Illankoon, I.M.C.S. and Lu, W.S. (2019). Optimising choices of ‘building services’ for green building: interdependence and life cycle costing. *Building and Environment*, 161(8), https://doi.org/10.1016/j.buildenv.2019.106247.

Optimising choices of ‘building services’ for green building: interdependence and life cycle costing

I.M. Chethana S. Illankoon[1] and Weisheng Lu[2]
[1]*School of Architecture and Built Environment, University of Newcastle, Australia*
[2]*Department of Real Estate and Construction, The University of Hong Kong, Hong Kong*

Abstract

By influencing energy consumption, water use, and indoor environment quality, ‘building service systems’ are indispensable to green building. In practice, building services are chosen separately by different professions while they are literally interdependent on each other in determining the overall effectiveness and efficiency of green building. In addition, these building services are chosen at the initial stage without necessarily considering their life-cycle costs (LCC). A more holistic view to consider the interdependence of various building services throughout their life cycle is highly desired. Hence, this research aims to examine building services in green building by considering both their interdependence and costs throughout the building life cycle. The Hong Kong BEAM (Building Environmental Assessment Method) Plus is selected for a case study. Initially, the credits related to building services are identified and mapped from the BEAM Plus. Afterwards, LCC of the credits are calculated using the net present value technique. It is discovered that by considering building services’ interdependence from a life cycle perspective, the choices of such building services could be much different. A significant proportion of the LCC is related to the operation, maintenance and replacement of the building services, which cannot be offset by the savings of green building on their own. However, there are benefits such as CO_2 reductions, which can be used to make up the LCC if they can be properly monetized. The research provides significant insights to developers and their consultants in choosing cost-effective building services with a view to better realising the value of green building.

Keywords: Green building; Building services; Life-cycle costing; BEAM Plus

1. Introduction

Green building (GB) is one of the most discussed phenomena across the globe. It is the building industry’s responses to contemporary challenges such as natural resource depletion, pollution, greenhouse gas (GHG) emissions, and human-induced global warming. GB advocates going beyond the traditional building codes to improve overall building performance and minimise lifecycle environmental impacts and cost (Gowri, 2004). Here, ‘building’ is a polysemous word which can be used as either a noun to represent a physical facility or a gerund to represent the building process. This echoes with the USEPA (2016) suggesting that GB is a structure or site that proves environmentally responsible and resource-efficient throughout its life cycle, or with Lu et al. (2018) arguing that GB is a construction process centred on sustainability. Widely propagated benefits of GB include: enrichment of biodiversity and protection of the ecosystem (Bianchini and Hewage, 2012), reduction of GHG emissions (Jones, 2015), improved health conditions for residents and greater social productivity (Singh et al., 2010), enhancement of aesthetic appeal and comfort for occupants (Zhang and Altan, 2011), and high property value (McAllister, 2012).

Evaluation of GB is conducted via green building rating tools (GBRT) on a voluntary yet market-based premise. Numerous options for GB evaluation exist. Building Research Establishment Environment Assessment Method (BREEAM) (2015) is the first ever GBRT. Similarly, Leadership in Energy and Environmental Design (LEED) developed by the United States Green Building Council (USGBC) (2015) is considered as one of the most widely used GBRT in the USA and worldwide. Green Star is commonly adopted in an Australian context (Green Building Council Australia, 2013). In Hong Kong, BEAM Plus (Building Environmental Assessment Method) is dominant in green building certification (Hong Kong Green Building Council [HKGBC], 2017). Previous studies comparing these GBRT, e.g. Cole (2003), Wu and Low (2010), and Zuo and Zhao (2013), discovered that they differ in terminologies, assessment methods, relative importance of the environmental themes and documentation requirements for certification. Nevertheless, they present a high degree of similarity. For example, they share common sustainability deliverables, including, *inter alia*, energy efficiency, water conservation, site selection, building materials, and indoor environmental quality (IEQ) (Wu and Low, 2010; Gou and Lau, 2014).

Most of these sustainability deliverables as prescribed in a GBRT are delivered by 'building services'. For example, IEQ concerns the thermal comfort of the occupants. IEQ credits are directly related to the heating ventilating and air-conditioning (HVAC) systems of the building. Similarly, the water use credits are directly related to the sanitary and plumbing services. In reality, these building services are interdependent on each other in determining the sustainability deliverables, and in turn, the overall GB performance in terms of effectiveness and efficiency. For example, mechanical, electrical, and plumbing (MEP) systems are linked with HVAC systems in determining energy efficiency, water use, IEQ, and overall GHG emissions. However, these building services are normally chosen by different professionals without necessarily considering their interdependence.

Moreover, in real-life practice, most building service systems are chosen without necessarily considering their life-cycle costs (LCC). Regardless of the potential savings and benefits from GB, the initial cost premium has always posed as a barrier. Partially against this backdrop, the life cycle thinking is introduced to provide an alternative perspective to justify the cost premium using the savings and benefits harvested through a longer period of time, e.g., a building's life span. In addition, LCC can provide a more holistic view considering the costs and benefits of GB than simply calculating the initial cost. However, irrespective of its importance, life-cycle costing, also sharing an acronym of LCC, is not commonly used in the initial stages of green buildings. There are many reasons for the lack of use of LCC (e.g., LCC calculations require considerable time and cost data, require expertise, high-quality professional judgement and forecasting (Ashworth, 1989)) and yet for many decades, these issues keep arising (Zuo et al., 2017). To summarise, building services play a pivotal role in determining the effectiveness and efficiency of a GB. Previous research without considering the interdependence of building services from an LCC perspective represents a significant knowledge void to GB stakeholders including developers, designers, consultants, regulators, scholars, and end users. A more holistic view of building services in GB by considering both their interdependence and their life cycle is highly desired.

The research aims to produce a life-cycle cost analysis of building services in GB by considering their interconnection from an LCC perspective, with a view to providing more holistic insights to GB stakeholders. Owing to the fact that a GB is evaluated based on a GBRT, this research analyses building services-related credits as stipulated in GBRT and their respective LCC. The rest of the paper is organised as follows. Subsequent to this introductory section is a literature review touching upon green building and its building services, and LCC in green building development. Section 3 is an elaboration of the research methodology. Basically, it is to check the credits related to building services, probing into their interconnection, and calculating their net present value throughout their life cycle. Section 4 presents the analytical results and findings. Section 5 is an in-depth discussion of the results and future prospects of building service deployment for GB. Conclusions are drawn in Section 6.

2. Literature review

2.1 Green buildings and building services

A building has three generic systems, namely, a structure system, an envelope system, and a 'building services' system. The Royal Institute of Chartered Surveyors (RICS) (2012) identified thirteen categories of building services when analysing building cost. However, according to the new rules of measurements, in buildings there are mainly three categories of building services, namely, drainage (above and below ground), mechanical services, electrical services and transportation (RICS, 2007). Rawlinsons (2017) presented a slightly different version of building services; there are five types of building services including plumbing, mechanical, electrical, fire, and transportation.

Building services are important to any building. They are particularly important to a building when it aims to obtain a certain GB certificate, as a considerable portion of the sustainability-related credits such as energy consumption, water use, and IEQ are directly contributed by them. According to Illankoon et al. (2017), energy criteria has the highest contribution of credits in most of the GBRTs. For example, 34.29% of credits from the BEAM Plus are from energy criteria. Further, IEQ and the water criteria provide the second and third highest contributions in GB certification when using the widely used GBRTs such as LEED, BREEAM, Green Star, Green Mark, and BEAM Plus (Illankoon et al., 2017). It is thus high on the agenda of building developers and their consultants to carefully chose building services to pursue a green building. The water credits can be obtained through an efficient sanitary and plumbing service, while the energy and IEQ credits can be obtained by installing efficient electrical and HVAC systems. Nevertheless, in real-life practice, building services are chosen by different professions without considering their interdependence to affect the sustainability goals. For example, when developing a cost optimising model for green buildings in an Australian context, Illankoon et al. (2019) illustrated that many optimal solutions can be derived considering the interdependence among green building requirements which are in many instances ignored due to the atomistic nature of the green building process. At best, the building services are coordinated for clash detection or buildability simulation at the detailed design stage; that relates to their spatial constraints rather than the achievement of sustainability goals.

Another problematic practice is that most building services are chosen at the initial design stage without necessarily considering their LCC. This could be attributed to negligence, not required, or the fact that the data and methodology to perform LCC are in absence. Due to the requirements for GB certification, building services installed in GB are expected to be more efficient, and thus more expensive except for some rare cases. There is a wide gap between the actual and the predicted energy performance in GBs (de Wilde, 2014); efficient operations and maintenance are vital to reduce this performance gap (de Wilde, 2014; Zhang, 2015) but they incur “recurrent costs” which will add to the overall LCC. This resonated with Cole’s (2007) statement that the initiatives taken for better wellbeing of occupants in GB have an impact on the LCC.

