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Comparative life-cycle cost (LCC) study of green and traditional industrial buildings in Sri Lanka

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ABSTRACT

The demand for green buildings is growing, but the trend is below the expected level due to the perceived higher construction cost required by building investors. In addition, the industry or the practitioners knowledge and awareness of major operational cost savings of facilities is questionable. on that note, this study aims to establish the cost implications of green buildings via a comparative life-cycle cost analysis of two green certified industrial and one traditional building. The industrial sector is one of the largest energy consuming sectors in the world with over 50% of the world's total delivered energy is absorbed by the sector. Energy consumption of industrial sector is likely to increase more due to the economic and population growth.The data for the analysis were extracted from construction, operation, and maintenance expenditure budget records of the selected organisations. The analysis shows that in terms of life-cycle costs, green industrial buildings are 17% cheaper than that of traditional buildings. Though the initial construction cost of a green industrial building is 29% higher, the operation and maintenance costs of green buildings result in 23% and 15% overall savings throughout the life cycle. The findings provide further empirical proof of the benefits of green buildings, especially in industrial manufacturing where it is expected to improve future uptakes and consequently the achievement of sustainable development initiatives.

1. Introduction

The building and construction industry has an increasing implication on global resources consumption. According to International Energy Agency [IEA] and the United Nations Environment Programme [UNEP] [13], buildings consume about 36% of global energy and produce 40% of Green House Gas (GHG) emissions. In addition, the primary energy demand has reached the largest annual increase (2.3%) in year 2018 since 2010 due to the increased energy demand by China, the United States, and India, where those countries accounted for 70% of the total energy demand growth globally. Although the demand for renewable energy has ever-growing since 2010, the share of fossil fuels is still above 80% in global primary energy demand [13]. For example, the building sector in the European Union handles 40% of fossil fuels based energy [41]. In another study, Diao, Sun, Chen, and Chen [42]highlighted that in the United States, 50% of natural gas is consumed by the building sector. In this end, sustainable development in the build environment has become a prime concern that has the ability to maintain ecological balance in the environment while avoiding the depletion of natural resources and other negative impacts of the construction industry [43–45].

Green building (GB) has emerged as the flagship of sustainable development to achieve the three pillars of the sustainable development: social, environmental and economic or the triple bottom line [46,47]. Thus, the modern-day buildings are expected to be 'green' by incorporating sustainable features in the form of sustainable sites, energy efficiency, water afficiency, sustainable material and resources, improved indoor environment quality, and health and productivity [15,39]. On the other hand, this also gives the impression that GBs are being "created using processes that are environmentally responsible and resource-efficient throughout the buildings' life-cycle", that expands and complements the classical building design concerns of economy, utility, durability, and comfort [35].

It was found that GBs save operational costs, energy consumption, and CO_2 emissions by 19%, 25%, and 36% respectively compared to traditional buildings [32]. Furthermore, GBs reduce carbon emissions by 35%, water usage by 40%, energy usage by 50%, and solid waste by 70% [2]. GBs are built with reused and recycled materials that mitigate the environmental impacts from construction and demolition waste [37]. Further, the utilisation of sustainable land use for GBs improve the urban biodiversity and protect the eco-system [10]. GBs also provide many social benefits beyond environmental and economic benefits such as ensure occupant well-being and health, and improve work-

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place productivity [48]. In fact, GB shows an increase of 25% of productivity and a significant reduction in absenteeism rate of employees compared to a traditional building [27].

Despite the benefits of GBs, the progress of construction industry's transition to GB technologies is still low [49]. Nelms, Russel and Lence [23] indicated that the slow progression to GB construction is due to the high initial construction costs and long payback periods of investments into GB technologies, especially due to active green design features which are high contributor to cost premium of GBs than passive features. On this note, Zhang, Platten and Shen [38] concluded that solar PV and heat pump technologies were comparatively more expensive to implement than the low-E window, insulation and solar heating appliances in GBs in China. Similarly, other studies reported that the acquisition of green technologies such as photovoltaic systems, redundant mechanical systems, geothermal strategies, incur expensive cost additions for GBs [21,26]. However, Aziz and Adnan[50] and Bartlett and Howard [51] commented that GBs generally operate more passively, are more energy and water efficient, require less or smaller plant and equipment to service them with commensurate less resources for their construction, and tend to be simpler to operate.

