A	H_A	H_A
	40 yrs.																	H_A	H_A	H_A	H_A
	50 yrs.																	H_0	H_A	H_A	H_A
	60 yrs.																	H_A	H_A	H_A	H_A
Fuzzy Upper NWLC	20 yrs.																				
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				

(Where H_A – Alternative Hypothesis, and H_0 – Null Hypotheses)

8.7 Interpretation of Correlation Analysis in the MS project

It can be seen from Table 8:19 that in the MS project, over a 20-year period, the rank-ordering of BCPs, according to the whole-life costing models, are all significantly positively correlated, over the discount rate values examined. This observation is consistent with results in the SPACE project, and it is deducible that performing whole-life cost modelling on office retrofit building options, over the 20-year period and lesser, tend to have limited benefits in the selection of BCPs, in the MS Office project.

Over a 30-year period, the rank-ordering, of all the whole-life costing models, considered, are significantly positively correlated, at the 3% discount-rate level. This is however, not the case, with the WLC and FU-NWLC models, and also with the NWLC and the FM-NWLC models. The situation is not unexpected, since uncertainties are modelled differently, in these respective models. It however, suggests that the potential for whole-life cost modelling becomes imperative, over the 30-year period.

It is equally observable that the rank-ordering of whole-life costing models, are correlated at the 5% discount rate and above, which supports the contention that, in the MS office retrofit project, the potential for whole-life costing could be undermined at higher discount rate scenarios. It could also be the case that, whole-life cost modelling in the MS Office retrofit project, has a more compelling benefit, under the prescriptive approach of discount rate selection.

Over the 40-year period, the rank-ordering of the WLC and NWLC models, are not significantly correlated, at the 3% discount rate level. This could be due to the number of retrofit scenarios examined, as there are identical trends in the rank-ordering patterns. The rank-ordering of the WLC and FL-NWLC models, with the FM-NWLC and FU-NWLC models, are however, not significantly positively correlated, over the 40-year period. The ranking correlation of the NWLC and the FL-NWLC models, are also not significantly positively correlated. It is therefore deducible, that the scope for whole-life costing is perhaps, more evident at the 3% discount rate value, and below.

At higher discount rate values of 5% and above, all the rank-orderings of the whole-life costing models considered, in the MS retrofit project, tend to be significantly positively correlated. This implies that discount rates, are perhaps the most influential variable in whole-life cost modelling.

Over the 50-year and 60-year period, the rank-ordering correlation coefficient of BCPs, in the MS Office retrofit project, in existing whole-life costing models, and the newly developed, Fuzzy New-Generation whole-life costing model, are not clear-cut, at the 3% discount-rate level. This suggests that, the critical region for whole-life cost modelling, is at discount rate values of 3% and lesser. There is also evidence of a positive significant correlation, in the rank-ordering observed, in the existing whole-life costing models, and the newly developed Fuzzy New-Generation whole-life cost model, at 5% discount rate level, and above. The rank-ordering observed in the FL-NWLC model however, exhibit marked similarities, with the WLC model, and this could pertain to the magnitude of uncertainties, recognised in the model framework.

8.8 Correlation Analysis in SPACE Project

Table 8:20 presents the correlation analysis of rank-orderings, in the SPACE project, based on declining discount rates. It can be seen that the rankings of BCPs, in the SPACE project, using the WLC and Fuzzy NWLC models, are mostly identical, over the period, considered. The rank-ordering of the FU-NWLC model, is however, not positively correlated with the WLC model. The 60-year period has the least levels of ranking similarity, based on the correlation coefficients, of paired whole-life costing models.

Table 8:20 Hypotheses summaries in SPACE project based on declining discount rates

		WLC	**NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
WLC	20 Years		H_A	H_A	H_A	**H_0**
	40 Years		H_A	H_A	**H_0**	**H_0**
	60 Years		H_A	**H_0**	**H_0**	**H_0**
NWLC	20 Years			H_A	H_A	**H_0**
	40 Years			H_A	**H_0**	**H_0**
	60 Years			**H_0**	**H_0**	**H_0**
Fuzzy Lower NWLC	20 Years				H_A	**H_0**
	40 Years				**H_0**	**H_0**
	60 Years				H_A	H_A
Fuzzy Mean NWLC	20 Years					**H_0**
	40 Years					H_A
	60 Years					H_A
Fuzzy Upper NWLC	20 Years					
	40 Years					
	60 Years					

(Where H_A – Alternative Hypothesis, and H_0 – Null Hypotheses).

Table 8:21 shows the correlation analysis of rank-orderings, in the SPACE project, including the cost of disruption. It can be seen that, by including the cost of disruption, there is a potential for the correlations between corresponding whole-life costing models, to be significant, over the 20-year life. This suggests that the cost of disruption, of retrofit options, in the SPACE project, tend to be more influential, over shorter life spans, and could impact on the selection of retrofit building configurations.

Table 8:21 Hypotheses Summaries in SPACE project based, on declining discount rates (including the Disruption Cost)

		Standard WLC	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	20 Years		H_A	H_A	H_A	H_A
	40 Years		H_A	H_A	H_0	H_0
	60 Years		H_A	H_0	H_0	H_0
Classical NWLC	20 Years			H_A	H_A	H_A
	40 Years			H_A	H_0	H_0
	60 Years			H_0	H_0	H_0
Fuzzy Lower NWLC	20 Years				H_A	H_A
	40 Years				H_0	H_0
	60 Years				H_A	H_A
Fuzzy Mean NWLC	20 Years					H_A
	40 Years					H_A
	60 Years					H_A
Fuzzy Upper NWLC	20 Years					
	40 Years					
	60 Years					

(Where H_A – Alternative Hypothesis, and H_0 – Null Hypotheses).

Table 8:20 and Table 8:21 shows the hypotheses testing of the rank-ordering of different whole-life cost models, using the declining discount rate schedules, specified by the HM-Treasury (2013).

Over a 20-year period, there is significant positive correlation between existing WLC and NWLC models, and the FL-NWLC and FU-NWLC models. When the cost of disruption is however, included in the whole-life cost framework, the FU-NWLC model is no longer positively correlated, with existing WLC and NWLC models, as seen in Table 8:21.

Over the 40-year period, the rank orderings of the WLC model, is correlated to the NWLC and the FL-NWLC models. The rank ordering, of the FL-NWLC model, is also positively correlated to that of the FU-NWLC model, at the 40-year estimated building retrofit life span. This suggests that, using the declining discount rate, will provoke research, regarding the mechanics of whole-life cost modelling, for appraising retrofit options. Also, the building retrofit life span of 40 years, constitutes a relevant estimation period, for whole-life cost modelling of retrofit options, in the SPACE project. The ranking correlation pattern in the SPACE project, over the 40-year period, is identical, as observed in Table 8:20 and Table 8:21. This implies that the influence of the cost of disruption, - a one-off cost, during installation of retrofit options, on whole-life cost decisions, diminishes, as the building life extends into the future.

In the SPACE project, over the 60-year period, there is no significant positive correlation, in the rank-ordering of existing WLC and NWLC models, with the Fuzzy New-Generation whole-life costing model. The output variants of the Fuzzy New-Generation whole-life costing model are however, significantly positively correlated with each other. Over the 60-year period, the correlation pattern between respective whole-life costing models, are visibly identical, as seen in Table 8:20 and Table 8:21.

8.9 Correlation Analysis in MS Project

Table 8:22 shows the hypotheses testing in the MS project, where declining discount rates are used. It can be observed that there is a significant positive correlation between the rankings of the WLC and NWLC models.

Table 8:22 Hypotheses Summaries in MS Project based on declining discount rates

		Standard WLC	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	20 Years		H_A	H_0	H_A	H_A
	40 Years		H_A	H_A	H_A	H_A
	60 Years		H_0	H_A	H_0	H_0
Classical NWLC	20 Years			H_0	H_A	H_A
	40 Years			H_0	H_A	H_A
	60 Years			H_0	H_0	H_0
Fuzzy Lower NWLC	20 Years				H_0	H_A
	40 Years				H_0	H_0
	60 Years				H_0	H_0
Fuzzy Mean NWLC	20 Years					H_A
	40 Years					H_A
	60 Years					H_0
Fuzzy Upper NWLC	20 Years					
	40 Years					
	60 Years					

(Where H_A – Alternative Hypothesis, and H_0 – Null Hypotheses).

The FM-NWLC and FU-NWLC models, also have significant positive correlation, at the 20-year and 40-year, estimated life. The results, do not however, reveal a distinctive pattern, and further research will be needed, to assess declining discount rates, on different variants, of whole-life costing models. It is however, suggested, that the use of declining discount rate schedule, in the whole-life costing of retrofit options, will buttress the need to further assess the performance of whole-life costing models.

Table 8:23 shows the hypotheses-testing in the MS project, based on declining discount rates, as well as, the cost of disruption. The inclusion of the cost of disruption has a visible effect on the rank-ordering, of the Fuzzy New-Generation whole-life costing model, but lesser effect on the correlation coefficients, of the WLC and NWLC models. This suggests better responsiveness in the Fuzzy New-Generation whole-life costing model. The effects of the cost of disruption, on the rank-ordering, also seem to diminish, after the 40-year period. Hence, the effects of the cost of disruption on whole-life cost decisions of retrofit options tend to be unnoticeable after the 40-year period in the MS project.

Table 8:23 Hypotheses Summaries in the MS project based on declining discount rates and Disruption cost

		Standard WLC	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	20 Years		H_A	**H_0**	H_A	H_A
	40 Years		H_A	**H_0**	**H_0**	**H_0**
	60 Years		**H_0**	H_A	**H_0**	**H_0**
Classical NWLC	20 Years			**H_0**	H_A	H_A
	40 Years			**H_0**	**H_0**	**H_0**
	60 Years			**H_0**	**H_0**	**H_0**
Fuzzy Lower NWLC	20 Years				H_A	H_A
	40 Years				**H_0**	**H_0**
	60 Years				**H_0**	**H_0**
Fuzzy Mean NWLC	20 Years					H_A
	40 Years					H_A
	60 Years					H_A
Fuzzy Upper NWLC	20 Years					
	40 Years					
	60 Years					

In Table 8:22, the hypotheses-testing in the MS project, is presented, where declining discount rates are used. It can be observed that there are significant positive correlations, in the rank-ordering of WLC and NWLC models, over the periods considered. The rank-ordering observed in the FM-NWLC and FU-NWLC models, are significantly positively correlated, over the 20-year, and 40-year period. The results do not however, reveal a distinctive pattern, and further research is needed to appraise the effects of declining discount rates in whole-life costing. It is however, suggested that the use of declining discount rates in whole-life cost modelling of retrofit options, in the MS office project, will buttress the need for improved robustness, in whole-life cost modelling.

Table 8:23 shows the hypothesis-testing in the MS project, where declining discount rates are used. It can be observed that there is significant positive correlation in the rank-ordering of the WLC and NWLC models. The rank-ordering of the FM-NWLC and FU-NWLC models, are also observed to have significant positive correlation, over the 20-year, and 40-year period.

In general, the results from the correlation analysis of the MS project, using declining discount rates, have not produced a distinctive pattern, and further research is needed to assess the effects of declining discount rate in whole-life cost modelling of office retrofit projects. Table 8:22 and Table 8:23, presents the summary of the hypotheses-testing of the rank-ordering, of different whole-life costing models, in the MS project, using the declining discount rate schedule, specified by the HM-Treasury (2013).

Over the 20-year period, there are significant positive correlations in the rank-ordering of the existing WLC and NWLC models, with the FM-NWLC and FU-NWLC models. This suggests that the FL-NWLC, and the WLC models, are not exactly substitutes, despite the minimal amount of uncertainties, considered in the model framework. It also follows that, the FL-NWLC model, is not significantly positively correlated with the FM-NWLC model. When the cost of disruption is included, the rank ordering of the FL-NWLC model, becomes better correlated, with that of the FM-NWLC model, as seen in Table 8:23. The hypothesis testing between the rank-ordering of the existing WLC and NWLC models, with the FM-NWLC and FU-NWLC models, are not significantly positively correlated, over the 20-year period. Although the correlation coefficient of whole-life cost modelling pairs, in the MS Project, are different from the SPACE project, the correlation patterns with the SPACE project, are identical

Over the 40-year period, there is significant positive correlation in the rank-ordering of existing WLC model, with the newly developed Fuzzy New-Generation whole-life costing model. The similarity in the rank-ordering, in the correlation of the WLC and Fuzzy New-Generation whole-life costing model, ceases, when the cost of disruption is included. This suggests that the cost of disruption, in the MS office project, is relatively higher than those of the, SPACE project. It also suggests that the initial costs play a more pivotal role, in the whole-life cost evaluation of retrofit options. Over the 40-year period, the rank-ordering of the NWLC model, are significantly positively correlated, with the rank-ordering of the FM-NWLC and the FU-NWLC models. When the cost of disruption is included, the rank-ordering of the NWLC model, ceases to be positively correlated. This suggests that future research should appraise alternative methods to evaluating the cost of disruption, in office retrofit projects. There is also a potential that the cost of disruption, becomes an influential variable, in the optimal selection of building retrofit configuration.

Over the 60-year period, there are no significant positive correlations, in the rank-ordering of the WLC and NWLC models. This suggests that marginal differences exist in the rank-ordering of both models, although this disparity, may not be particularly obvious. There are also no significant positive correlations in the rank-ordering, of office retrofit options, in the WLC model, with the FM-NWLC and FU-NWLC models. There are however, significant positive correlation, between the WLC and FL-NWLC models. The correlation patterns in the hypothesis tested for rank-ordering of BCPs, in the MS project, over the 60-year period, in the MS project are the same, with or without, the cost of disruption.

8.10 Pattern Matching of Results in SPACE and MS Projects.

The overall matching of the pattern of hypothesis tested in both case study projects – the MS and the SPACE project is 80%, as seen in Table A-6:1, displayed in Appendix A-6. Based on the correlation analysis, lower discount rate values (say, < 3%) tend to yield more null hypothesis, in which, no positive correlation is observed between the rank order of alternate whole-life costing models. This situation suggests, that the growing advocacy for declining discount rates, will by implication, require improved attention to the robustness of whole-life costing models, employable, for office retrofit buildings. At higher discount rates, the correlation levels, between whole-life costing models, are greater, and therefore, differences in the rank-ordering of BCPs, using existing whole-life costing models, tend to be minimal, as discount rate assumptions, tend to even out, the future costs, over the life of the office retrofit building.

Based on the compatibility of the hypothesis tested, in the MS and SPACE projects, as reflected in Table A-6:3, in Appendix A-6, it can be observed that, over the 20-year period, there are identical patterns in the rank-ordering of retrofit options in the MS and SPACE projects. Higher discount rate values of 7%, tend to provide identical ranking patterns, in both the SPACE, and MS projects. The pattern-matching in the MS and SPACE projects, based on the declining discount rate values, reveal that there are significant positive correlation between the WLC and NWLC models, at 20-year and 40-year period. However, there are no significant positive correlations, between the WLC and the NWLC models, at the 60-year period. There are however, observable limitations in the pattern-matching exercise, and it will be necessary to include more case-study projects, in order to allow for statistical generalisation, of the hypothesis-tested, in office retrofit projects.

It can be observed, that there are identical patterns, in the hypothesis-tested in the FM-NWLC and FU-NWLC models, with other whole-life costing models, over the estimated period. This is however, not the case, when matching results of the FL-NWLC model, and the FU-NWLC model, over the 60-year period. There is also a dissimilarity in the pattern-matching, of the FL-NWLC model, and the WLC and NWLC models, over the estimated periods considered. The matching result of the FL-NWLC model, and the NWLC models, over the 60-year period, are however, identical. It will be necessary for more case study projects to be assessed before statistical generalisation can be made, on the performance of respective whole-life costing models, in office retrofit buildings. The pattern-matching exercise in this work highlights the analytic generalisation of office retrofit buildings. The flexibility of the newly developed Fuzzy New-Generation whole-life costing model is also highlighted, and compared, with existing whole-life costing models. The newly developed Fuzzy New-Generation whole-life costing model therefore, provides a framework to consider the cost significance of disruption and revocability, and evaluate their effects on decision-outcomes, in whole-life costing scenarios.

8.11 Summary

This chapter covers the analysis and interpretation of the data, collected on two case study projects – SPACE and MS projects. Descriptive statistics, are used to assess the cost of disruption and revocability, in both projects. Inferential statistics, using the Spearman's rank correlation test, is used to test the null and alternative hypothesis developed in the ranking of BCPs, in different scenarios. A comparative analysis is conducted based on pattern-matching of the results, in the two case projects, to assess the comparability of the results. The implication of the results, are analysed and interpreted. The general discussion of results, are presented in the next chapter.

Chapter 9 Discussion and Validation of Results

9.1 Introduction

This chapter provides a discussion on the findings in the work. It commences with the conceptual issues that informed the studies, and the methodological adjustments to whole-life costing, and how this adds to the knowledge base. This work takes forward some insightful suggestions, proposed by researchers, and addresses some deficiencies, in previous works. This chapter also examines the implications, in the practice of whole-life costing. Subsequent sections discuss the insights, fostered by the evaluation of the cost of disruption and revocability, in whole-life cost modelling. The penultimate section presents the results from Semi-Structured Interviews, with building experts, used to externally validate, the newly developed fuzzy model.

9.2 Conceptual Issues in Model Development

The newly-developed, Fuzzy New-Generation Whole-life Costing model, have a number of similarities with existing models – Standard Whole-life cost (WLC) model, and the New-Generation whole-life costing (NWLC) model. The similarities are expressed as follows:

1) The models examined and developed in this work, are mathematical models. Although, this work identified approaches such as Simulation and Finite-Element methods (Farr, 2011) that could potentially, be used, in the development of whole-life costing models for retrofit options, it was proposed that a robust mathematical whole-life costing model, will provide an improved and sufficient framework, for model validation and development. This approach also builds on existing knowledge.

2) The newly developed, Fuzzy New-Generation whole-life costing model, retain the separation of whole-life costing elements, into distinct categories of Initial Capital Costs and Future costs. The Initial Capital cost, is often computed as a lump sum, which will generally include the cost of labour and materials, professional fees, preliminaries costs, and other associated legal and acquisition costs. The Future costs are also computed in annual values, with

different variations of the estimated building retrofit period. This distinction is retained in both the existing, and newly developed Fuzzy New-Generation whole-life costing model, and is consistent with industry standards, specified by the Chartered Institute of Public Finance and Accountancy (CIPFA), and the International Financial Reporting Standards (IFRS).

There are however, differences between the existing whole-life costing models – WLC and NWLC, and the newly-developed, Fuzzy New-Generation Whole-life costing model. These differences are stated, as follows:

1) The WLC model, does not consider the effects of revocability, in its framework. The NWLC model however, attempts to model revocability, over the life of buildings, through appraising cost estimates, using the Negative Binomial probability distribution. The newly developed Fuzzy New-Generation Whole-life costing model, recognises revocability, but converts the Negative Binomial probability distribution, into a fuzzy relation matrix, based on the cosine-amplitude formulae. This initiative is considered beneficial, in evaluating the cost of revocability, over a range, rather than using single estimates. Also, the aggregated fuzzy relations matrix, is used in meaningfully providing a three-point whole-life costing estimate, thus incorporating flexibility, into the mechanism of whole-life cost modelling in buildings.

2) The newly developed, Fuzzy New-Generation Whole-life costing model, appraises the cost of disruption, in the whole-life costing of retrofit options, in office buildings. This is considered, a significant, and often unrecognised variable, in the investment appraisal of office retrofit buildings. The cost of disruption is estimated, and added on to, the initial capital costs, of the building. Although, it can be argued that the cost of disruption, could be included in the WLC and NWLC frameworks. The inexactness in the cost of disruption will imply that a fuzzy logic framework, is perhaps the more suitable, rational, and logically verifiable approach to estimating the effects of disruption in retrofit options in office buildings. This also aligns with the principal aim of this work, which is to apply the principles of fuzzy logic, in the whole-life cost modelling of office retrofit buildings.