In summary, GB has many requirements to fulfil prior to its certification. Unavoidably, the GB professionals need to carefully evaluate all the inputs (e.g., building services, materials, and site aspects) and outputs (e.g., waste, energy efficiency, cost, and the environmental impact) when developing a GB (Robinson et al., 2012). Building services are indispensable inputs in GB for achieving such sustainability credits as stipulated in a GBRT. Yet, previous research and practice are inadequate without considering the fact that building services can be interlinked with each other to determine the overall success of GB. In addition, the choices of building services should be scrutinized from an LCC perspective by considering not only the capital costs but also the recurrent costs that happen throughout the GB lifecycle.

1.2 LCC in green building

LCC approach was initially developed in the mid-1960s to assist the U.S. Department of Defence in the procurement of military equipment (Epstein, 1996) and ever since this approach was very much popular among U.S. government agencies for decision-making (Goh and Sun, 2015). There is an international standard particularly designated for GB LCC analyses: ISO 15686-5:2017, 'Building and construction assets – service life planning – Part 5: LCC standard' (International Standard Organisation [ISO], 2017). According to the standard, LCC in construction commences from the planning stage and ends with the disposal stage; so-called 'gate to grave' analysis. The Australian National Audit Office (2001) provides a five-phase definition of a building lifecycle including design, purchase and construction, operations, maintenance, and development and disposal. Each phase generates various costs. The process of LCC literally involves assessing cost that arises from an asset over its life span, and evaluating alternatives that have an impact on this cost of ownership. The design, purchase, and construction costs are largely included as 'initial costs', which represent the current market prices. Apart from the initial costs, all other costs occur in different phases of the building life cycle. These costs need to be discounted back to present values. Equation 1 shows the formula for the net present value (NPV) calculation.

$$NPV\ (i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

Equation 1: NPV calculation

where i denotes the discount rate, t denotes the time of cash flow, R_t denotes the net cash flow, and N is the total number of periods.

Maintenance costs and annual savings occur annually throughout the life cycle of a green building. Therefore, to calculate annual costs and savings the present value of annuity (PVA) formula is used. Equation 2 shows the formula for PVA calculation.

$$PVA = R_m \times \left(\frac{1-(1+i)^{-N}}{i}\right)$$

Equation 2: PVA calculation

where i denotes the discount rate, R_m denotes the annual maintenance cost, and N is the total number of periods. The discount rate is established considering the time value of money and the associated risk. The minimum attractive rate of return is commonly used as the discount rate (Dell'Isola and Kirk, 2003).

Externalities and social benefits are not considered in LCC, as these costs and benefits fall under whole-life instead of LCC (ISO, 2017). The life cycle of a GB is normally set as 60 years. Initial costs are developed based on the first-cost principles. Maintenance data is obtained through industry norms and technical manuals. All the LCCs are normalised to one square meter of gross floor area of the GB.

There are many studies illustrating the benefits of GB in terms of energy and water savings (Eichholtz et al., 2010; Green Building Council of Australia, 2013; Kats et al., 2003; World Green Building Council, 2013). Kale et al. (2016) carried out a study using solar panels as an energy efficient method for residential buildings in India. According to this research, LCC of proposed solar panel system shows a 4% of energy cost saving when using a minimum capacity solar panel and 54% energy cost savings for desired capacity solar panel system (Kale et al., 2016). Dwaikat and Ali (2018a) analysed the LCC of a certified GB to identify the economic benefits. The building adopted green features including thermal insulation, 100% daylight, energy efficient lighting system, storm water harvesting system, building energy management system, floor cooling system and capable of generating 50% of its energy demand through an integrated PV system (Dwaikat and Ali, 2018a). In Hong Kong, Gao et al. (2014) carried out an LCC analysis for a rain water harvesting system for residential projects. According to Gao et al. (2014), existing roof areas cannot meet the huge water demands of high-rise buildings in Hong Kong and rainwater harvesting system can only supply 25.7% of the water required for washing machines in each residential building.

There is also prolific research on LCC for one single building services system for green buildings. For example, Sellers (2005) focused on rightsizing air-handling units considering the LCC for green buildings. Similarly, Briller and Hamilton (2011) illustrated how integrative design strategies used to achieve high LEED certification ratings for federal buildings in the USA can simultaneously result in substantial fossil fuel consumption reductions. The research used two specific strategies and these are discussed in terms of their energy savings potential and LCCs (Briller and Hamilton, 2011; Briller, 2008). Singh et al. (2011) used the LCC analysis (LCCA) framework to calculate the potential economic gains of IEQ improvements to the organisations. Kim et al. (2016) develop an optimisation model for the optimal GB systems by considering the thermal comfort in an educational facility. There are similar models considering the LCC of one building service system. In Hong Kong, there are studies on LCC approach for rain water harvesting (Gao et al., 2014), and PV panel evaluation (Lou et al., 2017) and for designing chillers (Cheng et al., 2016). All these research studies only focused on a single building service, excluding many other inter-linked services of a building.

de Wilde (2014) illustrated that there is a gap between the actual and the predicted energy performance in GB. The lack of efficient operations and maintenance is identified as one of the reasons for this performance gap (de Wilde, 2014; Zhang, 2015). Therefore, it is necessary to carry out regular maintenance throughout the building life-cycle for the buildings services to perform in the predicted standard of savings. However, the maintenance cost contributing to a significant proportion of the total LCC is completely ignored in most of the calculations. Dwaikat and Ali (2018b) calculated the LCC for a GB considering 60 year period and reported that building maintenance cost is 27% of the total LCC (Dwaikat and Ali, 2018b). Previous studies have clearly shown that costs of building services, both their initial installation and operation/maintenance, should be considered from a lifecycle perspective.

3. Research methodology

The research methodology adopted in this paper comprises a four-step process as follows:

Step 1: Identifying the credits in a GBRT associated with building services
Step 2: Mapping the credits associated with specific building services and understanding their interdependence
Step 3: Calculating LCC of the selected credits
Step 4: Analysing and recommending LCC-effective building services solutions for GB

3.1 Identifying the credits associated with building services

Since the aim of the research is to identify the optimal LCC solutions considering the buildings services, it is necessary to identify all the credits which have an influence on the building services. The credits are classified as using a method as shown in Table 1. The third category represents the credits which can be obtained through a design change. For example, the credit 'Natural lighting' representing energy key criteria can be obtained through a better design that allows maximum access to daylight for the purpose of improved health and comfort.

Table 1: Categorisation method of GB credits and their association with building services

Category	Elaborations
A	Credits that are directly influenced by building services
B	Credits without any/slight influence by building services
C	Credits with an influence from the building services, yet obtained through the building design

'Category A' credits directly influence one or more building service(s). For example, 'Peak electricity demand reduction' credit directly influences the Electrical system as well as the HVAC system of the building. To achieve this credit, the peak energy consumption of both systems must be reduced by using various options, one of which is to use a renewable energy generating system. 'Renewable energy systems' credit addresses this requirement.

'Category B' credits do not influence the GB services. For example, 'Timber used for temporary works' credit has no influence on the GB services. 'Category C' represents credits with an influence on the building services yet attainable through building design. For example, 'Energy efficient building layout' and 'amenity features' credits have an influence on building services, yet they are addressed through building design. This research focuses on 'Category A' credits.

3.2 Mapping the credits associated with specific building services and understanding their interdependence

After identifying the 'Category A' credits, these credits are mapped to understand the interdependence. Although there are credits that focus on the same type of building services, they are classified under different key criteria. Furthermore, there are certain credits that can be collectively considered for cost calculations and bundled together for optimum selection of credits.

Mechanical services for HVAC, sanitary and plumbing, and electrical services are key building services in any commercial building. Therefore, these separate systems are considered separately while estimating the life-cycle cost. Besides this, there are different credits that support each other to meet the requirement. As an example, credits focusing on lighting of the building, energy performance, peak energy demand, etc directly influence the LCC of electrical system. Yet, 'Interior lighting in areas normally occupied areas' credit is categorised in IEQ criteria and 'Peak electricity demand reduction' in energy criteria. These different credits are listed in different key criteria. Interior lighting uses the electrical energy and therefore, it should be considered when calculating the peak electricity demand in the GB. Consequently, for the GB to reduce the peak electricity demand, the energy required for interior lighting in peak time needs to be reduced. These two credits seem to be different, yet there is an interdependency between the two. There are many similar interdependencies in among these credits.