Some studies suggest that, the construction cost of GBs is not higher than traditional buildings. For example, Fullbrook, Jackson, and Finlay [8] concluded that the initial cost of GBs is 15% less than that of traditional buildings, based on a cost comparative analysis of a single academic building in New Zealand. Authors conclude that the purely sustainable features of a building add around 2–6% to the cost, compared with a traditional building. Moreover, a cost comparative analysis performed in the context of New Zealand shows that the construction of green and traditional office buildings have no significant cost difference [26]. In another cost comparison of a green bank building with a traditional building, Mapp, Nobe and Dunbar [21] estimated that there is no significant cost difference between the two buildings. However, Morris and Langdon [52] stressed that it is easier to assess the cost of active green features in comparison to traditional features, whereas assessing the added cost of passive features such as improved day lighting through good orientation and space planning is virtually impossible.

On another note, Dwaikat and Ali [5]) emphasised that there is very little evidence to support the argument that the cost of GBs is less than traditional. The results of several studies show that there is a premium cost attached to GBs which hinders their extensive application in different jurisdictions [19,29,38]. Those studies analysed the initial cost of green compared to traditional buildings, came up with a wide range of cost data. For instance, Ahn and Pearce [1] surveyed 87 construction-related firms and found that green was 5 to 10% higher than constructing a traditional building. Further, Houghton, Vittori, and Guenther [11] found that the initial cost of green healthcare buildings was up to 5% higher than traditional buildings. Studies in the US found higher initial costs of green school buildings ranging from 0% up to 18% [15]. However, a Sri Lankan study evidenced through a survey that the construction cost of green was estimated to be 20 to 25% higher than that of traditional buildings [2]. Furthermore, Kim, Greene and Kim [17] found that the initial cost of green residential buildings is 10.77% higher than that of traditional buildings. Therefore, the additional cost and the extra time involved in integrating green technologies have become the bottleneck problem for GBs.

The foregoing review indicates that the previous studies have analysed the green implications on construction cost of different types of building such as office, residential, healthcare, school, and bank. The investigation into industrial buildings has received less attention. Zuo and Zhao [39] hold a similar view on the need for research on industrial buildings, indicating that the majority of previous studies related to GB costs focused on commercial buildings such as offices. In the context of the industrial manufacturing sector, there is a growing interest on carbon–neutral products and reducing environmental impacts in the industrial process [53]. However, the manufacturing system is typically carried out in isolation and the industrial building and the services are considered to be supplementary to these operations [54]. Furthermore, the energy consumption of major building services such as heating, ventilation, and lighting in industrial sectors are difficult to differentiate from process related consumption [55] . Therefore, the GB concept is contemporary in industrial buildings as it plays a major role in moving society towards more resource-efficient industrial systems [57].

The industrial sector is the second largest sector contributing to the econmy of Sri Lanka with a share of Gross Domestic Product (GDP) of 27.4% in 2019 [56]. In addition, manufacturing industries are facing pressing challenges from stakeholders and national and international regulators to reduce the environmental impacts of their industrial activities. Therefore, an understanding of the asscociated cost of green industrial buildings throughout the life-cycle will benefit developing countries like Sri Lanka to implement green at an industrial level, where industrial manufacturing is a prime sub-sector of the economy. This study compares the life-cycle costs (LCC) of green and traditional industrial buildings to establish the potential for LCC savings over the higher initial cost of GBs. This research is expected to provide a valuable reference for industry practitioners to broaden their understanding of the significant GB technologies and its contribution to construction cost and running cost savings.