3) Another area of conceptual modification in this work, is in the consideration of the time-value of money. Previous works in whole-life costing, have predominantly used a single discount-rate value, over the period of estimation. The limitations of these approach, has been elaborately discussed in Chapter 3 of this thesis. This work utilises a declining discount rate approach, which attempts to provide a more equitable, and balanced approach to intergenerational equity. The declining discount rate values, are in line, with those published, in the Green Book by the HM-Treasury (2013). In using declining discount rate values, in whole-life cost modelling, this work better aligns with the objective of sustainability, with the goal of long-term investment appraisal of office retrofit buildings.

Besides the similarities and differences espoused in the models, other conceptual issues in the whole-life cost modelling of office retrofit options, are appraised. Previous works on whole-life cost modelling of buildings, have not made a clear distinction between revenues and costs. This oversight has led to previous whole-life costing models, being equated with, the net-present value (NPV) metric (Kirkham, 2005, Kishk, 2005, Ellingham & Fawcett, 2006). While, it is important for the NPV of projects to be evaluated, this work argues that, the objective for whole-life cost modelling in buildings, is different. Whole-life cost modelling aims to provide a means to systematically compare competing options, in buildings (Kishk, 2005, CIFPA, 2011, Fawcett, 2011, Caplehorn 2012), rather than estimate the balance between revenue and cost, which is the remit of cost-benefit analysis (Rogers & Duffy, 2012). Hence, whole-life cost modelling should focus on the strategic identification of all costs, that occur at different periods, over the life of the building, and aggregate them, towards providing a value that best aggregates, the initial and future costs, over the life of the building (CIFPA, 2011, Skinner *et al.,* 2011). A robust whole-life costing process, will inevitably provide data, which will enhance a robust cost-benefit analysis.

Given, the existence of different cost elements, at different times, over the lives of buildings, uncertainty analysis techniques, will be highly beneficial in robust whole-life cost modelling (Boussabaine & Kirkham, 2008). Probability theory, is particularly relevant in modelling uncertainties. However, using probability theory to provide single whole-life cost estimates, might still detract from the primary objective of whole-life cost modelling, and put to question, the integrity and credibility of whole-life cost values (Zadeh, 1995, Ross, 2009). Perhaps, this is one reason, behind the unpopularity of existing whole-life costing techniques (Clift & Bourke, 1999). This work has therefore developed, a Fuzzy New-Generation whole-life costing model, which outputs a three-point estimate, in the evaluation of office retrofit buildings. These three values, are approximate evaluations, and are analogous to the optimistic, realistic and pessimistic whole-life cost values, over the life of the building. Previous whole-life researchers, including Goh *et al.,* (2010), Skinner *et al.,* (2011) and Fawcett *et al.,* (2012), have canvassed for flexibility in whole-life cost modelling. This work thus, implements a flexible approach to whole-life cost modelling, based on the principles of fuzzy logic.

Previous works in whole-life cost modelling have also failed to highlight the relative desirability of comparable options in buildings (Kishk, 2004, Lau & Lew, 2009). In the extant literature, the primary objective of conducting a whole-life costing exercise is, to identify the most effective choice, among a range of competing options (Goh & Sun, 2015). The application of whole-life costing in buildings, will by implication, involve a mechanism for assessing the relative desirability of retrofit options. This work has utilised the Spearman’s rank correlation test, to evaluate, and compare the rank orders of retrofit options, in the SPACE and MS projects. Whole-life cost estimates have been computed, over selected time periods, and based on different discount-rate assumptions. The correlation coefficients obtained from the Spearman’s rank correlation analysis, was obtained, and the hypotheses regarding the extent of similarity of the rank orders, in respective building projects, were tested. This approach has provided an analytical approach to evaluating the relative desirability of BCPs in office retrofit building projects.

Lastly, previous works in whole-life cost modelling have implicitly focused on new builds, without considering the potentials of re-configuring existing builds. The newly developed model has been tested on existing buildings, and also has application for new buildings, as well. The major difference in both models might well be, the consideration of the cost of disruption. The cost of disruption, is a useful variable, in the economic appraisal of retrofit work, and applies mainly to existing buildings.

9.3 Rank Correlation Analysis in Case Retrofit Projects

The implications of the results from the newly-developed, Fuzzy New-Generation whole-life costing model, have been discussed, over different time periods, in order to highlight the contributions to knowledge of the new model.

9.3.1 20-Year Period

In the two case projects considered – the SPACE and MS Project, the business case of whole-life costing, over the 20-year period, is not significantly clear. Even when discount rate values, become significantly higher, significant correlation in the rank-ordering of whole-life costing models, is observed. In other words, the magnitudes of the cost of revocability and disruption, seem less influential on decisions-made, over the 20-year estimated building life. The ordinal differences in whole-life cost estimates of retrofit options, is also not weighty enough, to alter decision preferences in the SPACE and MS office retrofit projects. There are however, indications that the benefits of whole-life cost modelling, at this stage, is limited, to providing forecasts of the economic value of the building, but not much is achieved, by way of comparing retrofit BCPs.

The newly developed, Fuzzy New-Generation whole-life costing model, outputs a three-point estimates, for respective retrofit options, rather than the single-point estimate, provided, by the WLC and NWLC models. Regarding the rank-ordering, of retrofit options, it is observed that ,over the 20-year period, there are significant positive correlations, in the rank-ordering of BCPs, in the existing WLC and NWLC models, and the FU-NWLC model, in the MS and SPACE projects. This situation however, holds when the cost of disruption is not included. When the cost of disruption is included, the ranking correlation, are significantly different, and the rank-ordering of options, in the FU-NWLC model, is no longer positively correlated, with the existing WLC and NWLC models, in both case study projects. This suggests that the Fuzzy New-Generation Whole-life Costing framework, is more responsive, to the inclusion of variables in the model framework. Further research is however, needed to test the correlation coefficients, of ordinal variables, in more representative samples of office retrofit buildings.

9.3.2 40-Year Period

In the two case projects considered – the SPACE and MS Project, over the 40-year period, the benefits of whole-life cost modelling, is significantly clear. The rank-ordering in the Standard Whole-life costing model (WLC), and the New-Generation Whole-life Costing model (NWLC) are identical, and hence the NWLC's benefit in the rank-ordering of options, is suspect. In both the MS and SPACE projects, it is also observed that, over the 40-year period, there are changes in the rank-order of BCPs, when the cost of disruption, is included. There are also indications that the decision-effects of the cost of disruption, tend to peak, around the 40-year period. It is seen that the cost impacts of disruption, are influential in the ranking correlations, of the Fuzzy New-Generation whole-life costing model, and the existing WLC and NWLC models.

It should be noted that few changes, in the rank-orders of BCPs, in the MS, and the SPACE projects are observed. When the cost of disruption is included, in the SPACE project, there are no observable changes in the hypotheses tested. However, changes in the hypotheses-tested, in the MS project, based on the correlation coefficients, are considerable. For example, there was no significant correlation, between the rank-ordering of existing WLC model, and the Fuzzy New-Generation Whole-life costing model, after the cost of disruption, were included. This attests, to the influence of the cost of disruption, over the 40-year period, and suggests the need to pay more attention, to evaluating the cost effects of disruption, in office retrofit building projects.

9.3.3 60-Year Period

Over the 60-year period, the rank-ordering of variants, in the Fuzzy New-Generation Whole-life costing model, exhibit more similarities with each other, compared to the rank-ordering, observed in existing WLC and NWLC models. This is observed, in both the MS and SPACE projects. Also there are no statistically significant differences in the rank-ordering, between the WLC and NWLC models. This observation suggests benign differences in the framework of the WLC and NWLC models. Although, this could become more noticeable, over a lengthy time span, such as 60-years, and beyond. It is suggested that the mechanics of uncertainty modelling, in whole-life costing of office retrofit projects, is better highlighted in the Fuzzy New-Generation whole-life costing framework. There is however, the need for further work on larger samples of office retrofit building projects, in order to, generalise the results of the newly developed model, to other office retrofit building projects.

In summary, it can be suggested that empirical collection of initial and future cost data, on office retrofit buildings, will enhance the assessment of whole-life cost models. Future research should seek to perform a goodness-of-fit test, between the actual data and the predicted data, calculated from respective models. This line of inquiry will further enhance the assessment of models, to better reflect the costing realities, in office retrofit building projects.

In both projects considered - the MS and SPACE projects, the 20-year life span does not provide a sufficiently extensive period, to realise the benefits of whole-life costing. This suggests that, at the current time, competing retrofit options, still possess considerable initial costs, and there is need for both the building industry, and the Government to seek for innovative and sustainable ways, of minimising the acquisition and installation costs, of retrofit technologies, in office buildings. In the UK, the enhanced capital allowances, which up to January 2016, allows for 100% tax savings on funds, spent on energy-efficient technologies, in the first year of investment, provides a reasonable context, to explore the benefits of whole-life cost modelling. However, it will be necessary to extend tax savings, over more years, in order to further promote energy-efficient investments, in office retrofit building projects.

In the SPACE project, an expected retrofit life of 30 years, is not considered a convincing context to economically appraise retrofit options in office building projects, on a whole-life cost basis. The MS project, however, demonstrate some benefits of using whole-life cost modelling, in appraising building retrofit options, over the 30-year life span. It is therefore suggested that future research in office retrofit building projects, should focus on identifying the period, over which whole-life costing of office retrofit building options, becomes critical. Over the 40-year period, and beyond, the benefits of whole-life cost modelling, in the SPACE and MS projects, are evident. However, this is particularly significant, for discount rate values of around 3% and below.

There is a cultural angle to the domain of investment appraisal of office retrofit building projects. The pace of innovation in the industry has supposedly fuelled reliance on the pay-back periods as a more widely-used means, of investment comparison (Ma *et al.,* 2012). In the Semi-structured interview with building experts, it was suggested that building investors are barely satisfied with a payback period of 3 – 5 years on retrofit investments, and a payback period of 1½ years or less, is more commonly demanded by building investors. This attitudinal disposition of investors is not considered conducive for the practice of whole-life cost modelling, and could hinder the implementation of long-term, optimally performing, and economically-advantageous retrofit options.

9.4 Validation of the Results

Semi-structured interview were conducted, with 6 project team members, involved with the SPACE project, to assess the basis of the Fuzzy New-Generation whole-life costing model (see Appendix A-7). Eight members of the SPACE project team were approached, but only six people agreed to participate in the interviews. The 6 participants consisted of the Project Manager, Energy Consultant, Cost Consultant, Specialist Contractor, Project Evaluator and Building Manager.

An interview schedule was developed, and had three main objectives:

1. To assess the basis of the newly developed Fuzzy New-Generation Whole-life costing model
2. To find out, if whole-life costing was considered and conducted in the SPACE project
3. To find out the realistic life span of the SPACE retrofit project.

It was agreed by all the six respondents that, there were serious methodological challenges with existing whole-life costing techniques, and the proposed model is a commendable development, towards improving the practice of whole-life costing, for retrofit options. One disadvantage, expressed by two of the interviewees, was that the newly-developed model, had a rigorous mathematical form, and its procedures seem to be untraditional, and difficult to understand. Generally, the interviewees agreed with the basis of the new Fuzzy New-Generation whole-life costing model, and applauded its form, in appraising the cost of disruption, in its framework. The flexibility, in providing a three-point estimate, rather than a single figure, was also applauded by the interviewees.

One of the respondents said

> "*For us, as office owners, income generation is uppermost on our agenda, and we are quick to avoid disruption, because there is likelihood, we will not earn rent, when the work is on-going"*

It was however, suggested that future studies should test the results, of this new fuzzy New-Generation whole-life costing model in office building retrofits, as well as in other commercial building retrofit typologies.

Another respondent expressed that the

"*Flexibility is perhaps, the most beneficial aspect of the new model as, there is a possibility that 'whole-life costing assumptions are wrong'*".

All the respondents mentioned that some efforts were made to evaluate the whole-life cost implication of the retrofit options, prior to sanctioning the SPACE project. However, there were difficulties regarding the procedures. One of the respondents mentioned that

> *"Different components have different lives, and hence, it was considered inappropriate to evaluate the whole-life cost of the building, as a whole. Hence, efforts were made to assess the whole-life cost of individual components, within the building, but this was not extended to comparing options".*

Another respondent also commented that:

> "*There is interest in seeking out technical solutions, which balance costs. However, we do not get into, as much detail of summarizing this into a whole-life cost value, due to the complex assumptions required".*

It can be surmised from the interviews, that whole-life costing was not formally carried out, in sanctioning the SPACE retrofit project. Although, the project players were reasonably familiar with the purpose and intent of whole-life costing. It can be suggested that the methodological challenges in whole-life costing techniques, discouraged its use. The development of a more robust platform for whole-life costing, as provided in this work, and the empirical validation of the whole-life costing data, will therefore be useful in improving the practice of whole-life costing, in office retrofit buildings.

Regarding the realistic life span (number of years), before another major retrofit or refurbishment exercise will be necessary, there was no consensus from the interviews conducted. One of the respondents argued that:

> *"Whole-life costing should not exceed 15 years, as building investors are not willing to commit resources exceeding such period, and are also wary of the pace of innovation, regarding energy-efficiency techniques"*.

Another respondent mentioned that "*30-years seemed to be a realistic life span. However, allowance should be made, to replace, some shorter-lived equipment".*

Another respondent advised that "*20-years are perhaps the limiting life span for retrofit projects, on the basis of installed life".*

The limiting period suggested by another, of the respondent is that, "*a 40-year life span will suffice for whole-life costing*". These suggested life-spans for retrofit technologies, will suggest the need for reduced initial costs of retrofit initiatives. This will be necessary for the benefits of whole-life costing to be realised, in office retrofit building projects.

9.5 General Remarks

The aim of this work is to apply the principles of fuzzy logic in the whole-life cost modelling, of office retrofit buildings. In line with these, this has work developed the Fuzzy New-Generation whole-life costing model. This work builds on previous works in whole-life costing, and retains the format of existing mathematical models, with components of “initial capital costs” and “future costs” as principal variables, in the whole-life costing framework. It also evaluated, and justified, the cost of disruption in the initial costs, and also evaluated the cost of revocability, in Future costs. This inclusion, is a major contribution, in this work.

The cost of disruption, is specific to existing buildings, rather than new builds, and can vary significantly, depending on the commercial interests of respective organisations. It is expected that the cost of disruption, will be more significant, in goods-oriented organisations, rather than service-oriented organisations, as the possibilities for relocation of production sites, can be more difficult to arrange.

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

Revocability, as a concept, could be difficult to appraise. Revocability embodies initiatives within the control of building occupiers, as well as economic conditions out-with the control of building occupiers. Ellingham and Fawcett (2006) espoused on the external economic condition that influences cost revocability, which essentially refers to inflation. However, revocability, as described by Verbruggen (2013), can be exercised through internal factors, such as awareness of building users, on how to manage future costs. With regards to the future energy costs, this may be through optimising renewable energy sources, where possible, and it could also be through, switching to cheaper energy providers.

Revocability, could also be exercised through, raising building users’ awareness, on the costs of energy, and potential savings, drawing attention to energy-use, clear labelling of switches, and controls. In addition, poster campaigns to encourage good practice, attending training courses that foster utility cost savings, and encouragement of building users, to participate in cost-saving initiatives. In the SPACE project, it was estimated that staff awareness could save up to 2% of annual utility costs of the building (Rickaby, 2012). It is however, unclear, if this pertains to a single possible saving, or if this is incremental, over the life of the building. Revocability, is considered to relate to the future costs in buildings.

In conclusion, there seems to be evidence of underestimation of the whole-life costs of retrofit buildings. In previous whole-life cost modelling exercises, the cost of disruption has not been recognised, as a component of the initial cost, in retrofit scenarios. Equally, the implications of revocability, has not been explicitly considered, in future cost evaluation. There is therefore, reasonable argument that existing whole-life costing models, are limited in their assessments of the long-term costing implication of buildings.

9.6 Summary

This chapter provides a discussion on the research work. It commences with the conceptual issues informing the studies, and the methodological adjustments to whole-life costing, that improves the mechanics of whole-life cost modelling of office retrofit building projects. It goes on to discuss the results, and the implications of those results, for the practice of whole-life costing. The subsequent sections discuss the implication of the cost of disruption and revocability, in whole-life cost modelling. The penultimate section, attempts to externally validate the newly-developed model, through Semi-Structured interviews with building experts.

Chapter 10 Conclusion and Recommendations for Future Research

10.1 Introduction

This chapter brings together the contribution to knowledge, of the entire research work. The next section summarises the research work, and reviews the stated objectives. This chapter details the main findings, from the studies, and discusses their implications on the practice of whole-life costing, in office retrofit building projects. The rest of the chapter highlights the limitations of the study, and suggest recommendations for future work.

10.2 Summary of Research Work

This summary presents an overview of the Problem Statement, and how it connects with the objectives of the study. The research work addressed each of the objectives, and has contributed to the knowledge base, in distinct ways. This is discussed in the next section. The problem statement and research objectives are summarised below:

10.2.1 Problem Statement

It is recognised that office retrofit buildings, are becoming more popular in the Built Environment literature (Mansfield, 2009, Heo *et al.,* 2012, Ma *et al.,* 2012), and there is a need to appraise these building typologies, towards ascertaining their economic viability (Menassa, 2011). Whole-life costing provides an analytical framework, to aid rational, and realistic, decision-outcomes, in building investment appraisals (CIFPA, 2011, Capelhorn, 2012). This work commenced with a review of published literature on whole-life costing, and examined the application of whole-life costing, in the context of office retrofit building projects. The problems in the whole-life cost modelling of buildings were summarised as, unreliability of data, insufficient representation of uncertainties, and lack of robustness in the model framework (Ellingham & Fawcett, 2006).

The problems with data in office retrofit buildings, pertain mostly to the future Costs, and specifically, the energy costs (Wade *et al.,* 2003a, Christersson *et al.,* 2015). Energy simulation runs were developed, for different retrofit options, and the annual energy consumption of two case study building projects, were appraised. This assisted in improving, the reliability of the energy cost data, used in whole-life cost modelling.

The insufficient representation of uncertainties, was address by utilising advanced techniques of fuzzy logic and probability theory, to model uncertainties. The principal feature of these techniques, was allowance for flexibility in estimates, and their ability to capture diverse, heterogeneous data. It is argued that these inclusion, holds potential in improving the credibility of whole-life costing decisions, in retrofit scenarios. This new model also provided a robust analytical framework, within which the strength and influences, of identified cost variables, can be examined and understood.

The lack of robustness in whole-life cost models, are addressed by, identifying previously unrecognised uncertain variables. These are, the cost of disruption, and the cost of revocability. These cost variables, are evaluated using fuzzy logic techniques, and the potential contributions, to the whole-life costing framework is appraised.

10.2.2 Objectives of the Study

The aim of this study, is to apply the principles of fuzzy logic, in the whole-life cost modelling of office retrofit buildings. It is therefore considered important, in this current research, to re-orient the principles of whole-life costing, to better recognise, specific issues in the appraisal of office retrofit building projects. To this end, the Fuzzy New-Generation whole-life costing model, was developed, towards embodying disruption and revocability, in its framework. The stated objectives of the study, are reviewed and the main findings, are discussed, under the following headings:

1. <u>Appraise Existing approaches to Whole-life costing for retrofit options in office buildings</u>

Two mathematical whole-life costing models are identified, in the literature. They are the Standard Whole-life Costing (WLC) model, and the New-Generation Whole-life Costing (NWLC) model. One key problem with the WLC model, is that, it does not explicitly provide for uncertainties, in its framework. Another problem with the WLC model, is its treatment of decisions and outcomes, in buildings, as irrevocable (Ellingham & Fawcett, 2006). Hence, there is no flexibility in altering the project's course, over their expected life. The NWLC technique, strategically improves on the drawbacks of the WLC approach, especially in the areas of allowing for revocability of decisions, and outcomes. The modelling of revocability, in the NWLC approach however, assumes dichotomous values, of equal proportion, in successive years. This approach is limited, and there is scope for improving on the whole-life costing framework. It is argued, in this work, that robustness of whole-life costing models in retrofit scenarios, can be enhanced through modelling for uncertainties, in both the Initial and the Future Costs. The cost of disruption, and the cost of revocability constitute relevant uncertainties in the whole-life costing of office retrofit buildings. Revocability, connotes the potential for variability in the future costs, and disruption relates to the diminished building use, or unusability, over the period of implementing a retrofit initiative.