Determining the interdependences performs a crucial part of this research. As mentioned earlier, electrical system, HVAC system, and the sanitary and plumbing systems are considered in this research. Boundaries of each of these systems are defined as follows (Rawlinsons, 2017):

- Electrical system - To provide all light and power and emergency light and power, power outlets and light fittings, including main distribution board; sub-mains and distribution boards; emergency lighting systems; power sub-mains to mechanical equipment, etc.; systems such as telephone, internal telephone, public address, call, emergency warning and intercommunication, personal paging, clock and/or bell, TV antenna and closed circuit TV
- Sanitary and plumbing - To fit out the building with normal sanitary fixtures together with hot and cold water services and soil and waste plumbing systems together with all associated ancillaries. Exclusions are rainwater disposal systems and external services from the outside face of the building
- HVAC system - Comprises air conditioning, evaporative cooling, mechanical ventilation, specialist hospital services, and the like, reticulated steam and hot water systems.

All the 'Category A' credits are evaluated against these definitions. If any credit falls into any of the above three categories, it is considered as inter-dependent with the relevant building service. After defining the inter-dependent credits, each set of credits is evaluated against the inter-links. As an example, 'WUP2 Minimum water saving performances', 'WU1 Annual water performances', 'WU3 Water efficient irrigation' and 'WU4 Water recycling' are identified as inter-linked credits. To achieve water savings, it is necessary to use water-efficient irrigation, water recycling and use water efficient appliances. In summary, the inter-linked credits are not stand-alone credits when achieving GB goals. To attain the requirements of one or two credits the set of inter-linked credits should be bundled together. For example, in water criteria, 'WU6 Effluent discharge to foul sewers' is a stand-alone credit which does not require any requirement to be fulfilled as a basis to achieve this credit. However, to achieve 'WUP2 Minimum water saving performances' credit, it is necessary to carry out water recycling which is given in WU4 Water recycling' and use water efficient irrigation 'WU3 Water efficient irrigation' etc. Therefore, these credits are inter-linked.

3.3 LCC calculation

The LCC calculation follows the ISO 15686-5:2017, namely, 'Building and construction assets – service life planning – Part 5: LCC standard'. The main focus of this research is on the building services that contribute to the water, energy and IEQ key criteria of green buildings. Therefore, when calculating the LCC, the initial, operation, maintenance costs including necessary replacements and demolition costs are mainly considered in the calculations.

According to the ISO (2017), life-cycle costing in construction commences from the planning stage and ends with the disposal stage. Therefore, this study follows a 'gate to grave' analysis of life-cycle costs for general office buildings. The time period for this life-cycle cost calculation is 60 years. Further, all the costs are normalised to one square metre of gross floor area (GFA) of the building.

'IEQ16, Interior lighting in areas normally occupied' is assigned to IEQ criteria, and 'EUP1 Minimum energy performance' credit is assigned to energy criteria. Therefore, in such instances, the interconnected credits to the electrical system are identified. Afterwards, the proportion allocated for each credit in the LCC is determined. In an electrical system, there is an installation cost for the electrical equipment, wiring and so on.

Most of the initial costs are available on *Schedule of Rates* published by the Architectural Services Department Hong Kong (2016). The rates given in the schedules included for material (including wastage, cutting, and the like), labour, and plant/tools. For example, for the previously identified 'IEQ 16' and 'EUP1' credits, the lighting fixtures, wiring, tools used for fixing and labour including skilled and unskilled labour is included in these rates. Some of the rates required for this research was not available from the schedule. In such instances, *Quarterly Construction Cost Update* published by the Rider Levitt and Bucknell (RBL) (2018) was referred mostly for labour prices. It needs to point out that the rates given in the *Schedule of Rates* and *Quarterly Construction Cost Update* have followed different approaches in developing the costs, e.g., the inclusions and exclusions are different, making the rates differ from each other. Therefore, the preference is given to the *Schedule of Rates* while the *Quarterly Construction Cost Update* is referred to as a guide. After developing the rates, it was necessary to apportion it among the relevant credits. For the apportionment, it is necessary to identify the cost proportion contribution of various items in services. As an example, when calculating the LCC for 'IEQ16, Interior lighting in areas normally occupied', the total initial cost for the electrical system is calculated first and then the cost proportion for lighting is used to apportion the initial cost allocated to the 'IEQ16, Interior lighting in areas normally occupied' credit. Rawlinsons (2017) provides a detailed breakdown of cost proportions for each of the services separately. Therefore, Rawlinsons (2017) is used for allocation cost proportions for respective credits accordingly.

Next is to calculate the maintenance and demolition cost. Each component of a building service, has different maintenance requirements, depending on the system requirements. These maintenance requirements are based on maintenance manuals and guidance from maintenance engineers on specific products and materials. Systems such as air conditioning require regular maintenance, on an annual basis. The maintenance requirements are derived based on the detailed analysis provided by Dell'Isola and Kirk (2003), and Stanford (2010). Apart from maintenance, this study considered replacement of different components. As an example, usually, light fittings and fixtures need replacements throughout the life-cycle (Dell'Isola & Kirk, 2003). In such a scenario, light fittings and fixtures are replaced in the relevant year of the life-cycle and the cost is discounted to the present value.

There are utility costs that occur within the operational stages of a building. There are money savings from these systems which are identified as negative figures in the cost calculation (which ultimately reduces the cost). As an example, if the electrical system installed within the building is considered, there are regular electricity costs that the user needs to pay to the electricity provider. Further, due to certain changes in the system, the user might get certain cost savings as well. The maintenance cost and the operating costs/savings are once again apportioned based on electricity usage among various electrical systems. As an example, according to Burnett et al. (2008), an office building in Hong Kong consumes approximately 48% energy on air conditioning, 19% on lighting, 22% on office equipment and 11% on other. Therefore, after calculating the maintenance cost and the operating costs of electrical system, the net cost (after considering the savings) is apportioned based on these electricity usage percentages. Once the cost/saving proportion is allocated to the relevant system, it is again apportioned for the relevant credit based on the interdependencies. For example, the cost of energy is apportioned among different systems based on the energy use. Out of this cost/saving 48% is apportioned to HVAC system. That figure is again apportioned according to the dependencies, which is discussed in the analysis section. Same process is carried out for other services as well. Finally, LCC is checked against the industry reports and norms for validation. Based on the lowest LCC, optimal solutions were selected.

The discount rate is established considering the time value of money and the associated risk. The minimum attractive rate of return is commonly used as the discount rate (Dell'Isola & Kirk, 2003). The NPV is considered for calculating the time value for money. According to (Trading Economics, 2018a) the inflation rate in Hong Kong is 2.7% as at October 2018 and the interest rate on a 10-year government bond is 1.6% per annum (Trading Economics, 2018b). The discount rate considered in this research is 2.5%. However, this rate changes for each user, because the associated risk differs from one to another. Therefore, in order to calculate the life-cycle cost, a user should identify the associated discount rate.

There are many sensible assumptions made during the cost calculations. The initial cost is assumed to be similar across Hong Kong despite the location. The transport cost of these items is not included separately. There are many methods and innovative ways to achieve these credits. However, in this research, the only focus is on achieving the least requirements using the basic methods. At the end of the life cycle, an additional cost is added for handling material/items carefully for re-use. The remaining debris is assumed to be carried out to a site within a 15km radius for disposal. There are credits with a range of credits available. For example, ‘EU1 Reduction of CO_2 emissions’ can achieve up to 15 credits. However, this research only considered achieving the minimum required credits. Appendix 1 report the LCC for all the credits.

4. Analyses and results

4.1 Relevant credits in BEAM Plus

The BEAM Plus has five key criteria: Site Aspects (SA); Materials Aspects (MA); Energy Use (EU); Water Use (WU); Indoor Environmental Quality (IEQ); and some Innovations and Additions (I&A) bonus. A total of 79 credits are categorised under these key criteria. This paper analysed the credits associated with building services using the categorising methods as elaborated in the methodology section.

The Site Aspects (SA) key criteria of BEAM Plus are mainly concerned on location and design of the building, emissions from the site and site management (HKGBC, 2012). Therefore, all the underlying credits are focused on the site management, locations and the site management related activities. All of the credits except ‘SA15 Light pollution’ credit fell into Category A – “Credits directly influenced by building services”. This credit has a direct influence on the lighting system of the building. Therefore, only this credit is considered for LCC calculations from site aspects key criteria.

Likewise, Material Aspects (MA) key criteria focus on the selection of materials, their efficient uses and waste disposal and recycling (HKGBC, 2012). There are two credits that can be directly influenced by the HVAC system of the building, namely, 'MAP2 Use of non-CFC based refrigerants' and 'MA8 Ozone depletion substances'. These credits are thus chosen for the LCC calculation.

Energy Use (EU) key criteria focus on annual carbon dioxide or energy use, energy efficient systems and equipment and energy management. Water Use (WU) key criteria focuses on water quality, water conservation and effluent discharge. Indoor Environmental Quality (IEQ) key criteria include safety, hygiene, indoor air quality and ventilation, thermal comfort, lighting, acoustics and noise and building amenities. Most of the credits in these key criteria are directly influenced by various building services. Table 2 below reports that Category A credits considered in this research. The total credit point value of these credits is 79 credit points. In other words, the building services influences 62 credits out of 127 total credits. Building services are an indispensable part of GB that developers and consultants must consider carefully.