2. Literature review

2.1. Life-cycle cost of GBs

A line of arguments often presented to support the construction of GBs is that of the lower operational cost of this category of buildings. Although the initial cost of GBs may be high, subsequent costs such as operation and maintenance of GBs are lower than traditional [7]. For example, Kats et al. [16] reported that while the construction cost of gold-certified office buildings reaches a maximum of 16% higher than that of traditional buildings, its energy use was reduced by 33% on average. Kats et al. concluded that energy cost saving over 20 years outweighed the initial cost paid to construct GBs. Similarly, Kats [14] analysed 30 green gold-certified school buildings that were built in 10 different states over a period of five (05) years and indicated that the cost of schools is only 2% higher than that of traditional buildings, and that GBs offer benefits that are 20 times as large over a 20 year period. Savings in health and productivity costs due to increased earnings, reduction in respiratory diseases, and higher employee retention made up to 85% of total whole life cost savings, with savings in energy, water, and waste contributing to the remaining 15%. However, those studies limited the assessment mainly to cost savings due to energy use, and savings on water, waste, health, and productivity. Cost savings due to maintenance and other operating costs, namely administrative, insurance and taxes were largely ignored.

Giving due consideration to the LCC of GBs enables investors to identify the cost reduction benefits and value-added benefits of GBs. According to BS ISO 15686–5:2008 standard, the costs components of LCC includes construction, operation, maintenance and endlife.

A life-cycle approach should be considered to promote green construction while assessing the relevant costs of green [30]. Similarly, Zuo and Zhao [39] emphasised that the studies on economic aspects of GBs are comparatively lean, while a vast majority of existing studies highlight their importance. Further, Zuo et al. [40] reviewed the existing literature relating to GB evaluation focusing mainly on a life-cycle perspective and concludes that the uptake of LCC in the construction industry is rather slow. The authors further recommended the simplified methods of assessment for use in the early design phase to acknowledge which cost impacts are most important to consider.

LCC analysis of green was partially conducted considering different aspects of GBs. For example, Tam, Senaratne, Le, Shen, Perica and Illankoon [31] analysed the LCC of different timber alternatives to apply when constructing green residential buildings and recommended using sustainable timber applications that have LCC savings. Another study, Illankoon, Tam, Le and Wang [12] analysed LCC for concrete credit points of the Green Star rating tool in Australia and suggests supplementary cementitious materials (SCMs) in cement for the use in GBs. From LCC perspective, Dwaikat and Ali [6] estimated the life-cycle budget of a GB. They allocated 22% for design and construction cost, 48% for building energy cost, 2% for the building water and sewerage cost, another 27% for building maintenance cost, and only 1% for the endlife cost.

3. Methods

The research was conducted using quantitative data collection and comparative data analysis techniques. LEED has been in practice in Sri Lanka, even before the GREENSL® rating was introduced by the Green Building Council in Sri Lanka (GBCSL) in 2010. There are 37 certified buildings under GBCSL, where only 5 out of 37 are industrial manufacturing buildings [9]. However, LEED certification confirms that 102 buildings have been registered to-date and 51 (50%) of which have been green certified. Of which, 23 are industrial buildings. This provides the rationale for the selection of LEED certified GBs in Sri Lanka.

Table 1 presents the profile of LEED-certified GBs, which includes types of green spaces and the distribution of industrial manufacturing certified with different LEED certification systems. As observed from Table 1, the majority of green spaces, 23 (out of 51), are industrial manufacturing facilities in Sri Lanka, while the remaining green spaces includes office, lodging, retail, warehouse, higher education, laboratory, and apartment facilities. Considering the green industrial manufacturing facilities certified, the largest sample, 13 (out of 23) new buildings were certified under the LEED BD + C: NC (v3 −2009) rating system. The rating systems: LEED O + M: EB (v3) and LEED O + M: EB (v2) are used for the assessment of existing buildings. Globally, green industrial buildings have not been in the spotlight. Therefore, the current study focused the LCC analysis of green industrial buildings in Sri Lanka.

The comparative analysis requires the selection of buildings that are similar in terms of their characteristics which influence the LCC, in order to obtain reliable and accurate results. The profile information of the green and traditional buildings selected for the current study is given in the next section of this paper.

Table 1
Profile of LEED Certified GBs in Sri Lanka.

LEED Certified GBs	Categories	Number
Green Space Types	Industrial Manufacturing	23
	Office	10
	Lodging	7
	Warehouse and Distribution	3
	Retail	3
	Higher Education	2
	Laboratory	2
	Apartment	1
	Total	**51**
Industrial Manufacturing Buildings	LEED BD + C: NC (v3)	13
	LEED O + M: EB (v3)	5
	LEED BD + C: NC (v2)	3
	LEED O + M: EB (v2)	1
	LEED BD + C: NC (v4)	1
	Total	**23**

Adapted from: [34].