Established techniques of uncertainty modelling, are used, in evaluating the costs of revocability and disruption, in whole-life costing scenarios. The cost of disruption is evaluated, using fuzzy logic techniques, while revocability is appraised using probability theory, and fuzzy logic techniques. There are suggestions in the literature, that there is a potential for using Finite Element methods, and Simulation techniques in whole-life cost modelling (Farr, 2011). This is however, suggested as a line of inquiry for future research work.

It is also proffered, that the cost of revocability and disruption, have a place in the whole-life costing framework of office retrofit buildings, regardless of the generic approach used, in evaluating variables. This research, has evaluated the effects of revocability, in the whole-life costing of options in the SPACE and MS Office retrofit building projects. Economic revocability, pertains to uncertainties in the future cost outcomes, of buildings. Economic revocability, tend to be difficult, to precisely measure, and hence, the need for flexible and imprecise, modelling tools. Revocability seeks to address the variability prospects, in the future cost projections, in respective years, based on external economic trends, as well as, internal controls, exercised by building owner(s) and occupier(s).

The cost of disruption is appraised, as a one-off cost, which occurs during the implementation of a retrofit initiative. The cost of disruption could significantly alter the business case for office retrofit building projects. Previous methods of whole-life costing, have not explicitly considered the effects of disruption, in potential retrofit interventions. Hence, existing models could undermine relevant variables, which influence the eventual cost out-turn. One explanation for this limitation, in the current practice of whole-life cost modelling, is that existing whole-life costing models, are developed for new builds, in which case, the costs of disruption, is rather non-existent and hence, not considered in the model framework.

This study builds on the need to improve on the theoretical weaknesses of existing whole-life costing modelling procedures. In addition to the usual whole-life cost components (Initial Capital costs and Future costs), the cost of disruption has been evaluated, in respect of the initial costs, while the cost of revocability, is evaluated in respect of the future costs. This novel inclusion of previously unrecognised cost variables, in whole-life cost modelling, have potentials to highlight new insights, that could influence, and improve the quality of decisions-made, by building-owners and investors, and enhance the integrity of whole-life cost predictions, in office retrofit buildings.

2. Develop a Fuzzy New-Generation Whole-life Costing model for retrofit options in office buildings

This study has developed a new approach to whole-life costing, called the Fuzzy New-Generation whole-life costing model, for office retrofit buildings. The model output of the newly-developed model, is presented, in three estimates, called the Fuzzy lower, Fuzzy mean, and Fuzzy upper NWLC models. These estimates, represent a range of values, regarding the whole-life costs of retrofit options in office buildings. It is therefore argued, that a single-point whole-life cost estimate, could be misleading for investors and clients, requiring conclusive guidance on the most economical option, over the life of an office retrofit building configuration. The rationale for allowing for flexibility, in whole-life cost modelling, is based on the supposition that, whole-life cost scenarios, involve complex set of decision events, actions, and outcomes, with significant interdependencies, and uncertainties. It is therefore essential to allow for imprecision, in order to model future cost events, more realistically and credibly, as previously suggested by Ross (2009).

The Fuzzy New-generation whole-life costing technique improves on the theoretical weaknesses of whole-life cost models, in relation to the variability of future costs, by using fuzzy logic, which provides a mechanism, for imprecise modelling scenarios (Zadeh, 2008). The Fuzzy New-Generation whole-life costing model, has been developed to capture uncertainties, and respond more dynamically, to variable-changes, than existing whole-life costing techniques.

The principle behind the Fuzzy New-Generation whole-life costing model, and its procedural implementation is discussed in Chapter 5. The Fuzzy New-Generation whole-life costing model, is an advanced modelling framework, and the procedures for its implementation is presented in a 10-step flowchart, in Figure 5-1. The model inputs are the Annual future cost, Discount rate values, Estimated life of the building (in years), and the Revocability rate. The new model generates a Fuzzy relations matrix, and aggregates the Fuzzy whole-life future costs, into three estimates. The Fuzzy future cost matrix utilises the Negative Binomial probability distribution, in evaluating the likelihood of future cost events, occurring, thus building on the assumptions in the New-Generation Whole-life costing model, developed by Ellingham and Fawcett (2006).

3. Develop a mathematical algorithm that aids the implementation of the fuzzy new-generation whole-life costing model

Despite the merits of the Fuzzy New-Generation whole-life costing technique, its procedures could appear cumbersome, and its processes could be shrouded in computational details. To ease this difficulty, a software program, has been developed to evaluate the Fuzzy running costs, of retrofit options in office buildings. The software program was written, using Python® scripts, and has been used to ease the computational demands, of the newly developed model. The software is essentially useful, for the evaluation of future costs. The Python® Scripts, presented in Section 5.3.1 Automation of the Fuzzy Future Cost Computation, have been implemented using the Rhinoceros Software platform. The purpose of each of the software functions are itemised, and presented in the following sequence:

i. This function generates probabilistic coefficients of the Negative Binomial distribution.

ii. This function sums up the probabilities of each row, to facilitate the normalisation into standard probability values, between 0 and 1.

iii. This function normalises the probability values, between 0 and 1.

iv. This function positions the probability values, in order to correspond with future cost equivalents.

v. This function achieves the formulation of a square matrix, by inserting zeros into empty columns and rows, in order to allow matrix aggregation.

vi. This function aggregates the new matrix developed, by combining the future cost values into a fuzzy relation.

vii. This function limits the decimal point of normalised probability coefficients, into a rounded string.

viii. This function computes the progressive future costs, over the expected life based on the revocability rate.

ix. This function converts the array of future cost events, into a square matrix.

x. This function generates a continuum of fuzzy cumulative future cost values, for the matrix.

xi. This function generates the fuzzy lower, fuzzy mean and fuzzy cumulative future cost values

4. Validate the developed model using sample retrofit projects and compare the results with existing whole-life costing techniques

The implications of newly developed Fuzzy New-Generation whole-life costing model has been evaluated, by comparing the rank-order of retrofit options, using the Standard Whole-life Costing (WLC) model, and the New-Generation Whole-life Costing (NWLC) model, with options evaluated using the Fuzzy New-Generation Whole-life Costing model. In the SPACE project, the average cost of revocability, of retrofit options, can be up to 33%, over a 20-year period, 58% over a 40-year period, and 105% over a 60-year period. In the MS project, the average cost of revocability of retrofit options, can be up to 35%, over a 20-year period, 63% over a 40-year period, and 119% over a 60-year period. The added cost of disruption of retrofit options, can increase the initial costs, by up to 1.5% and 12%, in the MS and SPACE projects respectively.

The lack of consideration of revocability and disruption, in existing whole-life cost models, suggest the potential for underestimation, in the whole-life costs, of office retrofit options. Results from the SPACE project, suggest up to 2% underestimation in the whole-life costs, over a 20-year period, up to 21% underestimation, over a 40-year period, and up to 45% underestimation over a 60-year period. In the MS project, it was found that there is potential for up to 9% underestimation, in the whole-life costs of retrofit options, over a 20-year period; up to 30% underestimation, over a 40-year period; and up to 53% underestimation, over a 60-year period.

It is also implied from the study that, 20 years, does not provide an elaborate period, to realise the benefits of whole-life cost modelling, in office retrofit buildings. This suggests that competing retrofit options, have considerable initial costs, and there is a need to seek for ways of minimising the installation costs, of retrofit options, in office buildings. In the UK, the enhanced capital allowances, which as of January 2016, allows 100% tax savings of funds invested in specific energy-saving and environmentally-friendly projects, in the first year of investment, constitute a good focal point for policy makers. However, it will be necessary to extend tax savings, beyond the first year of investment, in order to further drive the appeal of investments in office retrofit building projects.

Regarding the rank-ordering of whole-life costing models, over the 20-year period, the two case projects revealed significant positive correlation between the existing Standard Whole-life costing model, and New-Generation Whole-life costing model, with the Fuzzy-lower New-Generation Whole-life costing model, Fuzzy-mean New-Generation whole-life costing model, and the Fuzzy-upper New-Generation whole-life costing model, over the discount rate values considered. The benefits of whole-life cost modelling, over the 20-year period, is not considered beneficial. Likewise, the benefits of whole-life cost modelling, in comparing building retrofit options, over the 20-year period, is limited.

Over the 40-year period however, the benefits of whole-life cost modelling in office retrofit buildings, become more evident. This is particularly applicable, when using discount rate values, of around 3% and below. Regarding the rankings of the whole-life costing models, over the 60-year period, the Fuzzy New-Generation whole-life costing model, bear more similarity in their rankings, with each other, in both the MS and SPACE projects, but are not significantly positively correlated, with the New-Generation Whole-life Costing model, and the Standard Whole-life costing model, at lower discount rate levels of, lesser or equal to 5%. This suggests that the magnitude of uncertainty in future cost events, are better highlighted, using the Fuzzy New-Generation whole-life costing model. Further research will however, be necessary in order to, ascertain the comparative performance of whole-life costing models, and this will involve including more representative samples of office retrofit building projects.

10.3 Contributions to Knowledge

This study has developed a new approach to whole-life costing, called the Fuzzy New-Generation Whole-life Costing model, for office retrofit buildings, and has provided a software program to aid its computation. The model output of the newly-developed Fuzzy New-Generation whole-life costing model, provides three estimates called Fuzzy lower, Fuzzy mean, and Fuzzy upper, New-Generation whole-life cost values. The Whole-life cost estimates of Building Configuration Permutations (BCPs), in two office retrofit building projects, are appraised, using the declining discount rate schedule, specified by the HM-Treasury (2013). This research evaluated the cost of revocability and disruption, in the whole-life costing of office retrofit buildings

In the SPACE Project, It was found that the average cost of revocability, relative to the initial capital cost of BCPs, can be up to 35%, over a 20-year period; up to 58%, over a 40-year period; and up to 105%, over a 60-year period. In the MS project, the average cost of revocability, of retrofit options, relative to the initial capital cost, can be up to 35%, over a 20-year period; up to 63%, over a 40-year period; and up to 119%, over a 60-year period. It was also found that the average cost of disruption relative to the initial capital cost of BCPs, can be up to 12%, irrespective of the estimated life of the building project.

Results from the SPACE project also suggest up to 2% underestimation, in the whole-life costs, over a 20-year period; up to 21% underestimation, over a 40-year period; and up to 45% underestimation, over a 60-year period. In the MS project, it was found that there is potential for up to 9% underestimation, in the whole-life costs, over a 20-year period; up to 30% underestimation, over a 40-year period; and up to 53% underestimation, over a 60-year period.

10.4 Limitations of the Study

The Fuzzy New-Generation whole-life costing model is based on a mathematical modelling framework, and retains the format of existing mathematical models with components of “initial costs” and “future costs” as principal variables, in the whole-life cost formulae. This work is limited, in adopting this distinct categories, of cost elements. The crucial limitation in using this distinct categories, is that it assumes same party, bears the initial and future cost obligations, over the course of the building, and could misrepresent the interests, of building stakeholders. This constitutes a limitation, in this work.

The Fuzzy New-Generation whole-life costing model, have also adopted, a three-point estimate, for the whole-life costs. Whilst this format, potentially improves on the single-point estimate, it is quite reductionist, and could undermine potentials, for better understanding revocability, in office retrofit building projects.

The study is also limited in its focus on ordinal rankings of retrofit options, and is constrained to the use of the non-parametric Spearman’s correlation test, to assess the rankings of BCPs, on a whole-life cost basis. This restrictive focus is adopted as a result of the primary function of whole-life costing, as a means of comparing competing alternatives. The study is also limited, in assuming that cost, is the sole basis, for ranking competing, investment options. In more realistic scenarios, other factors such as the least capital cost, “wow” factor, familiarity, aesthetics, prestige, innovation, or a combination of these, could constitute equally important considerations, to decision-makers. Hence, this work assumes that whole-life cost, is the supreme determinant, upon which decision-makers and clients, select building retrofit options, which in reality is an over-simplification, of the decision-making process.

The work is also limited in considering only two case projects, one of which is a secondary data-set, collected from published reports. Attempts have been made to verify the data. However, there are difficulties to achieving this. The study is also limited in its application, as it does not consider variability in the initial costs and future costs, caused by location, and differences in contractors pricing regime.

The external validity of the Fuzzy New-Generation whole-life costing model, through Semi-Structured interviews, provided a basis to test the proposed model. It will however, be helpful, to assess the validity of the model framework, using a more quantitative technique. In the case of the Fuzzy New-Generation whole-life costing model, testing the actual data of real-life office retrofit building projects, with the predictions, from the proposed model, will enhance the external validity and generalisability of the model. It will also be highly beneficial, for future studies, to robustly appraise the newly developed Fuzzy New-Generation whole-life costing model. The external validity of this work, is therefore considered moderate, as it aims to achieve analytic generalisation, rather than statistical generalisation.

10.5 Recommendations for Future Work

The Fuzzy New-Generation whole-life costing model is identical to the closed-form mathematical algorithm, and the components, identified in the Fuzzy New-Generation whole-life costing model, can potentially be modelled using a Simulation, or Finite-Element approaches. It is therefore useful for future research, to investigate the potentials of alternative cost modelling techniques in Office retrofit buildings, towards capturing the costing realities, of office retrofit building solutions. The mechanics of whole-life cost modelling in buildings; need to be periodically investigated, and re-appraised, to ensure that they reflect the costing realities, in emerging building typologies.

The approach to computing the cost of disruption, in retrofit buildings, are rather approximate, and future research can improve on the adopted approach to evaluating the cost of disruption. This will enhance the robustness of the Fuzzy New-Generation whole-life costing model, and will ascertain the applicability of the model framework. It will also be helpful, for future work, to examine the cost of disruption in larger samples of office retrofit building projects, as well as, in other building typologies, to better understand the economic effects of disruption. Future research should also examine, and seek to understand, the nature of the cost of disruption, in office retrofit building projects, and its inter-relationship, with other cost variables in whole-life costing scenarios.

Based on the case study projects considered in this work, the 40-year estimated life is a sufficient period for considering, and appraising retrofit options, on a whole-life costing basis. It is therefore, necessary for empirical cost data, to be collected, over the life of the retrofit building project. Future research work, should seek to conduct a goodness-of-fit test, between the estimated cost projections, and the actual cost projections, over the life of office retrofit buildings. Also, the rank-ordering of the WLC and NWLC models, are identical, and there is need to appraise the benefits of both models, in retrofit scenarios, with a view, to appraising their efficacy, in option selection.

Information regarding the expected level of savings, in retrofit options, are not yet available in the literature. Hence, future work should seek to provide data, on office retrofit buildings, towards appraising their whole-life cost implication. The availability of reliable cost data is still a challenge in the building industry, and hinders the practice of whole-life costing. It is therefore contemplated, that the uptake of building information modelling (BIM), should provide a better platform for whole-life cost modelling, to be implemented and validated. Future work should seek to inculcate BIM, in whole-life cost modelling procedures, towards improving the accuracy, and retention of cost data, as well as, enhancing the basis of whole-life cost modelling in buildings.

There is also a need for empirical assessment of the effects of declining discount rates, on different forms of whole-life costing models. It will also be useful to conduct sensitivity analysis on the revocability rates, in the future.

Also, there is a cultural angle to the domain of financial investment appraisal, of office retrofit buildings. This pertains to the emerging modern built environment, in which building organisations are less likely to tie-down capital in fixed assets, such as buildings, and could have preference for rents and lease forms, of building-occupancy. The pace of innovation in the retrofit building sector also seems to fuel reliance on the pay-back period, as a more useful means of investment evaluation. This situation is unlikely to be conducive, for the practice of whole-life cost modelling, and could inhibit the identification and implementation; of long-term cost-optimally, performing retrofit solutions.

Lastly, whole-life cost modelling have traditionally focused on “hard-data”, which are quantitatively defined, and have failed to harness subjective, and less-quantitatively defined data. Accordingly, the cost implication of qualitative metrics, such as use value, social value, cultural value, environmental value, prestige value, and heritage value, is not considered in the evaluation of office retrofit building options in this work. It is anticipated that, more attention, to these qualitative metrics, will enhance the purpose, and intent of whole-life cost modelling in retrofit scenarios.

10.5 Summary

This study on the whole-life costing of retrofit office buildings, has developed a new approach, and provided an analytical framework, for investment appraisal of office retrofit buildings. This approach can also be extended, to other retrofit building typologies. This chapter summarises, the key findings of the entire study, and discusses the implications for the research work. Recommendations regarding future work are stated, and the limitations of the work, are expressed.

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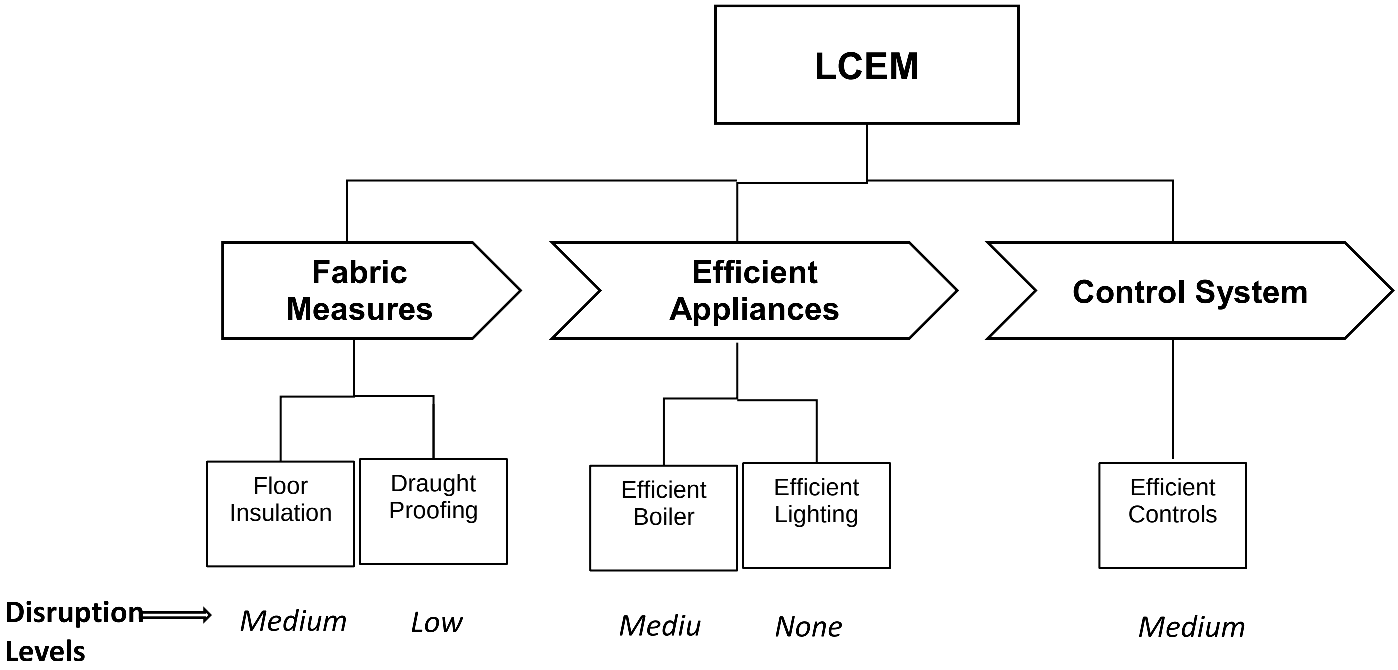
Appendix

Appendix A-1 – Evaluating Cost of Disruption in Retrofit Options



The computation of the disruption level in the **LCEM** is as follows:

$$\mu_{Floor\ Insulation} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{boilers} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{controls} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