Table 2: Category A credits that influence the building services

Sub-criteria	Code	Description	Attainable credits
Site Aspects (SA)			
Emission from the site	SA15	Light pollution	1
Material Aspects (MA)			
Prerequisites	MAP2	Use of Non-CFC based refrigerants	Required
Selection of materials	MA8	Ozone depletion substances	2
Energy Use (EU)			
Prerequisites	EUP1	Minimum energy performance	Required
Annual energy use	EU1	Reduction of CO_2 emissions	15
	EU2	Peak electricity demand reduction	3
Energy efficient systems	EU4	Ventilation systems in carparks	2
	EU5	Lighting systems in carparks	2
	EU6	Renewable energy systems	5
Provisions for energy management	EU10	Testing and commissioning	4
	EU11	Operations and maintenance	3
	EU12	Metering and monitoring	1
Water Use (WU)			
Prerequisites	WUP1	Water quality survey	Required
	WUP2	Minimum water saving performance	Required
Water conservation	WU1	Annual water use	3
	WU2	Monitoring and controlling	1
	WU3	Water efficient irrigation	1
	WU4	Water recycling	2
	WU6	Effluent discharge to foul sewers	1
Indoor Environment Quality (IEQ)			
Prerequisites	IEQP1	Minimum ventilation performance	Required

Security	IEQ1	Security	1
Hygiene	IEQ2	Plumbing and drainage	1
	IEQ3	Biological contamination	1
IAQ	IEQ6	Outdoor sources of air pollution	2
	IEQ7	Indoor sources of air pollution	3
	IEQ8	IAQ in carparks	1
Ventilation	IEQ9	Increased ventilation	1
	IEQ11	Localised ventilation	2
	IEQ12	Ventilation in common areas	1
Thermal comfort	IEQ13	Thermal comfort in air-conditioned premises	2
Lighting quality	IEQ16	Interior lighting in areas normally occupied areas	1

4.2 Mapping credits with building services

As illustrated in Section 3.2, the building services and the credits reported in Table 2 are mapped together. Figure 1 reports all the interdependent and inter-linked credits. The LCC cost is calculated for the respective service. Afterwards, it is apportioned based on the inter-dependences and inter-links given in Figure 1.

Illankoon, I.M.C.S. and Lu, W.S. (2019). Optimising choices of 'building services' for green building: interdependence and life cycle costing. *Building and Environment*, 161(8). https://doi.org/10.1016/j.buildenv.2019.106247.

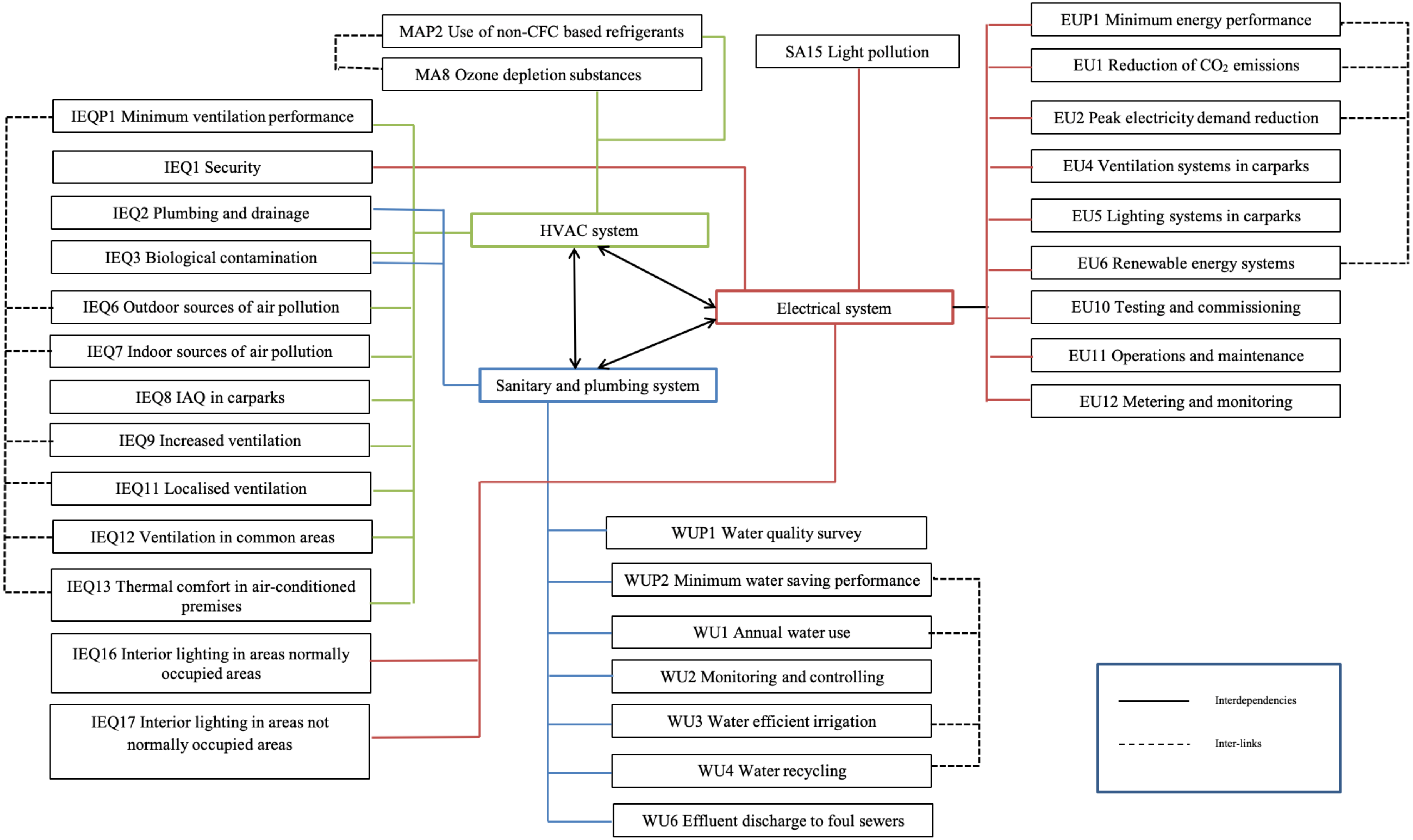

Figure 1: Inter-dependencies and inter-links among building services systems and green building credits

Figure 1, includes the three building services, namely; the HVAC system, electrical system and plumbing and sanitary system. The dotted links illustrate the inter-links between the credits. For example, there are inter-links among ‘EU1 Reduction of CO_2 emissions’, ‘EU2 peak electricity demand reduction’, and ‘EU6 Renewable energy systems’. As the name suggests, ‘EU2 peak electricity demand reduction’ credits required to reduce the peak energy demand (HKGBC, 2012). Similarly, ‘EU6 Renewable energy systems’ credit requires consuming renewable energy (HKGBC, 2012). If a green office building utilise photovoltaic (PV) panels to generate electricity, it will cater to all these three credits. The use of PV panel will reduce the energy use, CO_2 emissions and peak electricity demand. It acts as a renewable energy source. The costs and savings of installing PV panels must be borne by all these credits. Cost and savings are apportioned based on the mechanism given in Section 3.3. Identifying these inter-links are very much important in this research.

According to Figure 1, the electrical system is closely dependant on the credits relating to lighting, and energy reduction. Further, the HVAC system is IAQ and ventilation credits. These credits are also inter-linked together, which is considered in calculating the LCC as explained in Section 3.3.

4.3 Analysis of LCC for credits

The analysis of these credits comprises of three separate sections focusing on water use credits, energy credits and IEQ credits as follows.

4.3.1 *Analysis of energy use credits*

The HVAC systems have two types based on their cooling mechanisms: the water-cooled and the air-cooled HVAC systems. Therefore, this research considered both these options when calculating the LCC. Figure 2 below illustrates the LCC options from energy use credits. According to Figure 2, the highest LCC is from ‘EUP1 Minimum energy performance’ credit. The objective of this credit is to establish a minimum level of energy performance in the building (HKGBC, 2012). Therefore, both the HVAC and the electrical system contribute heavily to this credit.