The document survey which considers administrative records and documents was used to retrieve the cost data required for the current study. The cost data related to construction, annualised and periodic operation and maintenance (O&M), residual value and GB cost savings were collected from construction and O&M expenditure budget records, while referring to standard cost elements classified by the RICS new rules of measurement (NRM) 01 and Building Maintenance Costs Information Service (BMCIS). In terms of cost comparisons of major LCC elements, the current study excludes land acquisition cost (non-construction costs) and scheduled major repairs and replacements during the building running stage.

Net Present Value (NPV) analysis was used to measure the LCC of buildings. As guided in the International Standard ISO 15686–5:2008, all the costs were escalated at an assumed inflation rate and then discounted for the base year considering 5.5% inflation and a 4.26% discount rate, respectively. These rates were obtained from the Central Bank of Sri Lanka [4]. The analysis was was performed for 50 yeras for all buildings. Subsequently, a sensitivity analysis was performed for alternative analysis periods and discount rates.

3.1. Profile of selected green and traditional buildings

The current study compares the LCC of GBs with similar traditional industrial buildings in Sri Lanka to establish green implications on LCC of industrial buildings. For this reason, the study engaged three (03) green-certified garment buildings certified with LEED BD + C NC (V3) rating system.

Following the selection of GBs, a traditional building with similar physical and performance characteristics such as year of construction, number of floors, shape, Net Internal Area (NIA), designed life-cycle, building height, number of occupants, building envelope, orientation, climate and location of the above green industrial buildings, were selected to distinguish the green implication on LCC. Table 2 presents the profile of the selected four (04) buildings.

As shown in Table 2, in terms of building characteristics, the size and shape of the buildings, and type or function are almost similar for all selected buildings. However, one GBs were constructed in 2010, while other two (02) GBs and the traditional building were constructed in 2013. Further, in terms of their structure, the selected GBs are formed with steel frame while the traditional is with concrete structure. This difference would expect to have implications on embodied energy consumption and CO2 emissions, construction cost and residual value. Selected buildings used metal roofs (Galvanized sheets) and fibre cement roof with silver foil roof insulation that have lightweight, reflective and recyclable material qualities. However, the GBs also include concrete decks upto some extent to accomadate the GB technologies such as solar water heating and green roofs. Considering the building walls, GBs have used low thermal conductive materials with low emmisitive and heat reflective glasses, while the traditional building used concrete framework and concrete blocks and bricks for the walls. Therefore, GBs have high content of recyclable, regional and environmental friendly materials such as steel, glass and compressed stabilized-earth blocks, whereas the traditional building has more concrete content that have higher embodied carbon. Overall, it could be considered that the embodied energy consumption and CO$_2$ emissions of the selected buildings could be varied, due to their structural differences. However, the study excludes the environment cost of the buildings and only considers the initial construction cost, operation, maintenance and end of LCC [3]. These profile information allow a rational comparison of running costs between GBs and that of traditional buildings.

Table 2
Profile of the Selected Buildings.