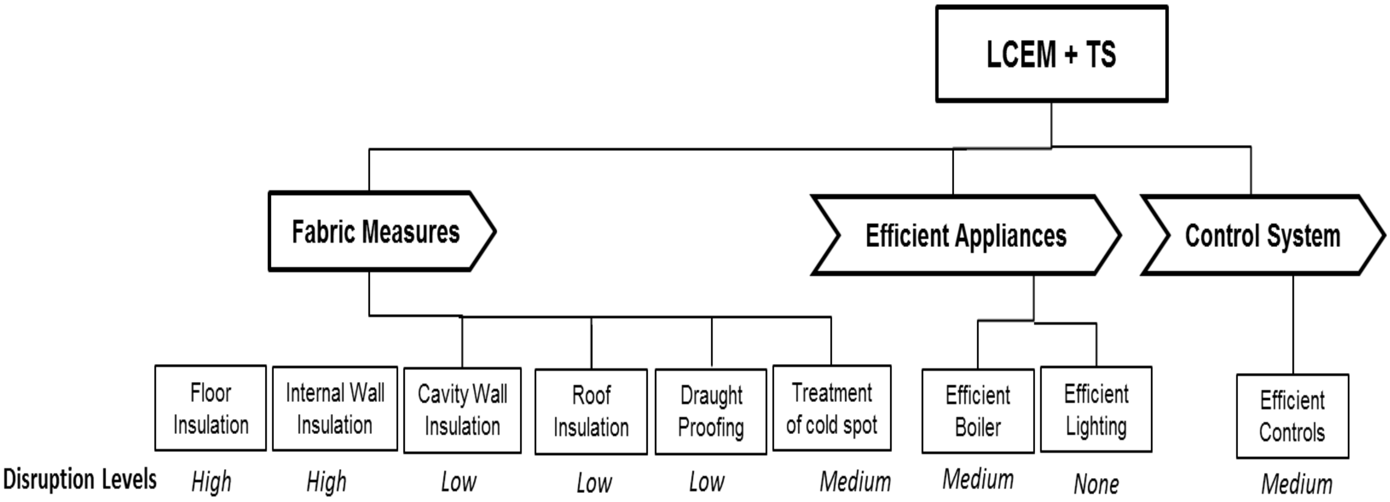
$$\mu_{draught\ proofing} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{LCEM} = \left(\frac{1.0}{7.5d} + \frac{0.9}{9.2d} + \frac{0.7}{10.9d} + \frac{0.4}{12d}\right)$$

Disrupted Days of **LCEM** package = { 4.8d, 7.1d, 8.3d }

Estimated Cost per day = £681.608

Estimated Disruption Cost = { £3271.72, £4839.42, £5657.35 }



The computation of the disruption level in the **LCEM + TS** is as follows:

$$\mu_{Floor\ insulation} = \left(\frac{0.8}{0.7} + \frac{0.9}{0.9}\right)\ x\ 10d$$

$$\mu_{Internal\ Wall\ insulation} = \left(\frac{0.8}{0.7} + \frac{0.9}{0.9}\right)\ x\ 10d$$

$$\mu_{Cavity\ \ Wall\ insulation} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 10d$$

$$\mu_{Roof\ \ insulation} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 10d$$

$$\mu_{draught\ proofing} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{treatment\ of\ cold\ bridges} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

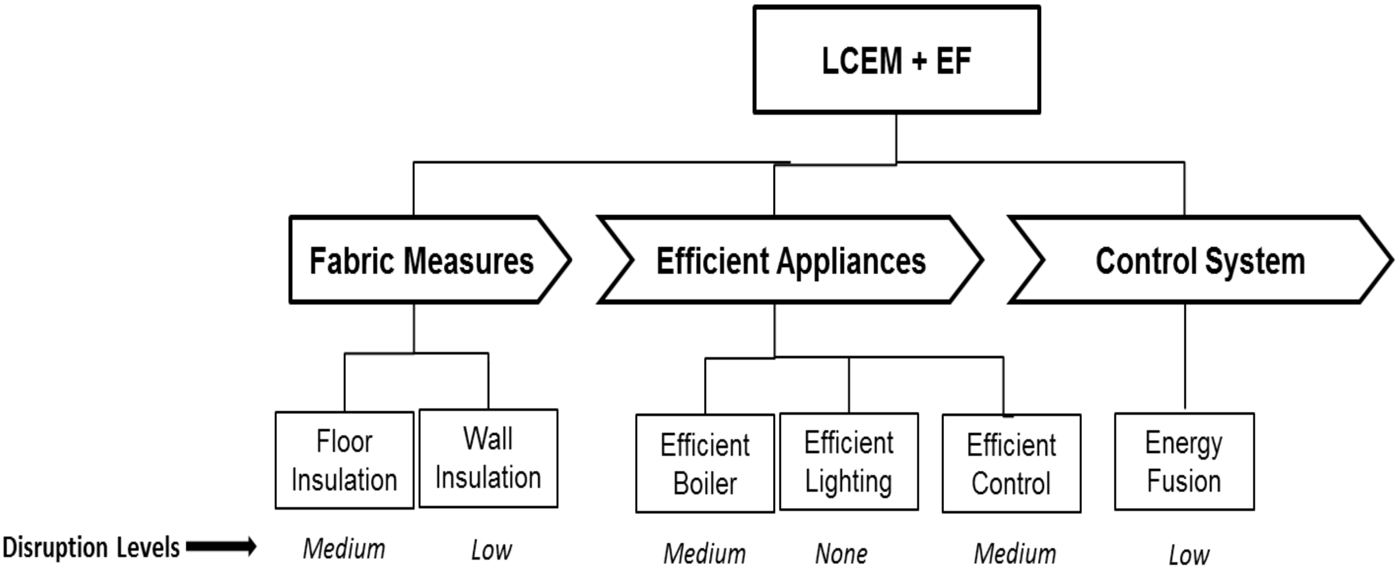
$$\mu_{Efficient\ boilers} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{Efficient\ controls} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

The project schedule (appendix B) indicates the package installation might happen over 60 working days. Thus including this yields a normalisation constant of 1.58

Disrupted Days of **LCEM + TS** package = {5.1d, 22.8d, 35.2d }

Estimated Disruption Cost = { £3476.20, £15,540.66, £23,992.61}



The computation of the disruption level in the **LCEM + EF** is as follows:

$$\mu_{Floor\ Insulation} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{boilers} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{controls} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

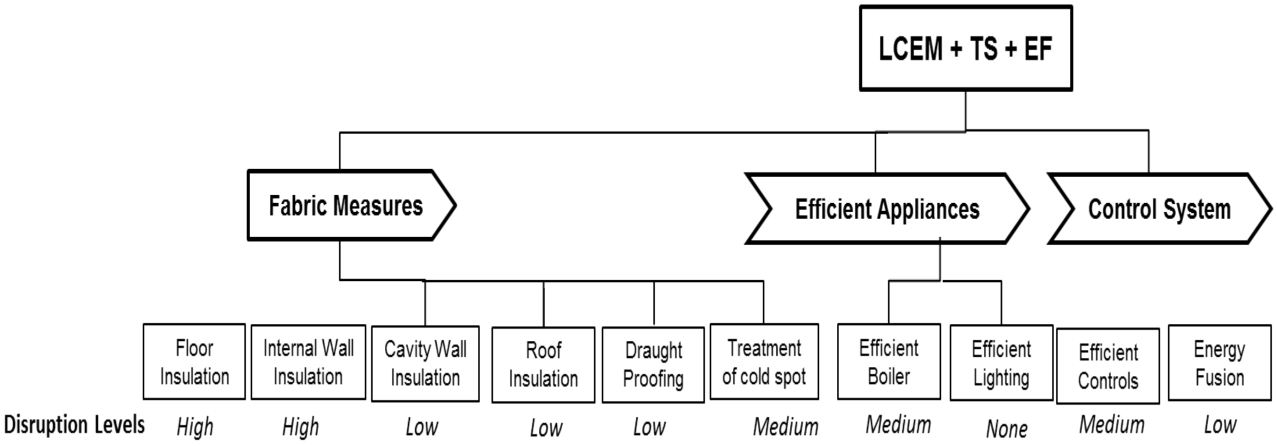
$$\mu_{draught\ proofing} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{Smart\ Controls} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

Number of days from project management schedule (appendix estimates installation over 45 working days. Incorporating this in the estimation yields:

Disrupted Days of **LCEM + EF** package = { 4.8d, 14d, 20.9d }

Estimated Disruption Cost = { £3271.72, £9542.51, £14,245.61}



The computation of the disruption level in the **LCEM + TS + EF** is as follows:

$$\mu_{Floor\ insulation} = \left(\frac{0.8}{0.7} + \frac{0.9}{0.9}\right)\ x\ 10d$$

$$\mu_{Internal\ Wall\ insulation} = \left(\frac{0.8}{0.7} + \frac{0.9}{0.9}\right)\ x\ 10d$$

$$\mu_{Cavity\ \ Wall\ insulation} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 10d$$

$$\mu_{Roof\ \ insulation} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 10d$$

$$\mu_{draught\ proofing} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{treatment\ of\ cold\ bridges} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

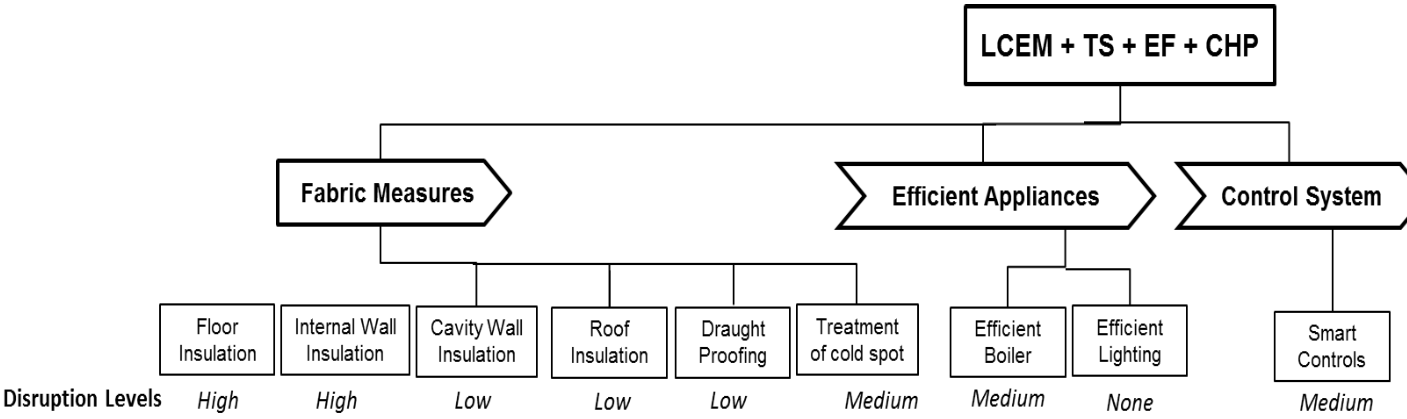
$$\mu_{Efficient\ boilers} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{Efficient\ controls} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{Smart\ Controls} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

Disrupted Days of **LCEM + TS + EF** package = { 5.1d, 36.3d, 57.7d }

Estimated Disruption Cost = { £3476.20, £24,742.37, £39,328.78}



The computation of the disruption level in the **LCEM + TS + EF + CHP** is as follows:

$$\mu_{Floor\ insulation} = \left(\frac{0.8}{0.7} + \frac{0.9}{0.9}\right)\ x\ 10d$$

$$\mu_{Internal\ Wall\ insulation} = \left(\frac{0.8}{0.7} + \frac{0.9}{0.9}\right)\ x\ 10d$$

$$\mu_{Cavity\ \ Wall\ insulation} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 10d$$

$$\mu_{Roof\ \ insulation} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 10d$$

$$\mu_{draught\ proofing} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{treatment\ of\ \ cold\ bridges} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

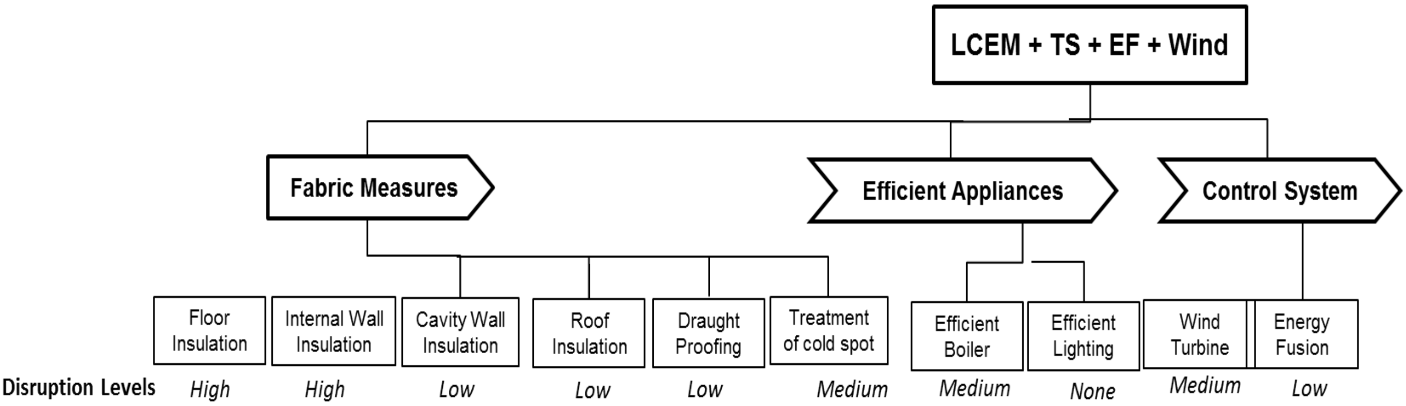
$$\mu_{Efficient\ boilers} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{Efficient\ controls} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{Smart\ Controls} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

CHP is considered non-disruptive!

Disrupted Days of **LCEM + TS + EF + CHP** package = { 5.1d, 36.3d, 57.7d }
Estimated Disruption Cost = { £3476.20, £24,742.37, £39,328.78}



The computation of the disruption level in the **LCEM + TS + EF + CHP** is as follows:

$$\mu_{Floor\ insulation} = \left(\frac{0.8}{0.7} + \frac{0.9}{0.9}\right)\ x\ 10d$$

$$\mu_{Internal\ Wall\ insulation} = \left(\frac{0.8}{0.7} + \frac{0.9}{0.9}\right)\ x\ 10d$$

$$\mu_{Cavity\ \ Wall\ insulation} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 10d$$

$$\mu_{Roof\ \ insulation} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 10d$$

$$\mu_{draught\ proofing} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{treatment\ of\ cold\ bridges} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{Efficient\ boilers} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

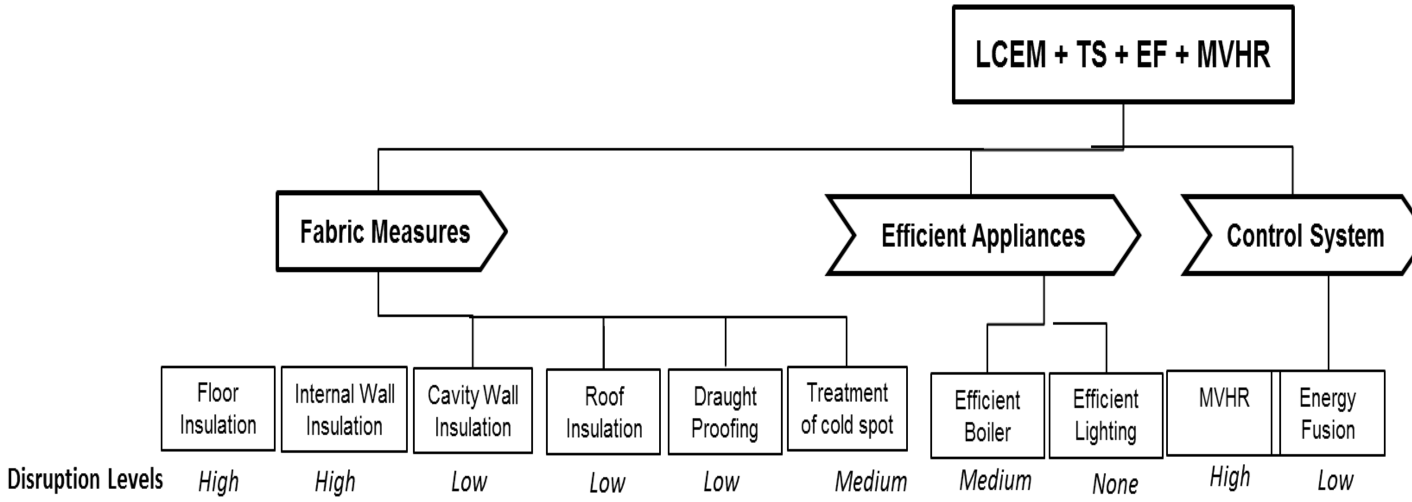
$$\mu_{Efficient\ controls} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{Smart\ Controls} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{Wind\ Turbiness} = (\ 1.6d \qquad 4.0d \qquad 6.3d)$$

Disrupted Days of **LCEM + TS + EF + CHP** = { 6.7d,   40.3d,   64d }

Estimated Disruption Cost =   { £4566.77,   £27,468.80,   £43,622.91}



The computation of the disruption level in the **LCEM + TS + EF + MVHR** is as follows:

$$\mu_{Floor\ insulation} = \left(\frac{0.8}{0.7} + \frac{0.9}{0.9}\right)\ x\ 10d$$

$$\mu_{Internal\ Wall\ insulation} = \left(\frac{0.8}{0.7} + \frac{0.9}{0.9}\right)\ x\ 10d$$

$$\mu_{Cavity\ \ Wall\ insulation} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 10d$$

$$\mu_{Roof\ \ insulation} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 10d$$

$$\mu_{draught\ proofing} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{treatment\ of\ cold\ bridges} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{Efficient\ boilers} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

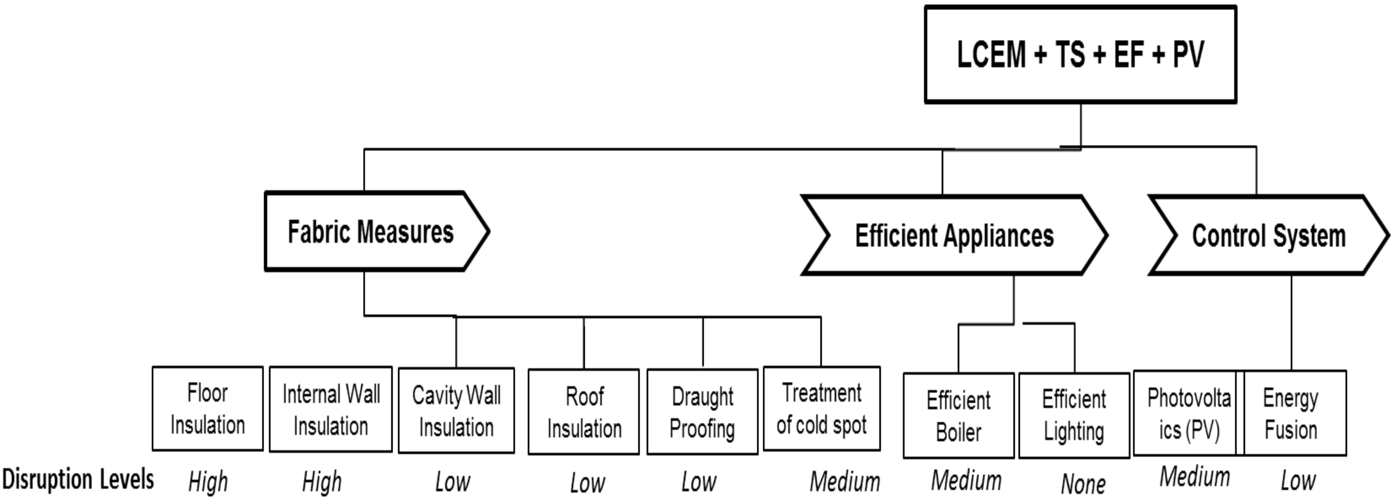
$$\mu_{Efficient\ controls} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{Smart\ Controls} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{MVHR} = (\ 3.2d \qquad 8d \qquad 14.4d)$$