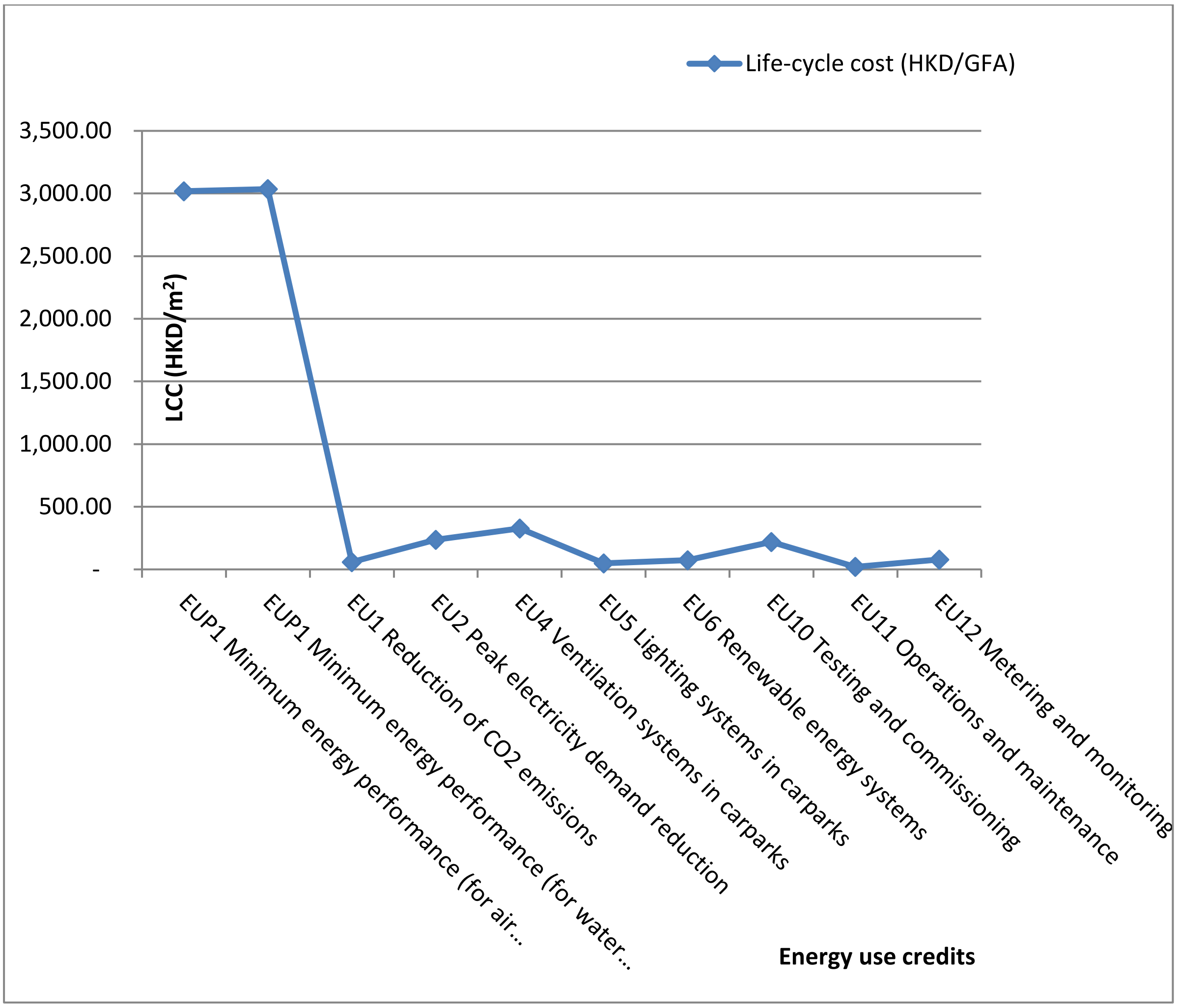

Figure 2: LCC for energy use credits

Most of the energy-related credits have significant energy saving potential. According to Burnett et al. (2008), both water-cooled and air-cooled HVAC system saves up to 38% to 39% of energy. Further, BEAM Plus certified buildings have a potential of 52% of electricity saving (HKGBC, 2017). The LCC calculations account for these LCC savings in energy. However, on the other hand, there are maintenance and operational costs. The initial cost is dwarfed due to this LCC saving, yet the maintenance costs once again add for the LCC of the building. In this research these savings are allocated among the credits based on the interdependencies. Therefore, the cost savings are not accumulated to one credit, rather it is dispersed among the relevant credits.

Credits such as 'EU3 Reduction of CO_2 emissions' credit is obtained by introducing PV panels as a renewable energy source. However, only 3% of the annual energy requirement is obtained from this PV panel system. Therefore, only one credit out of 15 is achieved through by using the PV panels. Further, this PV panel system contributes to obtaining 'EU2 Peak electricity demand reduction' and 'EU8 renewable energy system' credits. There are many studies carried out focusing on PV panels and its effectiveness in generating renewable energy such as follows:

- Tam et al. (2017), - when using PV panels there are net life-cycle cost savings. Tam et al. (2017) considered tax rebates and incentives in the Australian context. Due to the tax rebated, there were considerable savings throughout the life-cycle.
- Lou et al. (2017) - calculated payback periods for PV panels in Hong Kong including carbon trading

In these research studies, PV panels are considered as one option. For example, by using the PV panels, GB can reduce the peak electricity demand as well as minimise the energy use. Therefore, in this research, these electricity savings are apportioned among all these credits, which are inter-linked. Therefore, a more holistic approach is obtained. The use of PV panel is neither undervalued nor overvalued through the LCC calculation because the costs and savings are apportioned among all the relevant credits based on the inter-links.

‘EU11 Operations and maintenance’ credit requires to provide maintenance manuals and to provide training. Therefore, this credit only has a one-off initial cost at the initial stages of the building. ‘EU10 Testing and commissioning’ credit requires to carry out commissioning of the electrical and mechanical systems to ensure its performance (HKGBC, 2012). This credit also has an initial cost at the initial stages of the building.

In energy use credits, there are many credits focusing directly on reducing the carbon emissions. For example, HKGBC (2017) reported that BEAM Plus assessed projects save approximately 354,800 tons of CO_2 emission. Similarly, credits such as ‘EU1 Reduction CO_2 emissions’ encourage to reduce CO_2 emissions. However, these savings are not included in monetary terms in this life-cycle calculation because of the boundaries set out to calculate the LCC based on the ISO standard exclude the externalities (ISO [ISO], 2017). If these reductions can be quantified and measured in monetary terms using carbon financing, there can be saved from implementing certain credits. The monetised carbon savings can be apportioned among the credits with inter-links so that many credits might have a much lower LCC after deducting the savings.

4.3.2 *Analysis of water use credits*

Figure 2 below illustrates the LCC for credits in water use key criteria.

Illankoon, I.M.C.S. and Lu, W.S. (2019). Optimising choices of ‘building services’ for green building: interdependence and life cycle costing. *Building and Environment*, 161(8), https://doi.org/10.1016/j.buildenv.2019.106247.