	Building	GB 1	GB 2	GB3	CB
Building Characteristics	Year of construction	2010	2013	2013	2013
	Type of LEED certification	LEED BD + C: NC (v3) Gold	LEED BD + C: NC (v3) Gold	LEED BD + C: NC (v3) Gold	–
	No. of floors	2	1	1	1 + Mezzanine floor
	Shape	Rectangular	Rectangular	Rectangular	Rectangular
	NIA (m2)	4,515	3,809	3,567	4,032
	Storey height (m)	3.9	4.2	4.5	3.9
	Building height (m)	7.8	4.2	4.5	7.8
	Type of structure	Steel frame	Steel frame	Steel frame	Concrete frame
	Roof structure	High pitched gabled roof + Flat roof	High pitched gabled roof + Flat roof	High pitched gabled roof + Flat roof	Low pitched roof
	Roof material	Metal roof + 1,757 sq. ft. concrete deck for green roofs	Metal roof + 200 sqft concrete deck for solar water heating	Metal roof + 1,757 sqft concrete deck for green roofs	Fibre cement sheet
	Roof insulation	Foil insulation	Foil insulation	Foil insulation	Foil insulation
	Type of wall	Walls with a layer of Polystyrene Forms, steel mesh and concrete and low-e tempered glass windows	Compressed stabilized-earth block wall and plate glass (heat reflective coatings) and aluminum frames for windows	Walls with a layer of Polystyrene Forms, steel mesh and concrete, and Low-E tempered glass windows	Concrete blocks and bricks and glass windows
Geography	Orientation	East-west	East-west	East-west	Northeast-Southwest
	Glazing orientation	North-South	North-South	North-South	Northwest-Southeast
	Location	Southern	Western	Western	Western
	Climate condition	Tropical	Tropical	Tropical	Tropical
Performance	No. of building occupants	1320	1,400	1310	1,340
	Building occupancy profiles	5 working days from 8 am to 6 pm	5 working days from 8 am to 6 pm	5 working days from 8 am to 6 pm	5 working days from 8 am to 6 pm
	Maintenance cycle	Scheduled	Scheduled	Scheduled	Scheduled
	Cleaning cycle	Daily	Daily	Daily	Daily
	Type of function	Garment	Garment	Garment	Garment
	Water consumption (m3 per month)	1,063	1,375	363	2,104

Building	GB 1	GB 2	GB3	CB
Electricity consumption (kWh per month)	113,408	98,005	109,398	139,881
Energy consumption for cooling (kWh per month)	95,688	63,703	65,638	97,916

3.2. Green technologies implemented in the selected buildings

The selected buildings were green certified according to the LEED rating system that incorporates green technologies under various sustainable features such as sustainable sites (SS), water efficiency (WE), energy and atmosphere (EA), materials and resources (MR) and indoor environmental quality (IEQ) [33]. GBs selected for the current study have incorporated the following green technologies as summarised in Table 3.

As seen from Table 3, all buildings have implemented similar types of GB technologies under each sustainable features. However, in terms of WE feature, GB1 and GB3 includes more technologies that save water consumption compared to GB2. In the GB 3, sewage and waste water is treated with anaerobic treatment plants and the treated water is used for toilet flushing through a dual-flush system. Further, the rainwater and run off water is collected to a pond and used for gardening purpose. Similarly, GB1 and GB2 includes EA technologies such as solar water heating, sewing machines with direct-drive servo motors and a BAS system to optimise the energy performance. However, all GBs do not include renewable energy technologies such as solar power, biomass, wind turbines, etc.

4. Results

4.1. Construction cost

The construction works for the selected four (04) buildings were completed in 2010 and 2013. However, year 2018 was considered as base year for the LCC analysis and the construction costs of the buildings were converted to 2018 prices using the tender price indicies for year 2010, 2013 and 2018. In conducting the analysis, NRM 1 was used as a reference to identify the construction cost elements. According to NRM 1, the construction cost of buildings consists of facilitating work, building work, main contractor's preliminaries, main contractor's overheads and profit, project/design team fees, other development/project costs, client's contingencies, and taxes. Except the cost of facilitating and building works, the rest of the cost items were labelled as “Other costs”. The “cost of LEED certification” includes LEED registration fee, documentation costs, LEED consultancy, hiring LEED accredited professionals, etc.

As seen in Table 4, amongst the major construction cost elements, building work is the main contributor, contributing 77% and 80% to the total construction cost of green and traditional buildings respectively. On average, an additional cost of 9% of total construction cost is attributed to achieving LEED green certification. However, overall there is a difference of 29% between total construction cost of GBs and traditional building and the increased cost is due to structural materials used and the sustainable features implemented in these GBs. The steel structure and the glazing windows in the GBs require high cost compared to traditional concrete structure and walls made out of concrete blocks and bricks. The high cost of GB technologies such as sewage treatment plants (STPs), low flow fixtures for toilets and urinals, waterless urinals, dual plumbing, building automation system (BAS), low-e double glazing, solar water heating, electric refuelling stations, and sky lighting and other low cost GB technologies have been applied in the selected GBs, the cost of implementing these technologies caused to increase the construction cost of GBs reflected in increase of building works and facilitating works.