Disrupted Days of **LCEM + TS + EF + MVHR** = { 8.3d, 44.3d, 72.1d }

Estimated Disruption Cost = { £5657.35, £30,195.23, £49,143.94}



The computation of the disruption level in the **LCEM + TS + EF + PV** is as follows:

$$\mu_{Floor\ insulation} = \left(\frac{0.8}{0.7} + \frac{0.9}{0.9}\right)\ x\ 10d$$

$$\mu_{Internal\ Wall\ insulation} = \left(\frac{0.8}{0.7} + \frac{0.9}{0.9}\right)\ x\ 10d$$

$$\mu_{Cavity\ \ Wall\ insulation} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 10d$$

$$\mu_{Roof\ \ insulation} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 10d$$

$$\mu_{draught\ proofing} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{treatment\ of\ cold\ bridges} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{Efficient\ boilers} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{Efficient\ controls} = \left(\frac{1.0}{0.5} + \frac{0.9}{0.6} + \frac{0.7}{0.7} + \frac{0.4}{0.8}\right)\ x\ 5d$$

$$\mu_{Smart\ Controls} = \left(\frac{1.0}{0} + \frac{0.9}{0.1} + \frac{0.7}{0.2}\right)\ x\ 2d$$

$$\mu_{Wind\ Turbiness} = (\ 1.6d \qquad 4.0d \qquad 6.3d)$$

Disrupted Days of **LCEM + TS + EF + PV** = { 6.7d, 40.3d, 64d }

Estimated Disruption Cost = { £4566.77, £27,468.80, £43,622.91}

Appendix A-2 – Retrofit Interventions in SPACE Project

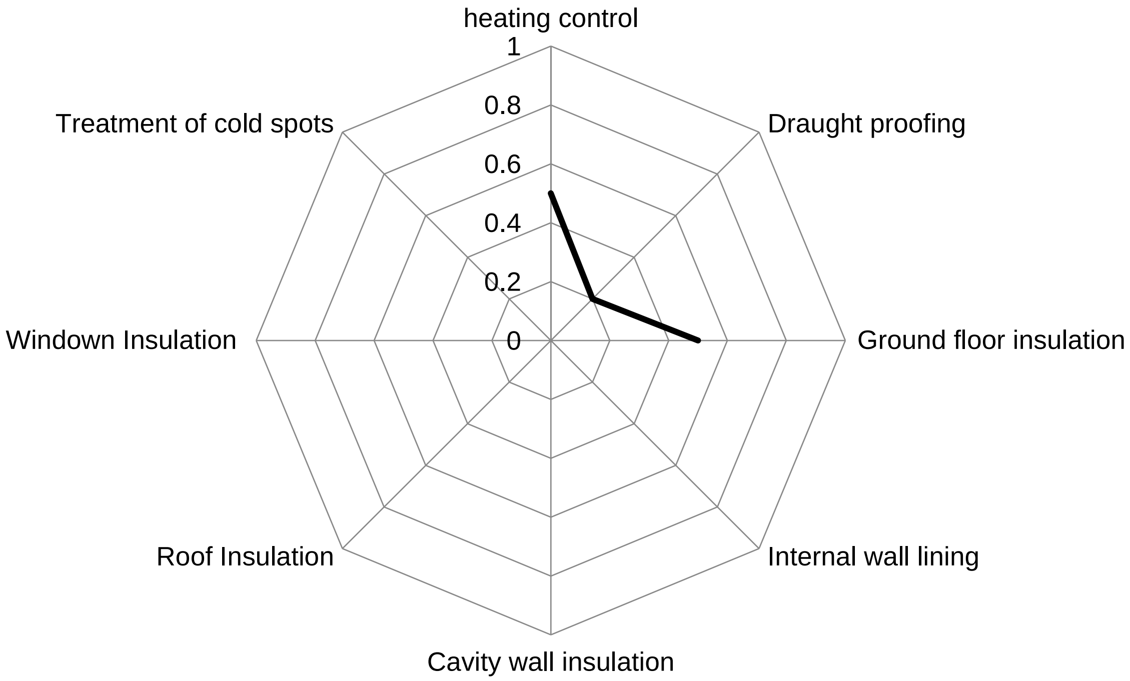


Figure A-2-1 BCP 2 (SPACE PROJECT)

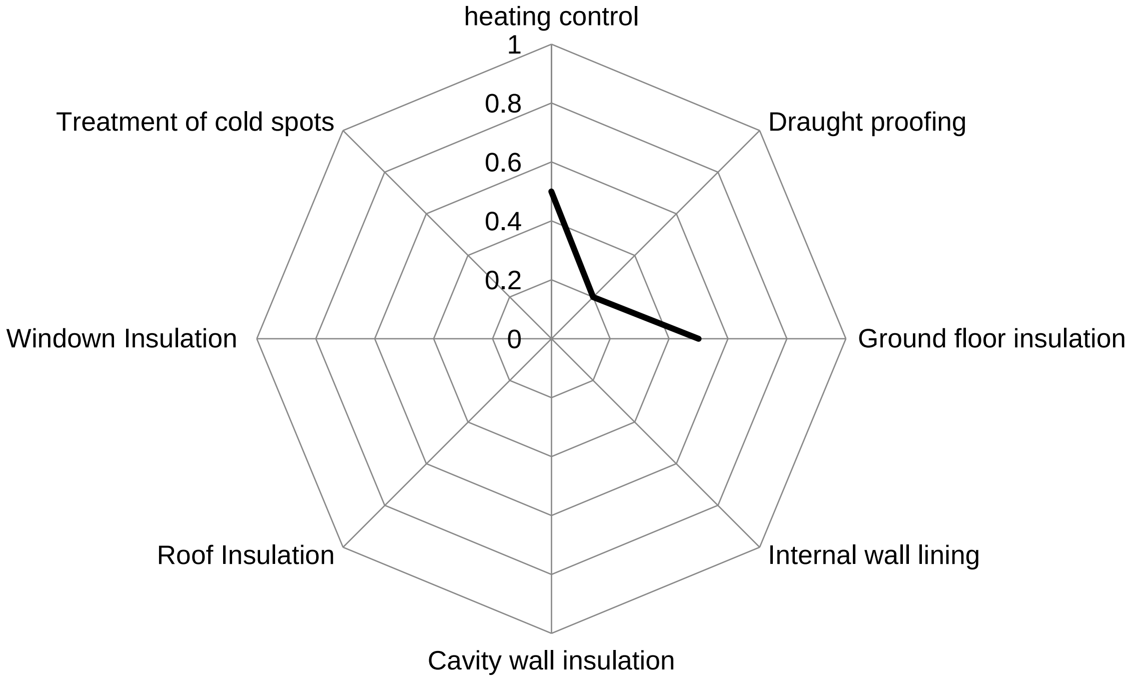


Figure A-2-2 BCP 2 (SPACE PROJECT)

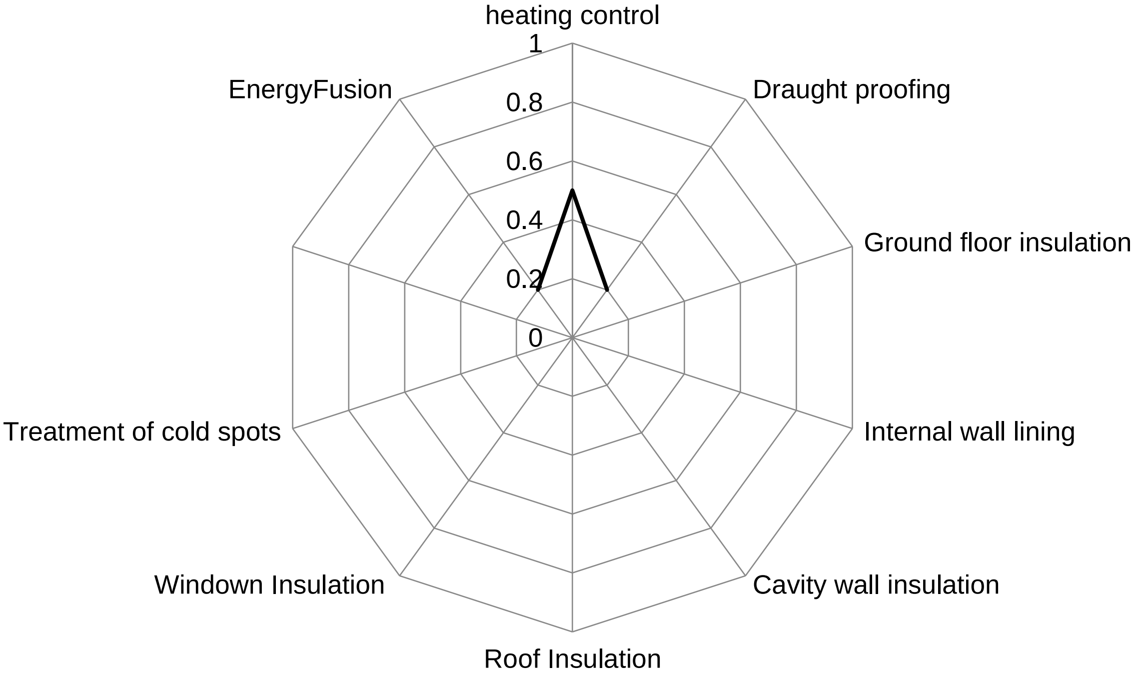


Figure A-2-3 BCP 4 (SPACE PROJECT)

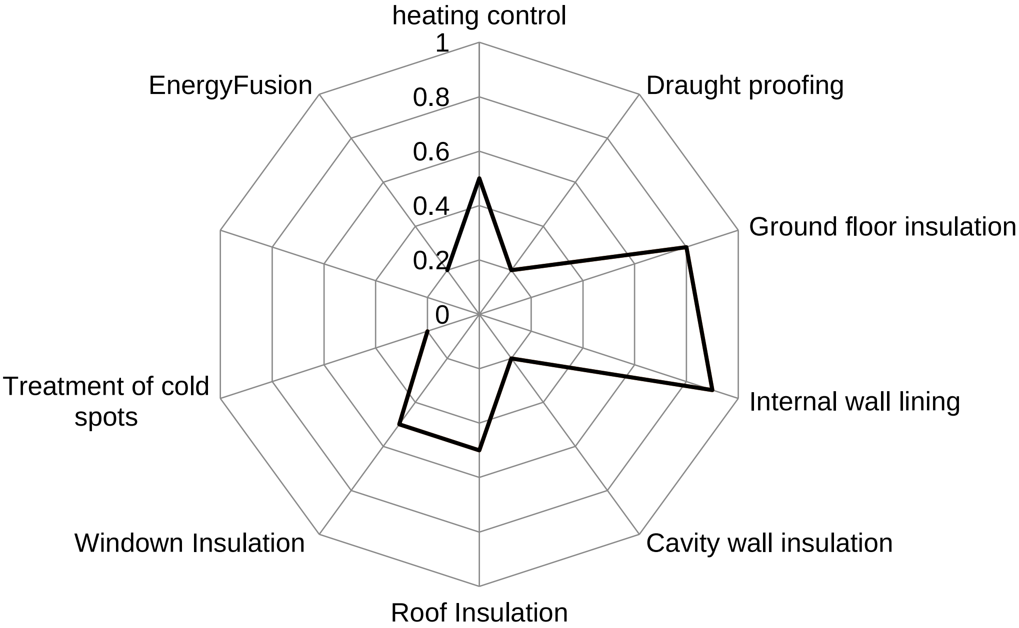


Figure A-2-4   BCP 5 (SPACE PROJECT)

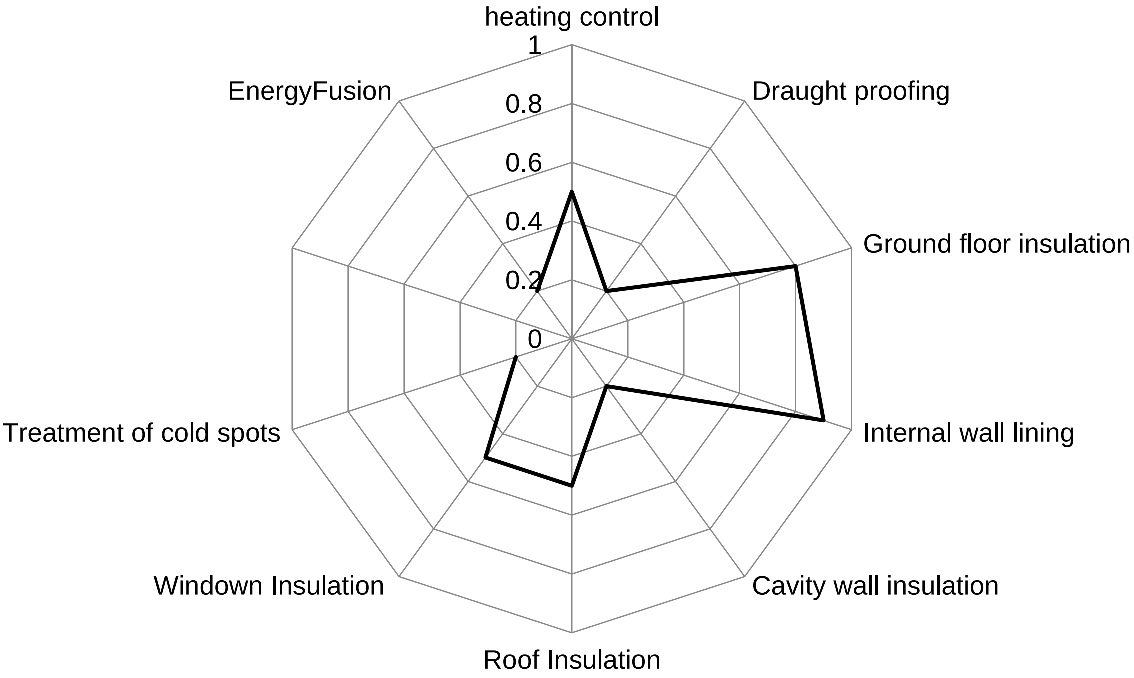


Figure A-2-5 BCP 6 (SPACE PROJECT)

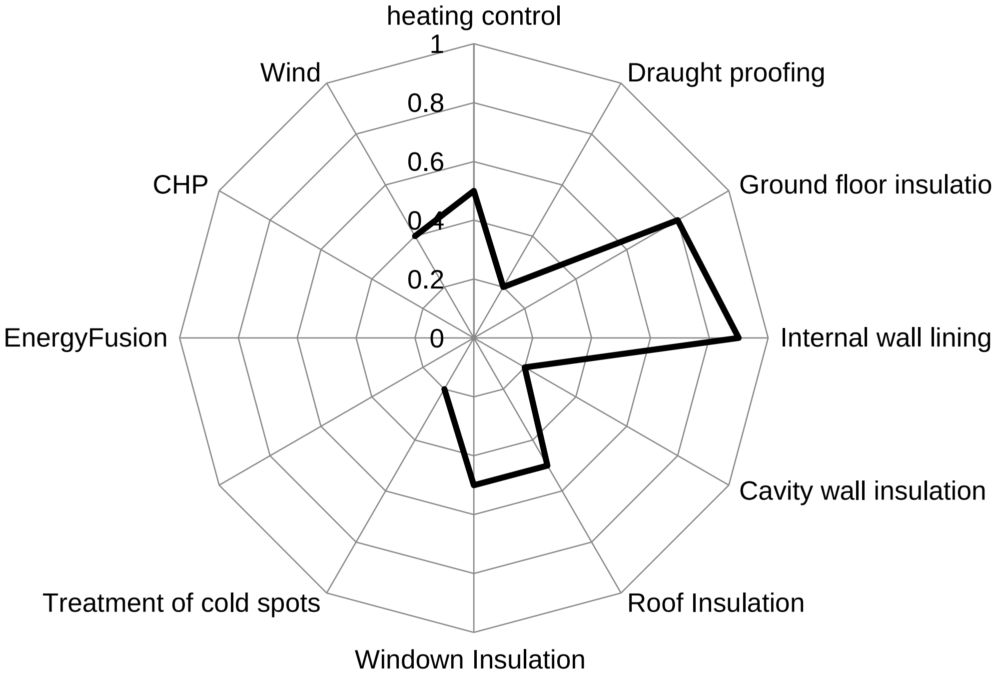


Figure A-2-6 BCP 7 (SPACE PROJECT)

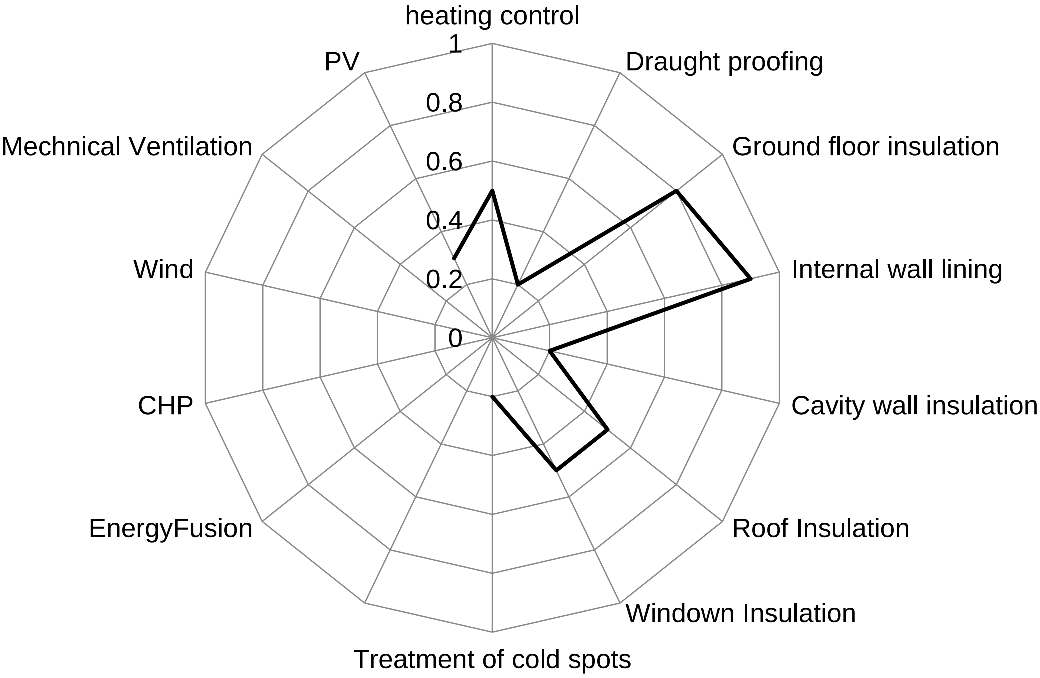


Figure A-2-7   BCP 9 (SPACE PROJECT)

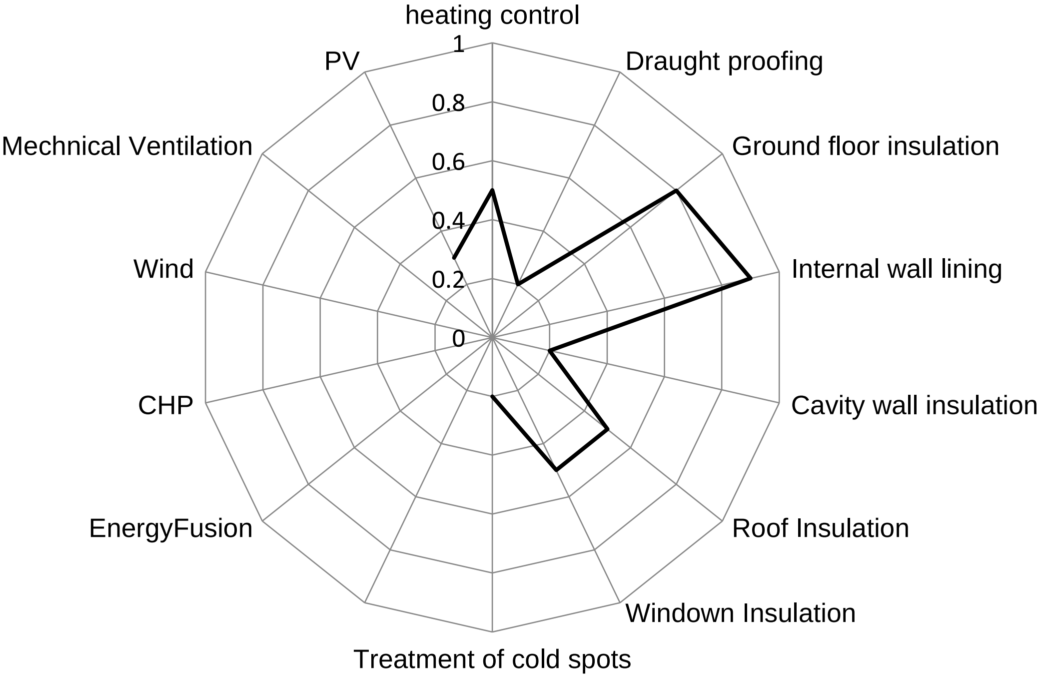


Figure A-2-8 BCP 10 (SPACE PROJECT)