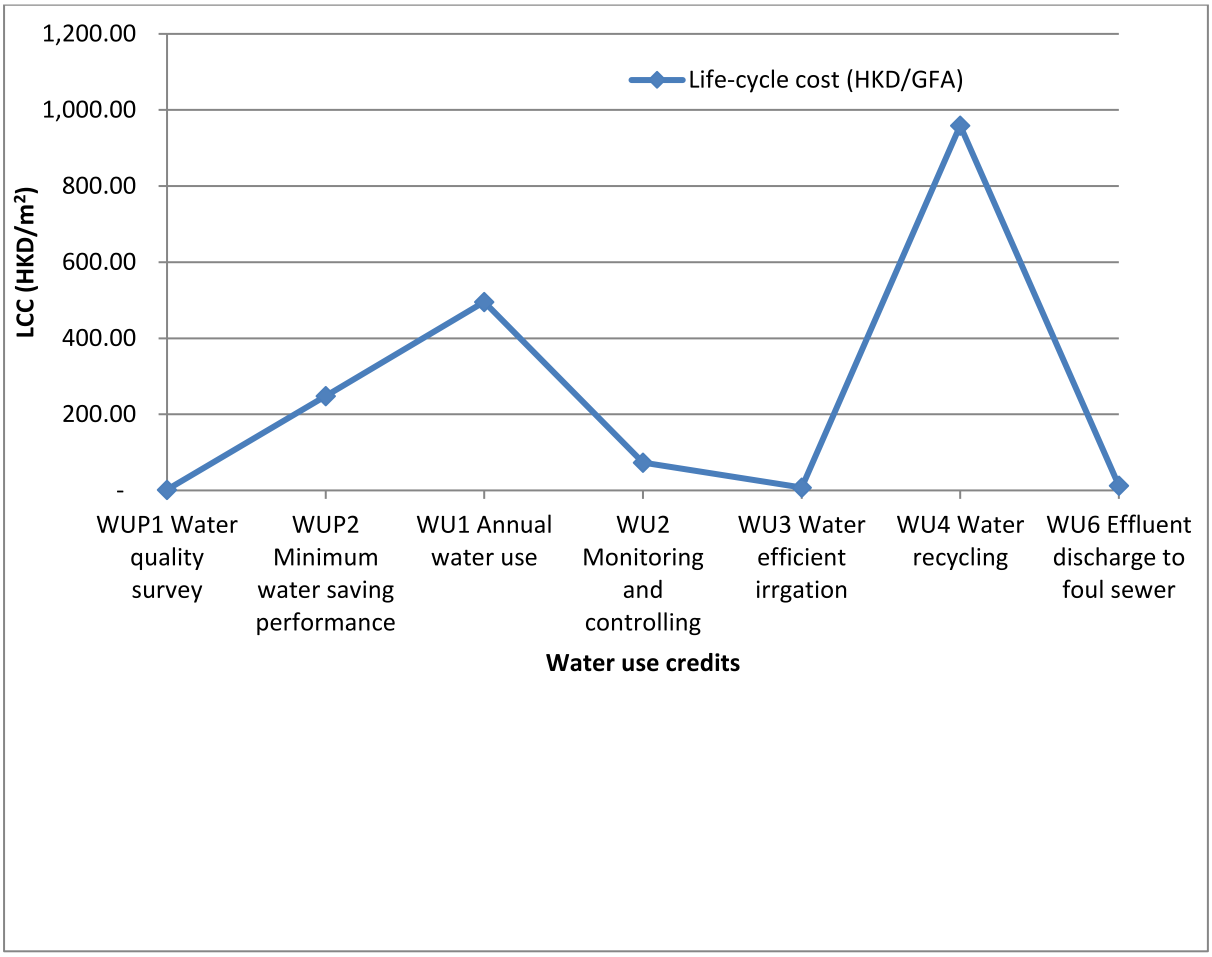

Figure 3: LCC for water use credits

According to Figure 3, ‘WU4 Water recycling’ credit has the highest LCC. When calculating the LCC, this research considered a combined system with rain water harvesting and grey water recycling. According to the Water supplies department (2011), the combined system with a 50m^3 capacity will incur annual maintenance cost of approximately HKD 70,000. Therefore, with 10% water saving was not enough to cover for the annual maintenance and operational costs. Therefore, the LCC for 60-year period is higher as given in Figure 3. These results are similar to the results reported by Gao et al. (2014). In this research the cost savings and also the initial cost of installing the water recycling facilitates are shared among the credits that are inter-linked (refer Figure 1). As a result, a certain amount of costs are shared among the ‘WUP2 Minimum water saving performance’ credit and WUI Annual water waste’ credit.

‘WUP1 Water quality survey’ incurs a one-off cost during the initial stage of the green building. Further for ‘WU3 Water efficient irrigation’ credits, a drip irrigation system is considered. When normalised to the gross floor area (GFA) of the building the cost of drip irrigation system is low. Further, this system saves the use of potable water use, making it a less LCC option. ‘WU6 Effluent discharge to foul sewer’ credit focus on reducing the volume of sewage discharge from the building (HKGBC, 2012). Therefore, this credit can be easily obtained by using proper sanitary fitment with a low LCC as illustrated in Figure 3.

4.3.3 *Analysis of IEQ credits*

IEQ is one of the key criteria in the BEAM Plus to concern about indoor air quality (IAQ), ventilation, thermal comfort, lighting, and acoustics (HKGBC, 2012). Apparently, most of the credits in this category are attainable via a proper choice of building services such as lighting system, HVAC system and also the sanitary and plumbing system.

Figure **4** illustrates the LCC calculations for the IEQ credits.

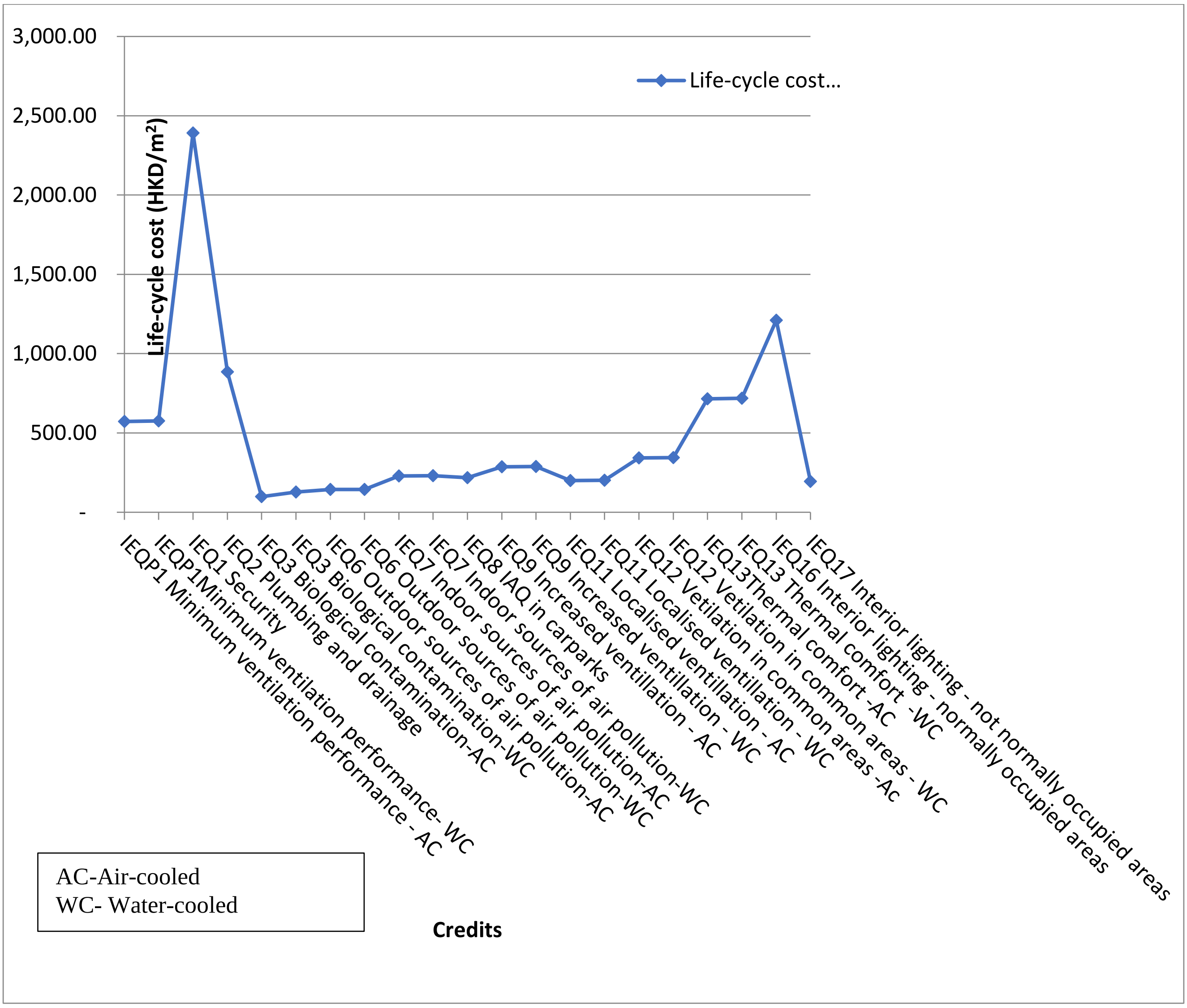

Figure 4: LCC for IEQ credits

According to

Figure **4**, the highest LCC is for 'IEQ1 Security' credit. The main reason for the high cost is the credit requires occupying security guards for CCTV monitoring and for patrolling throughout the building life-cycle. Unlike other credits, this credit does not have any direct saving throughout the building life-cycle except for the social benefits, which are not included in the calculations. Therefore, 'IEQ1 Security' has the highest LCC in IEQ key criterion. This credit is not inter-linked with any credit and it is a stand-alone credit. The cost of this credit is absorbed by this credit only as it does not support any other credits to indirectly.

'IEQ2 Plumbing and drainage' credit aims to reduce the potential of contamination of plumbing and drainage systems (HKGBC, 2012). Therefore, the LCC included the regular maintenance works throughout the project life-cycle to avoid any contamination and the like. The life-cycle water savings are from using the water saving appliances. The cost savings from water use reduction are attributed to the credits aiming for water saving. However, 'IEQ2 Plumbing and drainage' credit did not contribute to any water savings. As a result, the LCC for 'IEQ2 Plumbing and drainage' is comparatively higher compared to the other IEQ credits.

Other than those two credits, 'IEQP1 Minimum ventilation performance', 'IEQ13 Thermal comfort in air-conditioned premises' and 'IEQ14 Interior lighting in normally occupied areas' have LCC higher than HKD 500/m^2 (refer

Figure **4**). 'IEQP1 Minimum ventilation performance' and 'IEQ13 Thermal comfort in air-conditioned premises' focus on providing better thermal comfort to the occupant, which will derive social benefits and even increase in productivity. These social benefits are not counted in the LCC calculations according to the ISO standard framework (ISO, 2017). Further, these two credits form a part of a bundle of inter-linked credits (Referring to Figure 1). The cost of 'Thermal comfort in air-conditioned premises', 'Localised ventilation' is partially borne by 'Minimum ventilation performance and vice versa. However, the cost savings from the social benefits are not deducted by any of these credits which leads to higher LCCs. 'IEQ14 Interior lighting in normally occupied areas' credit included life-cycle energy savings due to lighting in green buildings. However, there are regular maintenance, replacements and operational costs attached to this credit.