4.2. Operation and maintenance costs (O & M)

According to the BMCIS classification, the building operation costs include insurance, utility, and administrative costs and taxes. Similarly, maintenance costs include the cost of fabric and decorations, building services, cleaning and external works, and repairs and replacement of minor systems/components. The insurance and taxes were considered as “other costs”. The present values of O&M costs were calculated at the discount rate of 4.26% for the analysis period of 50 years (the base year being 2018) using the O&M costs data collected from three (03) buildings, then normalised into cost per m2 of NIA and per head/occupant. Table 5 presents the normalised O&M unit costs.

As observed from the table, the operation to maintenance cost is approximately in the ratio of 80:20 in both green and traditional buildings. However, the cost of sub-elements of O&M differ between green and traditional buildings and within GBs due to integration of sustainable features.

The utility cost contribute significantly to total operation costs in both green and traditional buildings. However, there is a considerable saving in utilities cost in GBs over traditional buildings. This could be attributed to integrated green technologies as evidenced in Table 3. Although similar types of energy efficiency measures have been incorporated in the both GBs, the GB1 has higher utilities charges per head than GB2 and this could be due to large building area with increased building height. This is further supported by the performance data presented in Table 2 where electricity consumption and energy consumption for cooling are less in GB2 than GB1 which is less than CB. Similarly, it is to be noted that the saving in administrative cost of GBs are influenced by the integration of technologies belong to sustainable features of alternative transportation and construction of IAQ management plan. In addition, the building parameters such as number of occupants and services availability are partly responsible for differences in administrative cost. This is evidenced through increases in administrative cost with increase in number of occupants.

The comparison of maintenance cost shows that the services maintenance is the main contributor to maintenance cost of both green and conventional buildings. Similarly, the repairs and replacement is the second most significant element contributing to GBs’ maintenance cost. However, the comparison of services maintenance cost between the GBs shows a significance difference (over 50%) which could be attributed to differences in availability of services in the selected buildings. It is to be noted that the technologies implemented under indoor chemical and pollutant source control and construction waste management (Table 3) have contributed to huge saving in cleaning and external works in both GBs . Similarly, use of recycled materials has contributed

Table 3
Green Technologies implemented in the seleced buildings.

Sustainable Features	Sustainable Criteria	Green Technologies	GB1	GB2	GB3
SS	Development density and community connectivity	On-site conveniences in essential services	✓	✓	✓
	Alternative transportation	Bike racks and changing rooms	✓	✓	✓
		Provide transportation to work	✓	✓	✓
		Vehicle parking accessability	✓	✓	✓
		Low emitting and fuel-efficient vehicles with electric refuelling stations	✓		✓
	Site development - protect or restore habitat	Planting native species that require little maintenance		✓	✓
		Maximising the open space and designing and construction of the building in a location near wetlands or natural ponds.		✓	
	Heat island effect	Changing the colour of concrete paving and adding shade elements	✓		✓
		All roads, walks, and terraces are paved with cement-stabilized earth	✓	✓	
		Green roof	✓	✓	
		Photovoltaic roof	✓		✓
		Lightwait metal roof	✓	✓	✓
WE	Water efficient landscaping	High efficiency irrigation using reclaimed water	✓	✓	✓
		Storm water run-off - natural drainage such as grass paving and planted storm water retention areas	✓	✓	
		Storm water run-off - native plants, tall grasses, and shrubs	✓	✓	✓
	Innovative waste water technologies	Sewage treatment plants (STP)	✓		✓
		Waste water treatment plant			✓
		Rainwater harvesting			✓
	Water use reduction	Waterless urinals	✓		✓
		Low flow fixtures for toilets and urinals	✓	✓	
		Dual plumbing system	✓		✓
EA	Optimize energy performance	Energy-efficient lighting/plugs: high-efficiencyT5 tubes and LED lamps,	✓	✓	✓
		Insulations		✓	✓
		Low-e and heat reflective glazing		✓	✓
		Solar water heating	✓	✓	