Appendix A-3 – Retrofit Interventions in MS Project

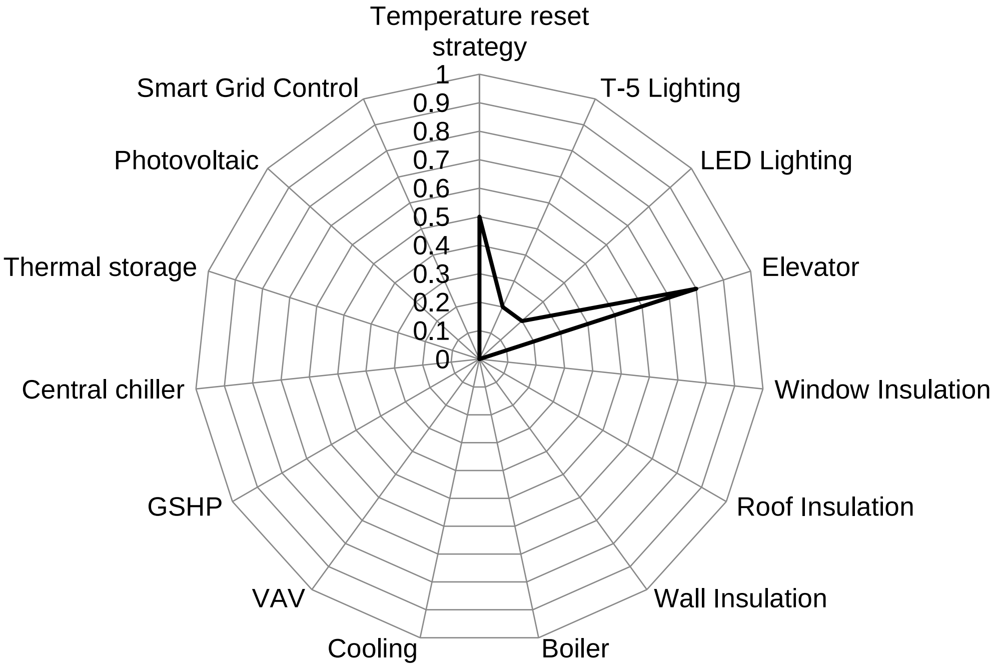


Figure A-3-1   BCP-5 in MS Project

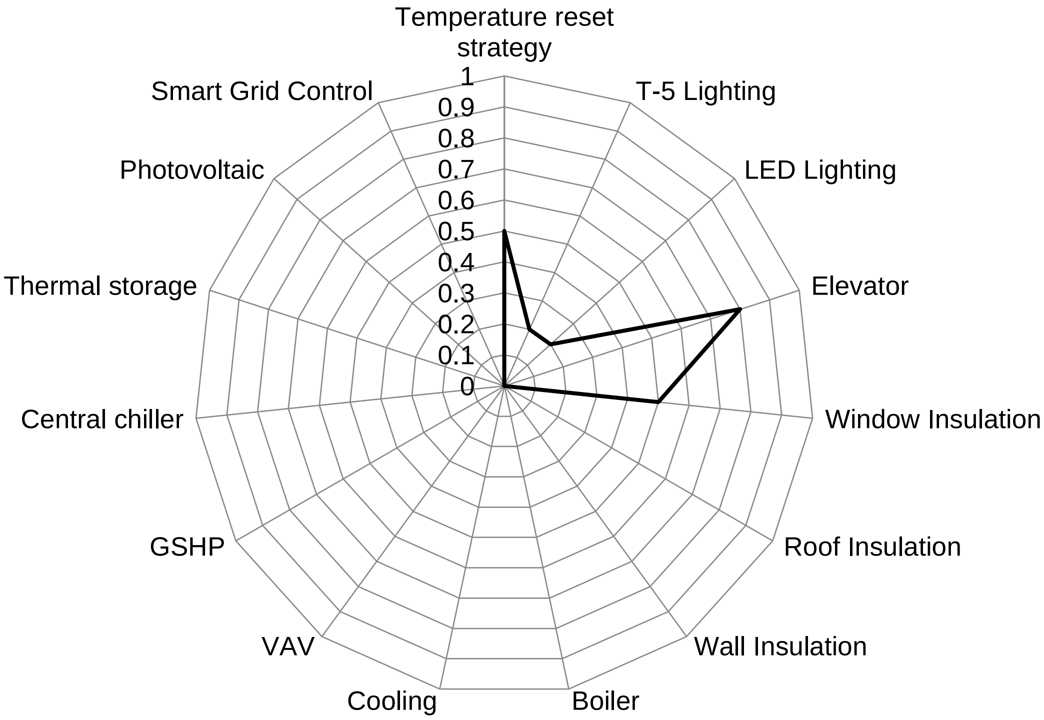


Figure A-3-2   BCP-6 in MS Project

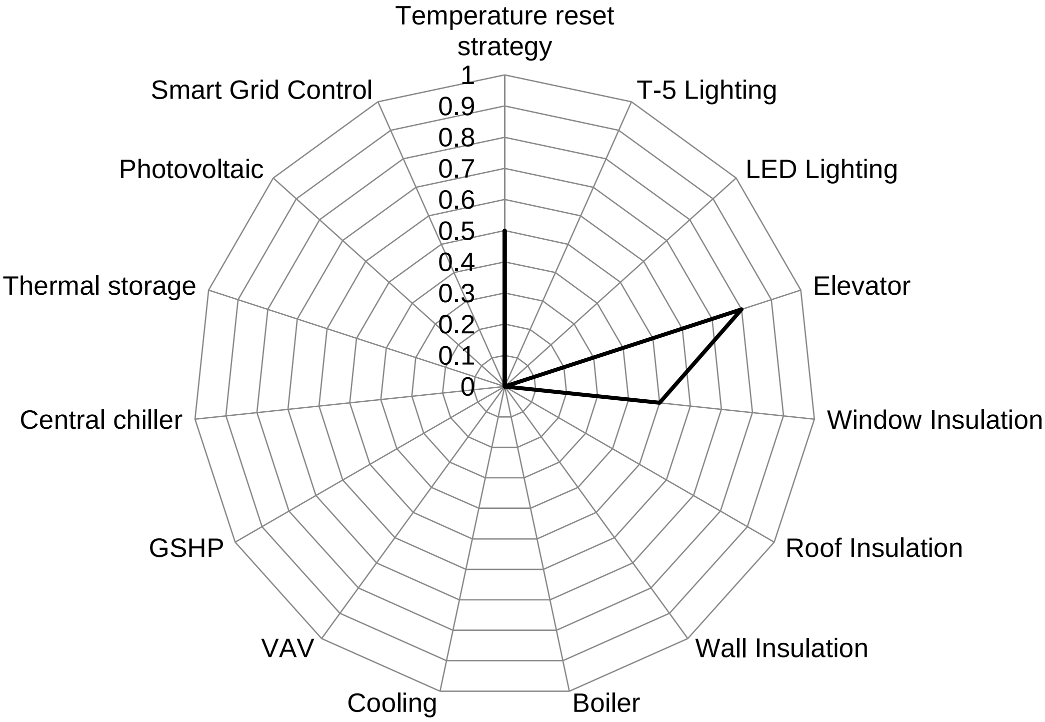
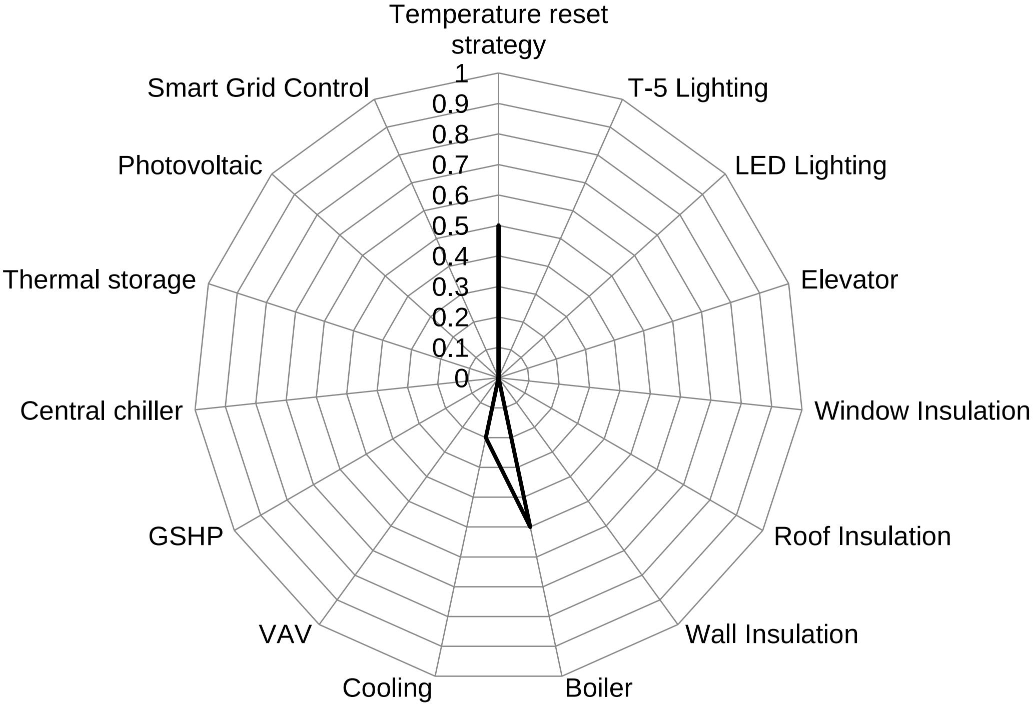