4.3.4 Other credits – Site aspect (SA) credits and material aspect (MA) credits

Apart from those credits, this research considered 'SA15 Light pollution' credit and 'MAP2 Use of non-CFC based refrigerants' credits. 'SA15 light pollution credit' requires HK$ 121/m^2 LCC including the savings from lighting and operation and maintenance costs. The LCC of 'MAP2 Use of non-CFC based refrigerants' and 'MA8 Ozone depletion substances' are less than HKD 500/m^2 range representing the HVAC system related costs. Both these credits are inter-linked and therefore, costs and savings are shared among the credits.

5. Discussion

Unlike previous studies focusing only on a single building service system, this research considered the interdependence of multiple building service systems and calculated their LCC using Hong Kong BEAM Plus as a case study. The results showed that there are many credits with lower LCCs. As illustrated in Figure 3, credits such as 'WUP1 Water quality survey', 'WU2 Monitoring and controlling', WU3 Water efficient irrigation and 'WU6 Water effluent discharge to foul sewer' are credits with lower LCCs in water use criteria with an influence on the sanitary and plumbing systems. Similarly, Burnett et al. (2008) also identified the water quality survey, monitoring and controlling and water efficient irrigation as credits with lower initial cost premium less than HKD4/m2. When analysing the other credits in water use criteria, 'WUP2 Minimum water savings performance' and 'WU1 Annual water use' incur LCC less than HKD 600/m2 while operating throughout the building life cycle. The lesser costs are due to the water savings from the appliances and the other systems in place. After developing a green LCC model for green buildings in Australia, Illankoon et al. (2019) also identified water efficient irrigation as one of the lower LCC options for water efficiency in certified green buildings. Figure 2 illustrates that all credits except 'EUP1 Minimum energy performance' have LCC lower that HKD 500/m2. Burnett et al. (2008) also illustrated that energy performance credit has the highest cost premium with HKD 36/m2 for an office building with a water cooled system. When considering the IEQ credits, 'IEQ2 Plumbing and drainage' credits have a higher LCC owing to the higher maintenance cost and lack of water savings attributed to the credit. Furthermore, 'IEQ1, Security' credit has the highest LCC not because of the expensive CCTV system but because of the guards required by the BEAM Plus rating tool.

The results show that a lot of savings due to energy savings, yet none of the credits could achieve net positive savings within the LCC the building. One of the reasons for this is the maintenance and replacement costs as discussed earlier in this paper. Therefore, it is evident that when designing for building services, it is important to focus on service maintenance also. Most of the designs have a significant focus on the life-cycle savings in terms of energy and water, yet it requires massive maintenance which dwarfs the net savings of the systems. Therefore, it is necessary to look into necessary maintenance costs when deciding for building services in the initial decision-making stages in green buildings.

One of the main highlights of this research is that interdependencies among credits are considered. When all the credits are considered for a period of 60 years, none of those credits gained a life cycle saving. The main reason is that the savings are apportioned among the relevant credits. There are many studies that illustrate significant savings in specific systems in GBs. However, it is necessary to note that, there are many supporting systems used to achieve that saving. As an example, using renewable sources such as PV panels can be a cost significant item. However, it contributes to many other GB credits. If the PV system is not considered due to the higher initial costs, the influence it has on other GB credits are also affected, which is rarely considered. This research intends to fill that gap. The LCC calculations looked into all the interdependent and inter-linked credits holistically.

There are many industry reports focusing on various savings from GB. For example, HKGBC (2017) illustrates various savings on energy, water and carbon emissions. However, according to the LCC calculations (See Figures 2,3, and 4), none of the credits can obtain net savings considering the building life-cycle. One of the reasons is the maintenance, operational and replacement costs. According to the literature, in the Malaysian context the operational costs amount to approximately 29% (including water costs) (Dwaikat and Ali, 2018b) and in the Canadian context operational and replacement cost added up to 50% of the total LCCs (Teshnizi et al., 2018). These figures illustrate the significance of maintenance and replacement costs in building life-cycle. These credits representing various building services could minimise the LCC through energy and water savings and reduce the impact of initial cost premiums. However, the maintenance and replacement costs have added up costs throughout to building life-cycle. Therefore, to obtain a holistic picture, it is necessary for the industry reports to provide an indication of operating, maintenance and replacement costs.

LCC has its boundaries. According to the ISO standard adopted for this LCC calculation, there are many savings in terms of carbon emissions when complying to the requirements of BEAM Plus rating tool (HKGBC, 2012). There is no such mechanism for the developers to claim these costs in monetary terms. When analysing the energy credits, there are many energy savings obtained throughout the life-cycle and there are many credits with lower LCCs (referring to Figure 2). If the reductions in CO_2 emissions can be directly monetised these savings can be added as a saving throughout the building life-cycle. For example, when a developer obtains 'EU1 Reduction pf CO_2 emissions', if there is a possibility for him to monetise that savings, it will be a significant enabler to reduce the LCC. Moreover, the developers will be more focused on gaining those points due to the financial benefits. Amidst the global trend of carbon trading, Lam et al. (2015) recommended setting up an emission exchange centre as a trading market covering Mainland China and Hong Kong. Recently, Hong Kong Shanghai Banking Corporation (HSBC) (2018) launched a new lending programme supporting the low carbon emissions in businesses and supply chains. Such programme can further encourage developers to truly embrace green building.

6. Conclusions

Building services are critical to any building, but they are particularly important to green building, as most of the sustainability deliverables such as energy consumption, water use, and indoor environment quality as prescribed by green building are directly contributed by them. Building service expenditure also represents a significant proportion of the cost that any green building developer and its consultants must carefully consider to optimise. This research critiqued that previous studies largely ignored the fact that building services are interdependent on each other in influencing sustainability goals. There exist opportunities to optimise some building services, like "killing two birds with one stone", to better achieve the overall performance of green building in terms of its efficiency and effectiveness. The research also argued that building services should be examined under a life cycle perspective as they are subject to effective operation and maintenance, which incur recurrent cost, throughout a building's life cycle. This research thus conducted a holistic cost benefit analysis of building services by considering both their interdependence and life cycle costing, with a view to recommending optimal building services design for green building. The Hong Kong BEAM Plus new buildings versions 1.2 was chosen for a case study.

It is discovered that, in the BEAM Plus, credits such as 'WUP1 Water quality survey', 'WU2 Monitoring and controlling', 'WU3 Water efficient irrigation', 'WU6 Water effluent discharge to foul sewer', 'EU1 Reduction of CO_2 emissions', 'EU6 Renewable energy systems', 'EU7 lighting system in carparks', 'EU11 Operations and maintenance', 'IEQ3 Biological sources of air pollution' and 'IEQ6 Outdoor sources of air pollution' have relatively lower life cycle costs in contributing to the sustainability goals of a green building. Designers can target more on these credits and their associated building services in optimising green building design. However, there are significant maintenance costs associated with building services. Therefore, it is necessary to look into building maintenance when designing for the building services at the initial stages of green building.

This research provides a fresh perspective to building services design within the context of green building exercise. The efforts of green building developers, designers, and consultants are diverted to building services and their interdependence with a life cycle costing perspective. Although the research adopted BEAM Plus as the case study, the analytical method as developed in this study can be applied to other green building rating tools for performing similar analyses. Future research can be conducted to compare these aspects across different green building rating tools. Future research is also recommended to use real-life green building operation data, should it be available, to verify the LCC analyses here, which are largely based on the attainable credits of a green building rating tool.

7. Acknowledgement

This research is partly supported by the Hong Kong Research Grants Council (RGC) General Research Fund (GRF) (Project No.: 17201917).

8. References

ARCHITECTURAL SERVICES DEPARTMENT HONG KONG 2016. Schedule of rates for term contracts for building works.

ASHWORTH, A. 1989. Life-Cycle Costing: A Practice Tool? *Cost Engineering,* 31**,** 8.

AUSTRALIAN NATIONAL AUDIT OFFICE 2001. Life cycle costing - Better practice guide.

BRILLER, D. & HAMILTON, B. 2011. Using leed® to facilitate the eisa goal of zero fossil fuel use in new federal buildings. *Strategic Planning for Energy and the Environment,* 30**,** 7-70.

BRILLER, D. L. Using LEED® to facilitate the eisa goal of zero fossil fuel use in new federal buildings. World Energy Engineering Congress 2009, WEEC 2009, 2008. 583-623.