Figure A-3-3 BCP-7 in MS Project



FigureA-3-4 BCP-8 in MS Project

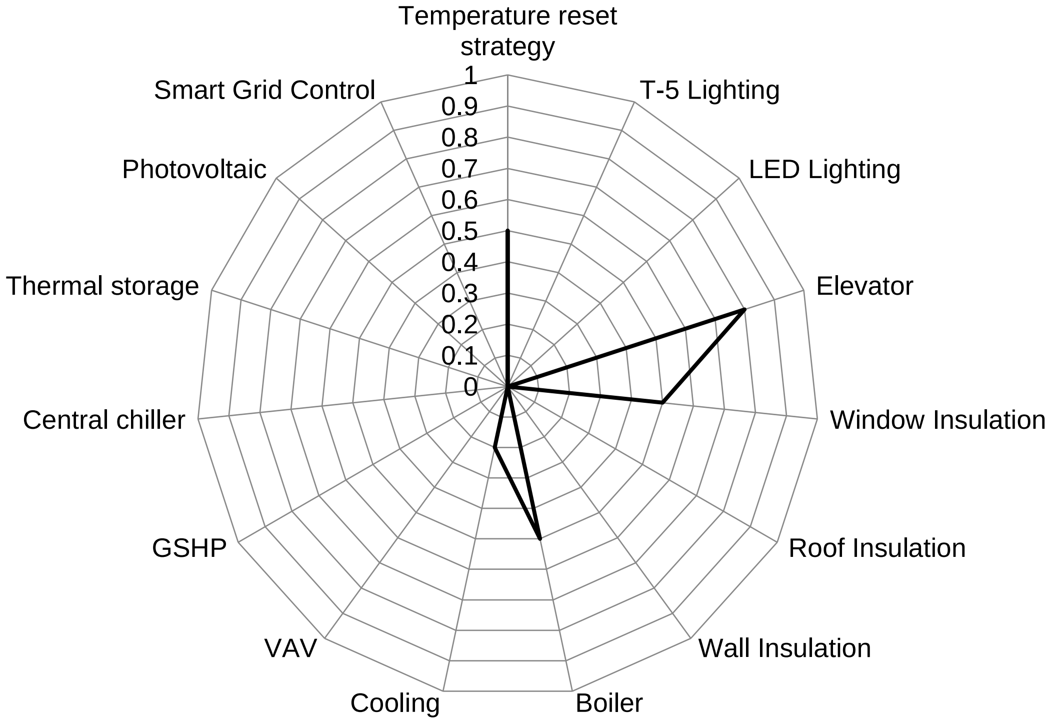


Figure A-1-5   BCP-9 in MS Project

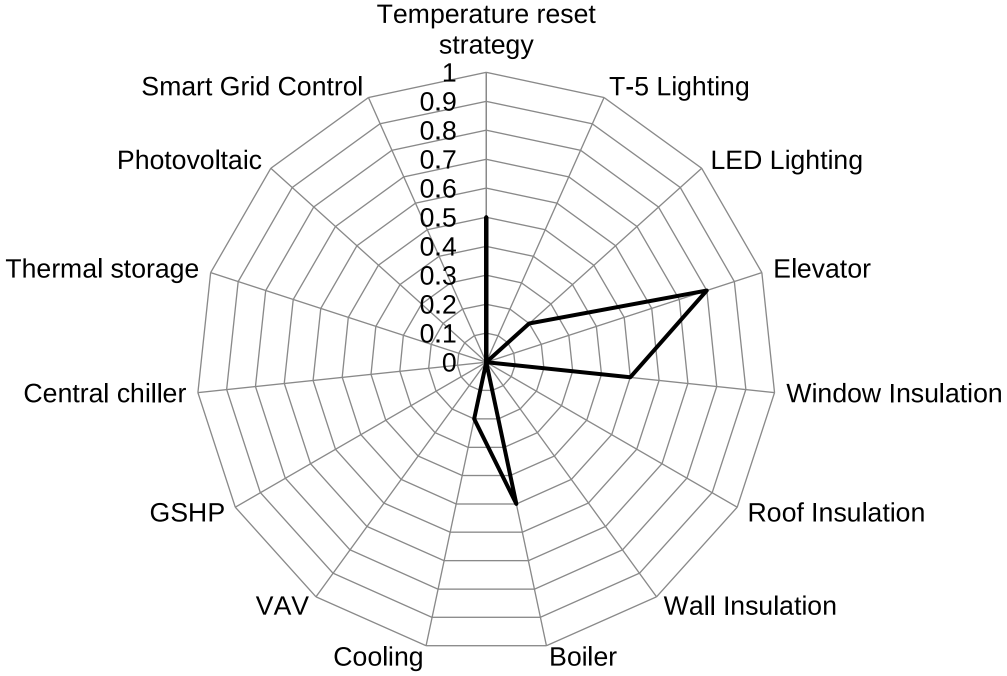


Figure A-3-6 BCP-10 in MS Project

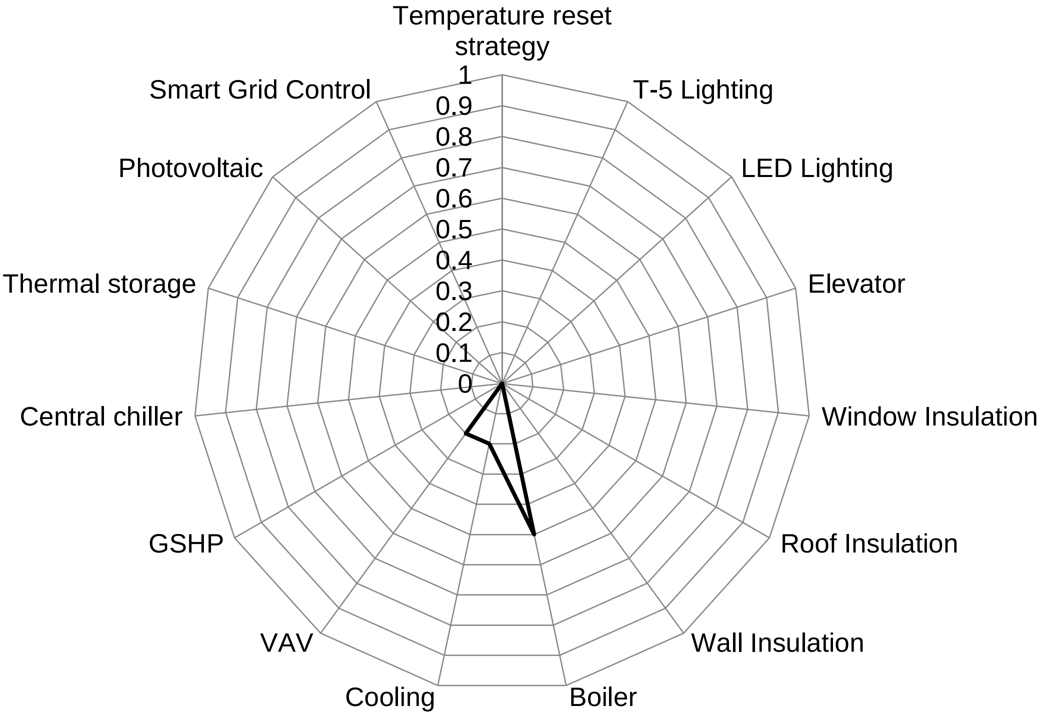


Figure A-3-7 BCP-11 in MS Project

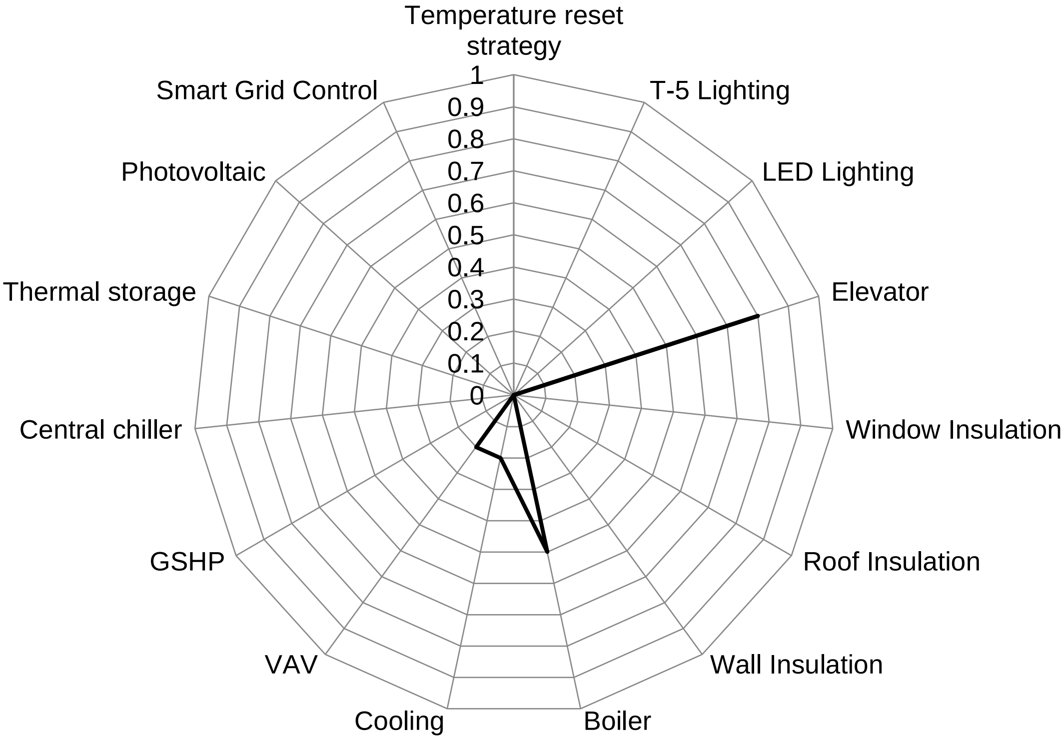


Figure A-3-8 BCP-12 in MS Project

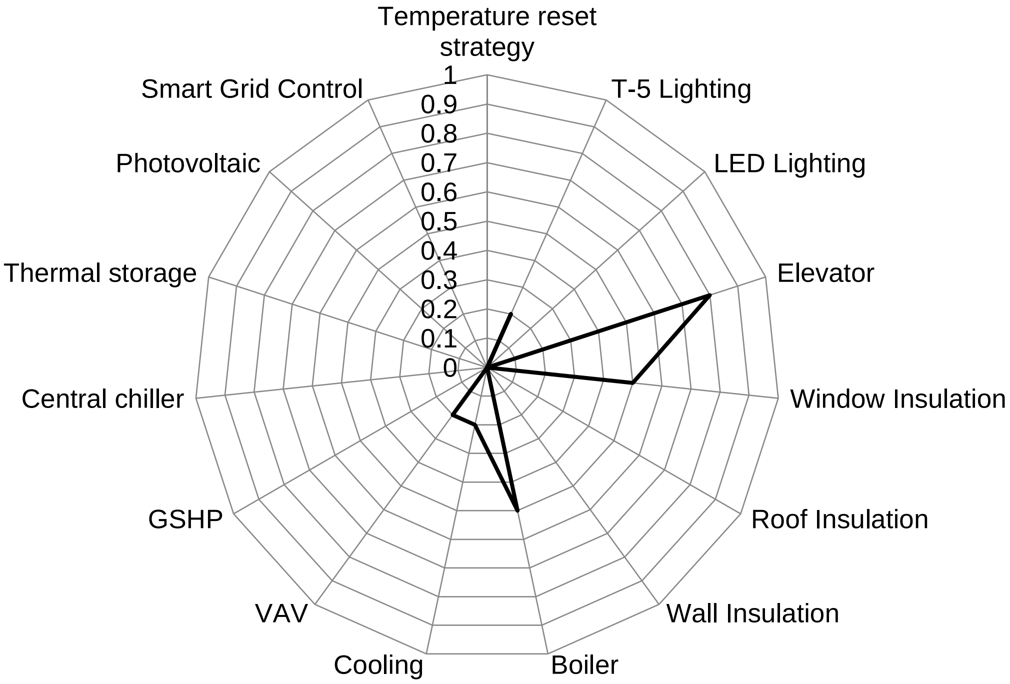


Figure A-3-9   BCP-13 in MS Project

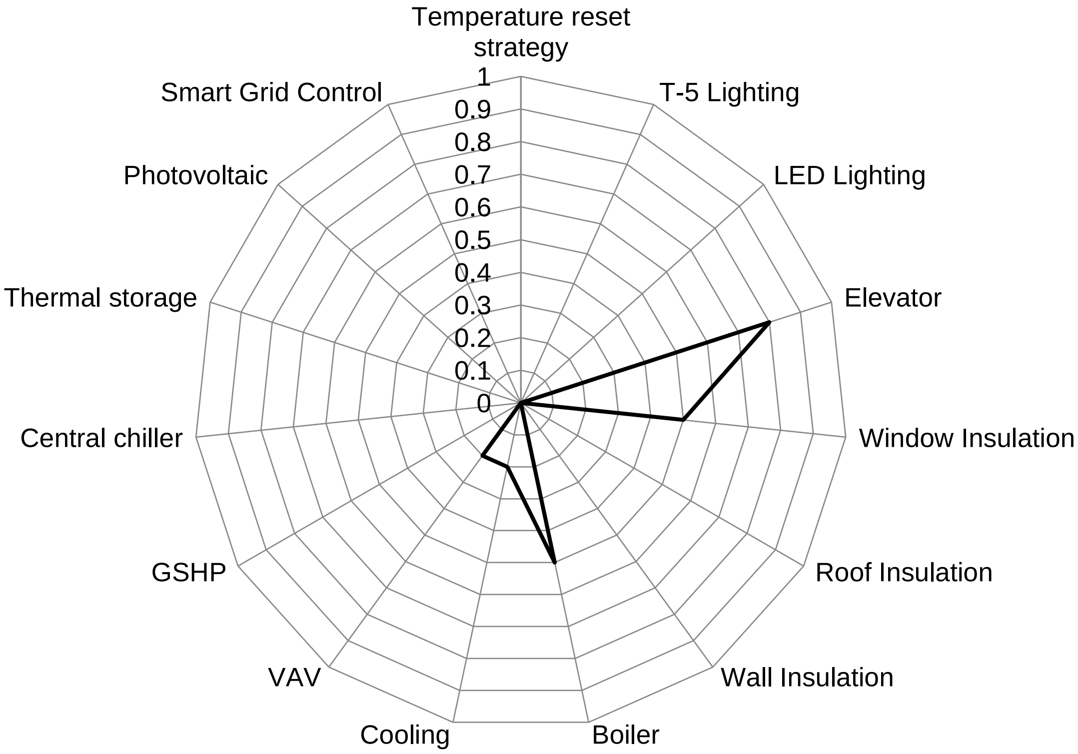


Figure A-3-10   BCP-14 in MS Project

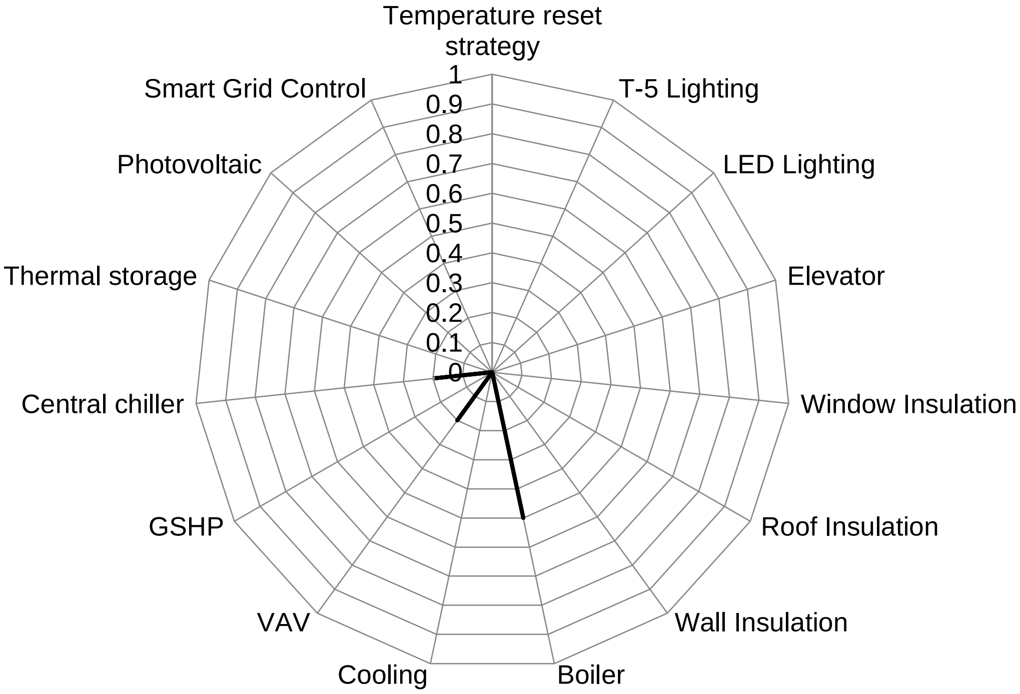


Figure A-3-11 BCP-15 in MS Project

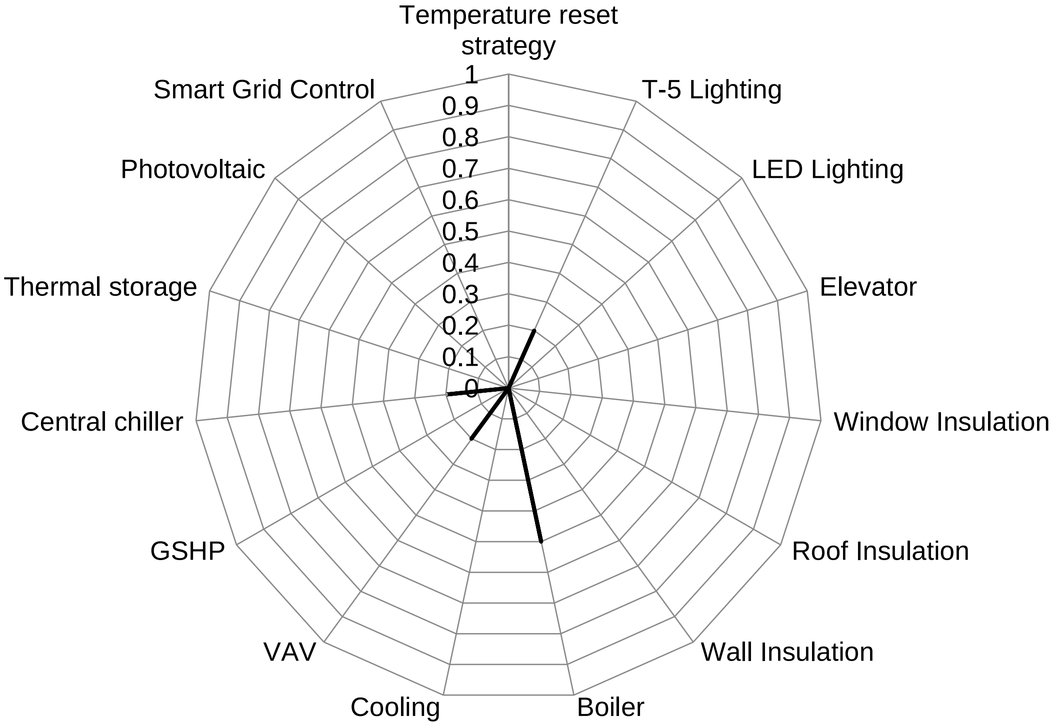


Figure A-3-12 BCP-16 in MS Project

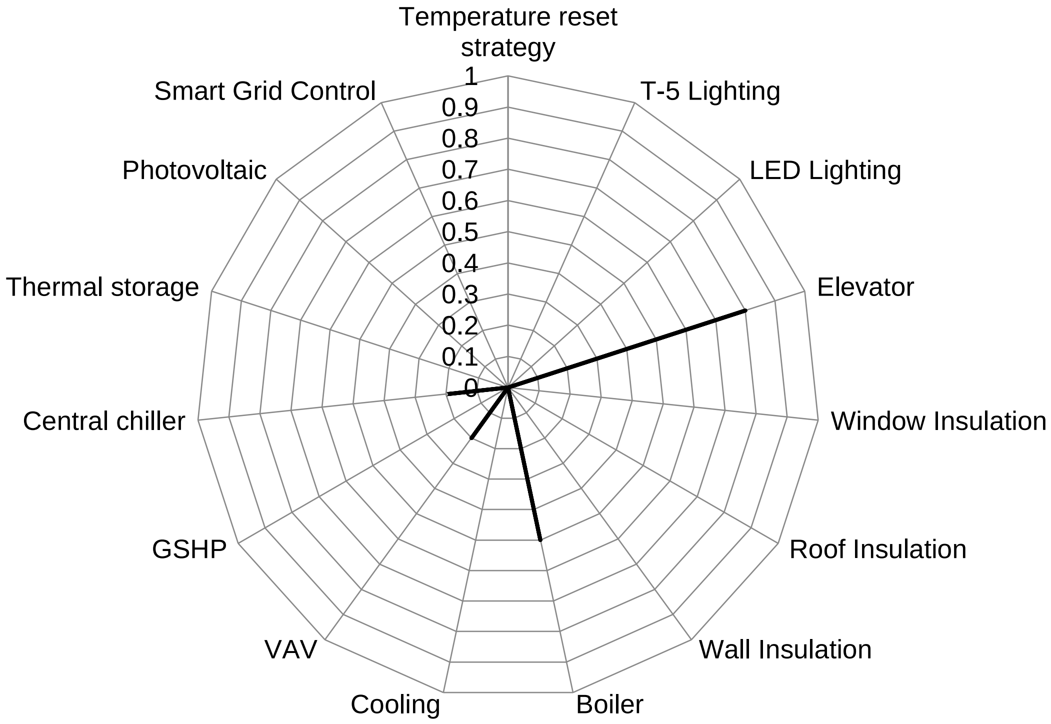


Figure A-3-13   BCP-17 in MS Project

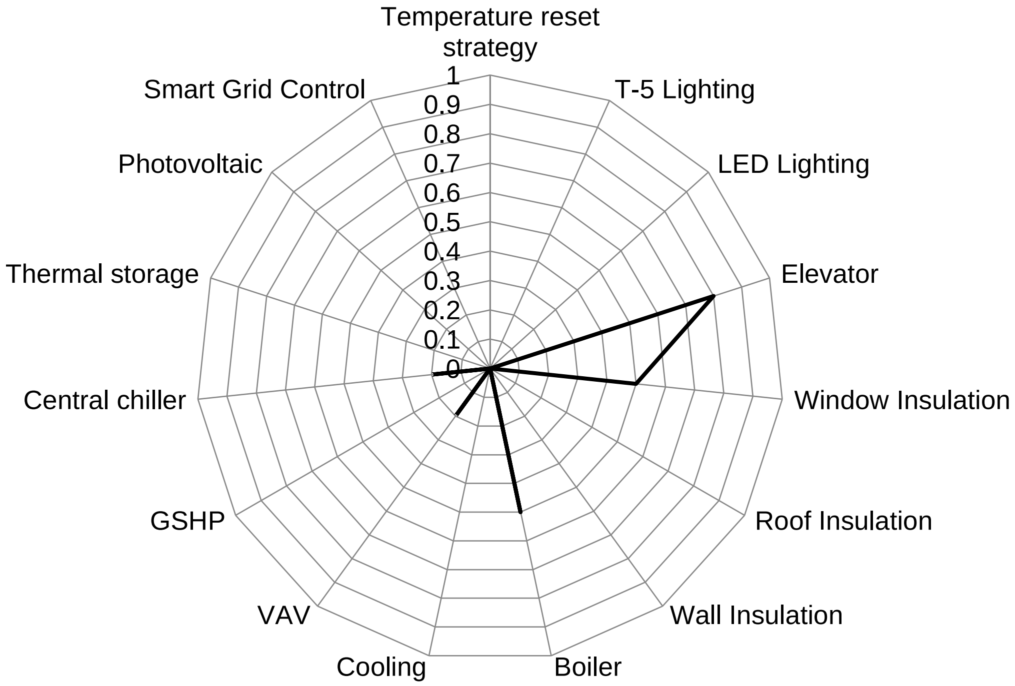


Figure A-3-14   BCP-18 in MS Project

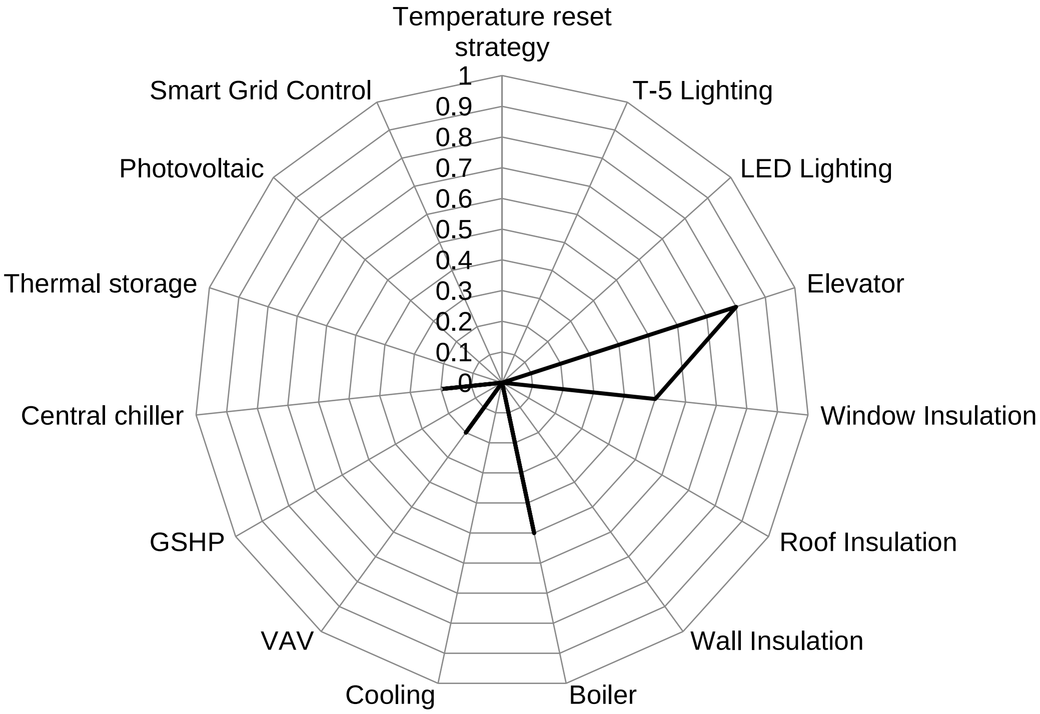


Figure A-3-15 BCP-19 in MS Project

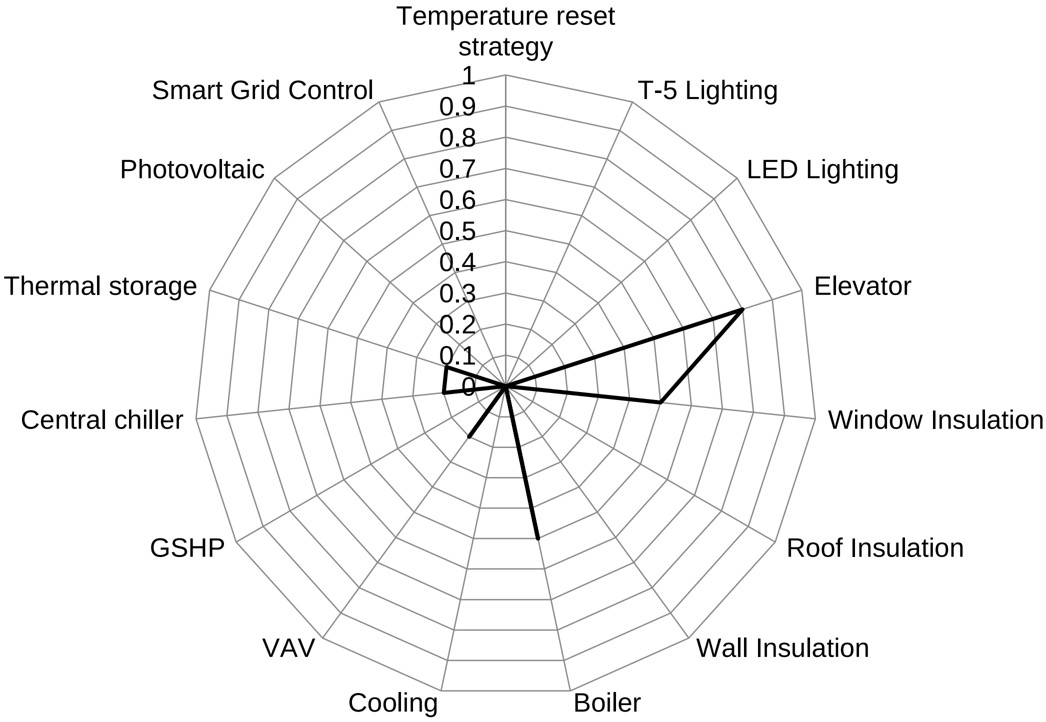


Figure A-3-16 BCP-20 in MS Project

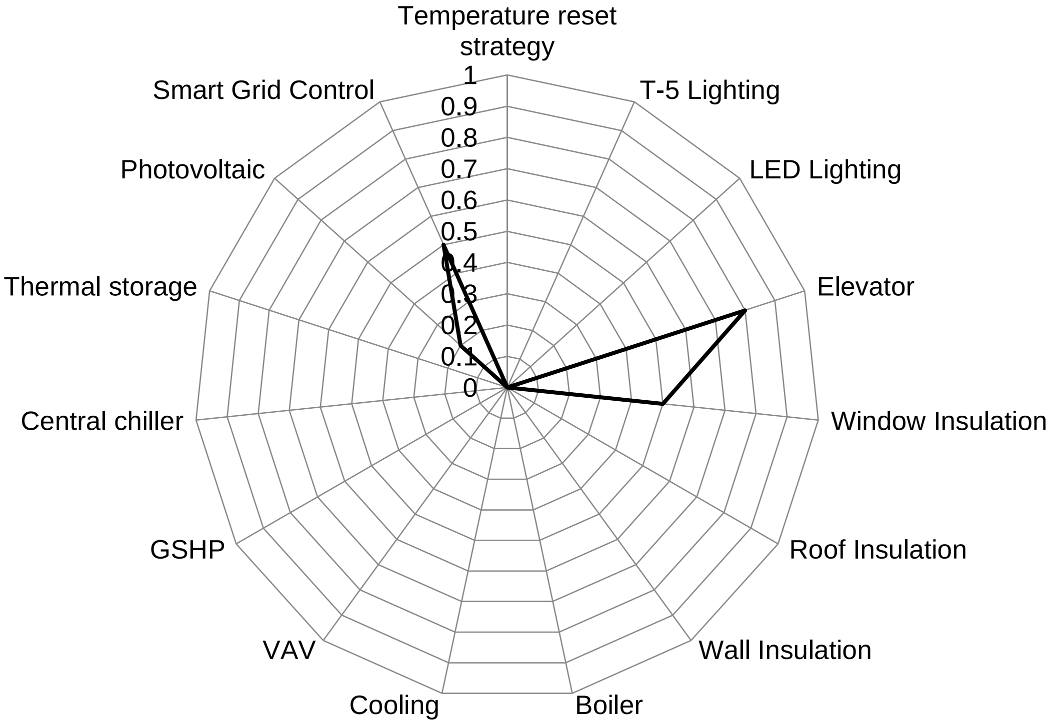


Figure A-3-17   BCP-22 in MS Project

Appendix A-4 – Spearman Correlation Coefficient for SPACE project

Table A-4:1 Correlation coefficient at Discount Rate of 3% over 20 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	1.000**	1.000**	1.000**
Classical NWLC		1.000**	1.000**	1.000**	1.000**
Fuzzy Lower NWLC			1.000**	1.000**	1.000**
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:2 Correlation coefficient at Discount Rate of 3% over 30 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	1.000**	0.745*	0.745*
Classical NWLC		1.000**	1.000**	0.745*	0.745*
Fuzzy Lower NWLC			1.000**	0.745*	0.745*
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed

Table A-4:3 Correlation coefficient at Discount Rate of 3% over 40 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	0.745*	0.321	0.273
Classical NWLC		1.000**	0.745*	0.321	0.273
Fuzzy Lower NWLC			1.000**	0.576	0.527
Fuzzy Mean NWLC				1.000**	0.988**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:4 Correlation coefficient at Discount Rate of 5% over 20 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	1.000**	1.000**	1.000**
Classical NWLC		1.000**	1.000**	1.000**	1.000**
Fuzzy Lower NWLC			1.000**	1.000**	1.000**
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:5 Correlation coefficient at Discount Rate of 7% over 20 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	1.000**	1.000**	1.000**
Classical NWLC		1.000**	1.000**	1.000**	1.000**
Fuzzy Lower NWLC			1.000**	1.000**	1.000**
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:6 Correlation coefficient at Discount Rate of 9% over 20 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	0.891**	1.000**	1.000**
Classical NWLC		1.000**	0.891**	1.000**	1.000**
Fuzzy Lower NWLC			1.000**	0.891**	0.891**
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

**Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:7 Correlation coefficient at Discount Rate of 5% over 30 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	1.000**	1.000**	1.000**
Classical NWLC		1.000**	1.000**	1.000**	1.000**
Fuzzy Lower NWLC			1.000**	1.000**	1.000**
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:8 Correlation coefficient at Discount Rate of 7% over 30 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000	1.000**	1.000**	1.000**	1.000**
Classical NWLC		1.000	1.000**	1.000**	1.000**
Fuzzy Lower NWLC			1.000	1.000**	1.000**
Fuzzy Mean NWLC				1.000	1.000**
Fuzzy Upper NWLC					1.000

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:9 Correlation coefficient at Discount Rate of 9% over 30 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	1.000**	1.000**	1.000**
Classical NWLC		1.000**	1.000**	1.000**	1.000**
Fuzzy Lower NWLC			1.000**	1.000**	1.000**
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:10 Correlation coefficient at Discount Rate of 7% over 40 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	1.000**	1.000**	1.000**
Classical NWLC		1.000**	1.000**	1.000**	1.000**
Fuzzy Lower NWLC			1.000**	1.000**	1.000**
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:11 Correlation coefficient at Discount Rate of 9% over 40 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	1.000**	1.000**	1.000**
Classical NWLC		1.000**	1.000**	1.000**	1.000**
Fuzzy Lower NWLC			1.000**	1.000**	1.000**
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

**Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:12 Correlation coefficient at Discount Rate of 7% over 50 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	1.000**	0.745*	0.745*
Classical NWLC		1.000**	1.000**	0.745*	0.745*
Fuzzy Lower NWLC			1.000**	0.745*	0.745*
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:13 Correlation coefficient at Discount Rate of 9% over 50 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	1.000**	1.000**	1.000**
Classical NWLC		1.000**	1.000**	1.000**	1.000**
Fuzzy Lower NWLC			1.000**	1.000**	1.000**
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

All Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:14 Correlation coefficient at Discount Rate of 5% over 60 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	1.000**	0.733*	- 0.564	- 0.564
Classical NWLC		1.000**	0.733*	- 0.564	- 0.564
Fuzzy Lower NWLC			1.000**	- 0.818**	- 0.818**
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:15 – Correlation coefficient at Discount Rate of 7% over 60 years

Parameters	Correlation Coefficients Standard WLC	Classical NWLC	Fuzzy Lower NWLC	Fuzzy Mean NWLC	Fuzzy Upper NWLC
Standard WLC	1.000**	1.000**	1.000**	0.733*	0.745*
Classical NWLC		1.000**	1.000**	0.733*	0.745*
Fuzzy Lower NWLC			1.000**	0.733*	0.745*
Fuzzy Mean NWLC				1.000**	0.988**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-4:16 Correlation coefficient at Discount Rate of 9% over 60 years

Parameters	Correlation Coefficients Standard WLC	Classical NWLC	Fuzzy Lower NWLC	Fuzzy Mean NWLC	Fuzzy Upper NWLC
Standard WLC	1.000**	1.000**	1.000**	1.000**	1.000**
Classical NWLC		1.000**	1.000**	1.000**	1.000**
Fuzzy Lower NWLC			1.000**	1.000**	1.000**
Fuzzy Mean NWLC				1.000**	1.000**
Fuzzy Upper NWLC					1.000**

**Values are statistically significant at the 0.01 level (2-tailed)

Appendix A-5 – Spearman Correlation Coefficient for MS project

Table A-5:1 Correlation coefficient at Discount Rate of 3% over 20 years

Parameters	Standard WLC	Classical NWLC	Fuzzy Lower NWLC	Fuzzy Mean NWLC	Fuzzy Upper NWLC
			Correlation Coefficients		
Standard WLC	1.000**	0.825**	0.616**	0.783**	0.764**
Classical NWLC		1.000**	0.631**	0.921**	0.909**
Fuzzy Lower NWLC			1.000**	0.639**	0.651**
Fuzzy Mean NWLC				1.000**	0.982**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:2 Correlation coefficient at Discount Rate of 5% over 20 years

Parameters	Standard WLC	Classical NWLC	Fuzzy Lower NWLC	Fuzzy Mean NWLC	Fuzzy Upper NWLC
			Correlation Coefficients		
Standard WLC	1.000**	0.616**	0.904**	0.959**	0.636**
Classical NWLC		1.000**	0.720**	0.682**	0.959**
Fuzzy Lower NWLC			1.000**	0.884**	0.740**
Fuzzy Mean NWLC				1.000**	0.688**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:3 Correlation coefficient at Discount Rate of 7% over 20 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.889**	0.896**	0.929**	0.927**
Classical NWLC		1.000**	0.785**	0.790**	0.863**
Fuzzy Lower NWLC			1.000**	0.928**	0.872**
Fuzzy Mean NWLC				1.000**	0.927**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:4 Correlation coefficient at Discount Rate of 9% over 20 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.949**	0.956**	0.999**	0.940**
Classical NWLC		1.000**	0.923**	0.950**	0.992**
Fuzzy Lower NWLC			1.000**	0.955**	0.910**
Fuzzy Mean NWLC				1.000**	0.941**
Fuzzy Upper NWLC					1.000**

**Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:5 Correlation coefficient at Discount Rate of 3% over 30 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.469*	0.797**	0.618**	0.347
Classical NWLC		1.000**	0.685**	0.397	0.837**
Fuzzy Lower NWLC			1.000**	0.578**	0.604**
Fuzzy Mean NWLC				1.000**	0.560**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed

Table A-5:6 Correlation coefficient at Discount Rate of 5% over 30 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.834**	0.636**	0.784**	0.805**
Classical NWLC		1.000**	0.567**	0.788**	0.840**
Fuzzy Lower NWLC			1.000**	0.645**	0.631**
Fuzzy Mean NWLC				1.000**	0.914**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:7 Correlation coefficient at Discount Rate of 7% over 30 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000	0.616**	0.833**	0.959**	0.636**
Classical NWLC		1.000	0.730**	0.682**	0.959**
Fuzzy Lower NWLC			1.000	0.779**	0.750**
Fuzzy Mean NWLC				1.000	0.688**
Fuzzy Upper NWLC					1.000

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:8 Correlation coefficient at Discount Rate of 9% over 30 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.880**	0.937**	0.981**	0.904**
Classical NWLC		1.000**	0.886**	0.927**	0.945**
Fuzzy Lower NWLC			1.000**	0.910**	0.910**
Fuzzy Mean NWLC				1.000**	0.911**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:9 Correlation coefficient at Discount Rate of 5% over 40 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.697**	0.761**	0.753**	0.695**
Classical NWLC		1.000**	0.619**	0.641**	0.995**
Fuzzy Lower NWLC			1.000**	0.627**	0.635**
Fuzzy Mean NWLC				1.000**	0.621**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:10 Correlation coefficient at Discount Rate of 7% over 40 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.767**	0.892**	0.736**	0.715**
Classical NWLC		1.000**	0.688**	0.819**	0.867**
Fuzzy Lower NWLC			1.000**	0.750**	0.730**
Fuzzy Mean NWLC				1.000**	0.959**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:11 Correlation coefficient at Discount Rate of 9% over 40 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.876**	0.916**	0.918**	0.904**
Classical NWLC		1.000**	0.767**	0.815**	0.877**
Fuzzy Lower NWLC			1.000**	0.939**	0.872**
Fuzzy Mean NWLC				1.000**	0.938**
Fuzzy Upper NWLC					1.000**

**Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:12 Correlation coefficient at Discount Rate of 5% over 50 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.530*	0.756**	0.675**	0.778**
Classical NWLC		1.000**	0.415	0.563**	0.686**
Fuzzy Lower NWLC			1.000**	0.642**	0.494*
Fuzzy Mean NWLC				1.000**	0.820**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:13 Correlation coefficient at Discount Rate of 7% over 50 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.728**	0.903**	0.767**	0.799**
Classical NWLC		1.000**	0.683**	0.784**	0.823**
Fuzzy Lower NWLC			1.000**	0.757**	0.682**
Fuzzy Mean NWLC				1.000**	0.819**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed

Table A-5:14 Correlation coefficient at Discount Rate of 9% over 50 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.889**	0.898**	0.929**	0.929**
Classical NWLC		1.000**	0.745**	0.794**	0.872**
Fuzzy Lower NWLC			1.000**	0.939**	0.872**
Fuzzy Mean NWLC				1.000**	0.938**
Fuzzy Upper NWLC					1.000**

All Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:15 Correlation coefficient at Discount Rate of 5% over 60 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.516*	0.793**	0.732**	0.537**
Classical NWLC		1.000**	0.590**	0.505*	0.587**
Fuzzy Lower NWLC			1.000**	0.636**	0.368*
Fuzzy Mean NWLC				1.000**	0.632**
Fuzzy Upper NWLC					1.000**

* Values are statistically significant at the 0.05 level (2-tailed)
** Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:16 Correlation coefficient at Discount Rate of 7% over 60 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.728**	0.887**	0.767**	0.743**
Classical NWLC		1.000**	0.687**	0.784**	0.924**
Fuzzy Lower NWLC			1.000**	0.778**	0.675**
Fuzzy Mean NWLC				1.000**	0.876**
Fuzzy Upper NWLC					1.000**

** Values are statistically significant at the 0.01 level (2-tailed)

Table A-5:17 Correlation coefficient at Discount Rate of 9% over 60 years

	Correlation Coefficients				
Parameters	**Standard WLC**	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	1.000**	0.913**	0.898**	0.929**	0.892**
Classical NWLC		1.000**	0.800**	0.881**	0.872**
Fuzzy Lower NWLC			1.000**	0.939**	0.785**
Fuzzy Mean NWLC				1.000**	0.801**
Fuzzy Upper NWLC					1.000**

**Values are statistically significant at the 0.01 level (2-tailed)

Appendix A-6 – Pattern Matching in Retrofit Projects

Table A-6-1 Pattern Matching of Hypothesis Tested in the MS and Space Project (Y = similar hypothesis, N = different hypothesis)

		Standard WLC				**Classical NWLC**				**Fuzzy Lower NWLC**				**Fuzzy Mean NWLC**				**Fuzzy Upper NWLC**			
	Discount Rate / **No's of Years**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**
Standard WLC	20 yrs.					Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	30 yrs.					Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y
	40 yrs.					N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y
	50 yrs.					Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y	N	N	Y	Y
	60 yrs.					N	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y	N	Y	Y
Classical NWLC	20 yrs.									Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	30 yrs.									Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y
	40 yrs.									N	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y
	50 yrs.									N	N	Y	Y	Y	N	Y	Y	N	N	Y	Y
	60 yrs.									Y	Y	Y	Y	Y	N	Y	Y	N	N	Y	Y
Fuzzy Lower NWLC	20 yrs.													Y	Y	Y	Y	Y	Y	Y	Y
	30 yrs.													Y	Y	Y	Y	Y	Y	Y	Y
	40 yrs.													Y	Y	Y	Y	Y	Y	Y	Y
	50 yrs.													Y	N	Y	Y	N	N	Y	Y
	60 yrs.													N	N	Y	Y	N	N	Y	Y
Fuzzy Mean NWLC	20 yrs.																	Y	Y	Y	Y
	30 yrs.																	Y	Y	Y	Y
	40 yrs.																	Y	Y	Y	Y
	50 yrs.																	N	Y	Y	Y
	60 yrs.																	Y	Y	Y	Y
Fuzzy Upper NWLC	20 yrs.																				
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				

Table A-6-2 Table showing overall frequency of correlation (No of years) based on the Hypothesis tested in MS project

		Standard WLC				**Classical NWLC**				**Fuzzy Lower NWLC**				**Fuzzy Mean NWLC**				**Fuzzy Upper NWLC**			
	Discount Rate / **No's of Years**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**
Standard WLC	20 yrs.					100%				100%				100%				100%			
	30 yrs.					100%				100%				100%				75%			
	40 yrs.					75%				100%				75%				75%			
	50 yrs.					100%				100%				75%				100%			
	60 yrs.					75%				75%				100%				75%			
Classical NWLC	20 yrs.									100%				100%				100%			
	30 yrs.									100%				75%				100%			
	40 yrs.									75%				100%				100%			
	50 yrs.									75%				75%				100%			
	60 yrs.									75%				75%				100%			
Fuzzy Lower NWLC	20 yrs.													100%				100%			
	30 yrs.													100%				100%			
	40 yrs.													75%				75%			
	50 yrs.													75%				100%			
	60 yrs.													75%				75%			
Fuzzy Mean NWLC	20 yrs.																	100%			
	30 yrs.																	100%			
	40 yrs.																	100%			
	50 yrs.																	75%			
	60 yrs.																	100%			
Fuzzy Upper NWLC	20 yrs.																				
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				

Table A-6-3 Table Showing Overall Frequency of Correlation (Discount Rates) based on the Hypothesis Tested in SPACE Project

		Standard WLC				**Classical NWLC**				**Fuzzy Lower NWLC**				**Fuzzy Mean NWLC**				**Fuzzy Upper NWLC**			
	Discount Rate / **No's of Years**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**
Standard WLC	20 yrs.					100	100	100	100	60	100	100	100	40	60	100	100	40	60	100	100
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				
Classical NWLC	20 yrs.									60	100	100	100	40	60	100	100	40	60	100	100
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				
Fuzzy Lower NWLC	20 yrs.													60	60	100	100	60	60	100	100
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				
Fuzzy Mean NWLC	20 yrs.																	100	100	100	100
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				
Fuzzy Upper NWLC	20 yrs.																				
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				

Table A-6-4 Table Showing Overall Frequency of Correlation (Discount Rates) based on the Hypothesis Tested in the MS Project

		Standard WLC				Classical NWLC				Fuzzy Lower NWLC				Fuzzy Mean NWLC				Fuzzy Upper NWLC			
	Discount Rate / **No's of Years**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**	**3%**	**5%**	**7%**	**9%**
Standard WLC	20 yrs.					60	100	100	100	80	100	100	100	60	100	100	100	40	100	100	100
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				
Classical NWLC	20 yrs.									60	80	100	100	40	100	100	100	100	100	100	100
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				
Fuzzy Lower NWLC	20 yrs.													40	100	100	100	60	100	100	100
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				
Fuzzy Mean NWLC	20 yrs.																	80	100	100	100
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				
Fuzzy Upper NWLC	20 yrs.																				
	30 yrs.																				
	40 yrs.																				
	50 yrs.																				
	60 yrs.																				

Table A-6:5 Table showing Pattern matching between MS project and SPACE project based on the declining-discount rates alone

		Standard WLC	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	20 Years		Y	N	Y	N
	40 Years		Y	Y	N	N
	60 Years		N	N	Y	Y
Classical NWLC	20 Years			N	Y	N
	40 Years			N	N	N
	60 Years			Y	Y	Y
Fuzzy Lower NWLC	20 Years				N	N
	40 Years				Y	Y
	60 Years				N	N
Fuzzy Mean NWLC	20 Years					N
	40 Years					Y
	60 Years					N
Fuzzy Upper NWLC	20 Years					
	40 Years					
	60 Years					

(Y = similar hypothesis, N = different hypothesis)

Table A-6:6 Table showing Pattern matching between the MS and SPACE project based on the (disruption and revocability)

		Standard WLC	**Classical NWLC**	**Fuzzy Lower NWLC**	**Fuzzy Mean NWLC**	**Fuzzy Upper NWLC**
Standard WLC	20 Years		Y	N	Y	Y
	40 Years		Y	N	Y	Y
	60 Years		N	N	Y	Y
Classical NWLC	20 Years			N	Y	Y
	40 Years			N	Y	Y
	60 Years			Y	Y	Y
Fuzzy Lower NWLC	20 Years				Y	Y
	40 Years				Y	Y
	60 Years				N	N
Fuzzy Mean NWLC	20 Years					Y
	40 Years					Y
	60 Years					Y
Fuzzy Upper NWLC	20 Years					
	40 Years					
	60 Years					

(Y = similar hypothesis, N = different hypothesis)

Appendix A-7 – External Validation of Newly Developed Model

Letter of Introduction

Olubukola Tokede,
PhD Researcher
Room D60,
School of Engineering and the Built Environment,
Edinburgh Napier University,
Merchiston Campus,
Edinburgh, EH10 5DT
October 19, 2015

Name of Interviewee
Role of Interviewee in SPACE Project
Address

Dear Sir/Ma,

Whole-Life Costing in the SPACE Project

As part of my PhD research investigation at Edinburgh Napier University, I have developed a new whole-life costing model for Office retrofit buildings using fuzzy logic techniques.

I will be grateful, if you would grant me permission to interview you (through the telephone, or in person) in order to seek your opinion on the performance of these models.

The estimated time of the interview will not exceed fifteen minutes (15 minutes)

I undertake that I will not reveal the identities of interviewees that participate in this exercise and will observe good and professional ethical conduct throughout the investigation and afterwards. Your participation in this study is completely voluntary.

There are no foreseeable risks associated with this investigation. However, if you feel uncomfortable answering any questions, you can withdraw from the interview at any point. It is very important to learn your opinions.

If you wish, I will keep you informed of progress throughout and I will be more than happy to share my findings with you. My thesis will also be available at the University library.

Yours Sincerely,

Olubukola (Bukky) Tokede

Interview Schedule

Section A – General Questions

1. Are you aware if any whole-life costing exercise was conducted, prior to the sanctioning of the desired retrofit option in the SPACE building retrofit project? , If yes, what technique/model was used?

2. What will you consider a realistic life span (which implies, the number of years, before another major retrofit / refurbishment exercise of this scale will occur) of the SPACE building?
    - A. 1 – 20 years
    - B. 21 - 40 years
    - C. 41 – 60 years
    - D. Over 60 years (Please provide, an indicative no. of years)

Section B –Basis of Proposed Model in the SPACE Project

A new whole-life costing model has been developed to consider revocability and disruption. Revocability addresses the potential for variability in future costs, while Disruption relates to the diminished use or unusability of the project over the course of installing the retrofit package. The whole-life costing exercise have been conducted over the expected life of the SPACE building project

3. How do you assess the inclusion of revocability and disruption in these whole-life cost framework?
4. Do you think presenting the whole-life cost estimate over a range, will be beneficial for you, as an investor in retrofit projects.
5. In what ways do you think, whole-life costing could be improved in order to fulfil your investment appraisal objectives