BURNETT, J., CHAU, C., LEE, W. & EDMUNDS, K. 2008. Costs and financial benefits of undertaking green building assessments.

CHENG, Q., WANG, S. & YAN, C. 2016. Robust optimal design of chilled water systems in buildings with quantified uncertainty and reliability for minimized life-cycle cost. *Energy and Buildings,* 126**,** 159-169.

DE WILDE, P. 2014. The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction,* 41**,** 40-49.

DELL'ISOLA, A. J. & KIRK, S. J. 2003. *Life cycle costing for facilities : economic analysis for owners and professionals in planning, programming, and real estate development : designing, specifying, and construction, maintenance, operations, and procurement,* Kingston, MA, Kingston, MA : Reed Construction Data.

DWAIKAT, L. N. & ALI, K. N. 2018a. The economic benefits of a green building–Evidence from Malaysia. *Journal of Building Engineering,* 18**,** 448-453.

DWAIKAT, L. N. & ALI, K. N. 2018b. Green buildings life cycle cost analysis and life cycle budget development: Practical applications. *Journal of Building Engineering,* 18**,** 303-311.

EICHHOLTZ, P., KOK, N. & QUIGLEY, J. M. 2010. Doing well by doing good? Green office buildings. *The American Economic Review,* 100**,** 2492-2509.

EPSTEIN, M. J. 1996. *Measuring corporate environmental performance: Best practices for costing and managing an effective environmental strategy,* Chicago, Irwin Professional Publishing.

GAO, X., KIM, Y. & LEE, H. W. 2014. Life-cycle Cost Analysis of Using Rainwater Harvesting Systems in Hong Kong Residential Buildings. *Journal of the Korean housing association,* 25**,** 53-62.

GOH, B. H. & SUN, Y. 2015. The development of life-cycle costing for buildings. *Building Research & Information***,** 1-15.

GREEN BUILDING COUNCIL AUSTRALIA 2013. Introducing Green Star. Green building council Australia, .

GREEN BUILDING COUNCIL OF AUSTRALIA 2013. The value of Green Star - A decade of environmental benefits. Green building council Australia.

HKGBC 2012. BEAM Plus New Buildings. Version 1.2 HKGBC [HKGBC].

HKGBC 2017. Hong Kong: Green building in action.

ILLANKOON, I. M. C. S., TAM, V. W. Y., LE, K. N. & SHEN, L. 2017. Key credit criteria among international green building rating tools. *Journal of Cleaner Production,* 164**,** 209-220.

ILLANKOON, I. M. C. S., TAM, V. W. Y., LE, K. N. & WEERAKOON, S. V. 2019. Life-cycle cost model for green star office buildings in Australia. *In:* KAPARAJU, P., HOWLETT, R. J., LITTLEWOOD, J., EKANYAKE, C. & VLACIC, L. (eds.) *Smart Innovation, Systems and Technologies.*

ISO [ISO] 2017. Buildings and constructed assests - Service life planning. *Part 5: Life cycle costing.* Switzerland: International Standard Organisation [ISO],.

KALE, N. N., JOSHI, D. & MENON, R. 2016. Life cycle cost analysis of commercial buildings with energy efficient approach. *Perspectives in Science,* 8**,** 452-454.

KATS, G., ALEVANTIS, L., BERMAN, A., MILLS, E. & PERLMAN, J. 2003. The costs and financial benefits of green buildings. *A Report to California’s Sustainable Building Task Force. USA.*

KIM, J., HONG, T., JEONG, J., KOO, C. & JEONG, K. 2016. An optimisation model for selecting the optimal green systems by considering the thermal comfort and energy consumption. *Applied Energy,* 169**,** 682-695.

LAM, P. T. I., CHAN, E. H. W., YU, A. T. W., CAM, W. C. N. & YU, J. S. 2015. Applicability of clean development mechanism to the Hong Kong building sector. *Journal of Cleaner Production*, 109**,** 271-283.

LOU, S., LI, D. H., CHAN, W. W. & LAM, J. C. 2017. Life-cycle analysis of photovoltaic systems in Hong Kong. *Journal of Renewable and Sustainable Energy*, 9**,** 045901.

RAWLINSONS 2017. Australian construction Handbook,. Perth, Western Australia: Rawlinson publishing.

RIDER LEVITT AND BUCKNELL (RBL) 2018. Quarterly construction cost update, Hong Kong. Hong Kong: Rider Levitt and Bucknell (RBL).

ROBINSON, A. P., CHEN, V. C. P., FERREIRA, S. & KUNG, P. A study of Multivariate Modeling for a multiple-stage, multiple-objective (MSMO) decision-making framework for "Green Building". World Energy Engineering Congress 2012, WEEC 2012, 2012. 1455-1473.

ROYAL INSTITUTE OF CHARTERED SURVEYORS (RICS) 2007. New rules of measurement (NRM2). London.

ROYAL INSTITUTE OF CHARTERED SURVEYORS (RICS) 2012. Elemental Standard Form of Cost Analysis Principles, Instructions, Elements and Definitions London.

SELLERS, D. A. 2005. Rightsizing air handlers for lowest life-cycle cost. *HPAC Heating, Piping, AirConditioning Engineering*, 77**,** 26-34.

SINGH, A., SYAL, M., KORKMAZ, S. & GRADY, S. 2011. Costs and benefits of IEQ improvements in leed office buildings. *Journal of Infrastructure Systems*, 17**,** 86-94.

TAM, V. W. Y., LE, K. N., ZENG, S. X., WANG, X. & ILLANKOON, I. M. C. S. 2017. Regenerative practice of using photovoltaic solar systems for residential dwellings: An empirical study in Australia. *Renewable and Sustainable Energy Reviews*, 75**,** 1-10.

TESHNIZI, Z., PILON, A., STOREY, S., LOPEZ, D. & FROESE, T. M. 2018. Lessons Learned from Life Cycle Assessment and Life Cycle Costing of Two Residential Towers at the University of British Columbia.

TRADING ECONOMICS. 2018a. *Hong Kong inflation rate* [Online]. Available: //tradingeconomics.com/hong-kong/inflation-cpi [Accessed 30 December 2018].

TRADING ECONOMICS. 2018b. *Hong Kong interest rates* [Online]. Available: https://tradingeconomics.com/hong-kong/interest-rate [Accessed 30 December 2018].

WATER SUPPLIES DEPARTMENT 2011. Total eater management water reclamation initiatives: grey water reuse and rainwater harvesting systems in new developments. Hong Kong.

WORLD GREEN BUILDING COUNCIL 2013. The business case for green buildings.

ZHANG, X. 2015. Green real estate development in China: State of art and prospect agenda—A review. *Renewable and Sustainable Energy Reviews,* 47**,** 1-13.

Appendix 1: LCC for credits

Energy credits	**Life-cycle cost (HKD/GFA)**	**IEQ credits**	**Life-cycle cost (HKD/GFA)**
EUP1 Minimum energy performance (for air cooled system)	3,018.50	IEQP1 Minimum ventilation performance - AC	571.99
EU2 Minimum energy performance (for water cooled system)	3,035.16	IEQP1Minimum ventilation performance- WC	575.60
EU3 Reduction of CO2 emissions	58.90	IEQ1 Security	2,390.71
EU4 Peak electricity demand reduction	236.11	IEQ2 Plumbing and drainage	884.76
EU6 Ventilation systems in carparks	327.05	IEQ3 Biological contamination-AC	98.31
EU7 Lighting systems in carparks	48.42	IEQ3 Biological contamination-WC	127.09
EU8 Renewable energy systems	73.62	IEQ6 Outdoor sources of air pollution-AC	143.00
EU10 Testing and commissioning*	220.00	IEQ6 Outdoor sources of air pollution-WC	143.90
EU11 Operations and maintenance*	20.00	IEQ7 Indoor sources of air pollution-AC	228.80
EU12 Metering and monitoring	79.22	IEQ7 Indoor sources of air pollution-WC	230.24
Water credits		IEQ8 IAQ in carparks	218.03
WUP1 Water quality survey*	2.00	IEQ9 Increased ventilation - AC	285.99
WUP2 Minimum water saving performance	247.91	IEQ9 Increased ventilation - WC	287.80
WU1 Annual water use	495.81	IEQ11 Localised ventilation - AC	200.20
WU2 Monitoring and controlling	73.06	IEQ11 Localised ventilation - WC	201.46
WU3 Water efficient irrigation	7.51	IEQ12 Ventilation in common areas -Ac	343.19
WU4 Water recycling	959.12	IEQ12 Ventilation in common areas - WC	345.36
WU6 Effluent discharge to foul sewer	13.02	IEQ13Thermal comfort -AC	714.98
		IEQ13 Thermal comfort -WC	719.50
		IEQ14 Interior lighting - normally occupied areas	1,210.38
		IEQ17 Interior lighting - not normally occupied areas	193.66

*- credits with initial cost only