Sustainable Features	Sustainable Criteria	Green Technologies	GB1	GB2	GB3
		Use of energy meters on major mechanical systems and sub-metering for all systems	✓	✓	✓
		Sewing machines with direct-drive servo motors	✓	✓	
		Building automation/ management systems		✓	
		Time-scheduled control of lighting	✓	✓	✓
	Refrigerant management	HVAC system with reduced refrigerant charge and increased equipment life	✓	✓	✓
MR	Construction waste management	Use of construction debris in the sub-base for paving on the site, recycle construction waste	✓	✓	✓
	Use of recycled content	Steel and glazing	✓	✓	✓
	Regional materials	Compressed stabilized earth block		✓	
	Renewable Materials	Bamboo	✓	✓	✓
IEQ	Outdoor air delivery monitoring	Installing CO_2 and airflow measurement equipment and feeding the information to the heating, ventilating and air conditioning (HVAC) system and building automation system (BAS).	✓	✓	✓
	IAQ plan during construction	Topsoil segregation for reuse, stabilizingplants, silt traps, and stormwater-collection ponds to prevent soil erosion	✓	✓	✓
	IAQ plan before occupancy	Two-week flush-out with outdoor air	✓	✓	✓
	Low emitting materials	Floor finishes include polished concrete tile, rendered and cut concrete, tile, and wood	✓	✓	✓
	Indoor chemical and pollutant source control	Nonhazardous finishes and materials: Bamboo, gypsum board and tabletops MDF	✓	✓	✓
	Lighting	Occupant controls for lighting and task lighting	✓	✓	✓
	Thermal comfort design and verification	Energy-efficient mechanical cooling (evaporative cooling, adjustable diffusers)	✓	✓	✓
		Passive cooling using buiding orientation, massing, controlled fenestration and ventilation, shading, thermal mass and solar reflective roofs.	✓	✓	✓
	Lighting and views	Daylighting, sky lighting	✓	✓	✓

Table 4
Construction cost of green and traditional buildings.

Construction Costs Elements	Cost (LKR)										Saving
	GB 1	%	GB 2	%	GB 3	%	Avg. GB	%	CB	%	
Building Works	260,050,455	81	225,732,767	74	217,118,354	75	234,300,525	77	189,758,016	80	23
LEED Certification	23,103,255	7	35,427,509	12	25,000,000	9	27,843,588	9	0	0	0
Other Costs	15,093,645	5	26,483,977	9	30,000,000	10	23,859,207	8	29,082,816	12	−18
Facilitating Works	22,642,725	7	18,245,110	6	17,100,000	6	19,329,278	6	17,833,536	8	8
Total Construction Cost	**320,890,080**	**100**	**305,889,363**	**100**	**289,218,354**	**100**	**305,332,599**	**100**	**236,674,368**	**100**	**29**
Cost per m ^{2}	**71,072**		**80,307**		**81,082**		**77,033**		**58,699**		**31**

Table 5
Operation and Maintenance Costs of Green and Traditional Buildings.

O & M Costs Elements	Cost (LKR)										Saving
	GB 1	%	GB 2	%	GB 3	%	Avg. GB	%	CB	%	
Operation Cost	**1,845,880,995**	**82**	**1,321,882,978**	**83**	**1,190,268,663**	**83**	**1,452,677,545**	**84**	**1,894,709,376**	**84**	**−23**
Cost per m ^{2}	**408,833**		**347,042**		**333,689**		**366,468**		**469,918**		**−22**
Cost per occupant	**1,398,395**		**944,202**		**908,602**		**1,081,666**		**1,413,962**		**−24**
Utilities	929,579,805	50	573,921,075	43	467,587,329	39	657,029,403	53	934,166,016	49	−30
Administrative Cost	750,799,350	41	403,567,359	31	417,806,277	35	524,057,662	37	512,705,088	27	2
Other Costs (insurance and taxes)	165,501,840	9	344,394,544	26	304,875,057	26	271,590,480	9	447,838,272	24	−39
Maintenance Cost	**402,534,825**	**18**	**262,657,213**	**17**	**239,991,327**	**17**	**301,727,788**	**16**	**353,860,416**	**16**	**−15**
Cost per m ^{2}	**89,155**		**68,957**		**67,281**		**76,117**		**87,763**		**−13**
Cost per occupant	**304,951**		**187,612**		**183,199**		**224,667**		**264,075**		**−15**
Services	155,925,525	39	98,397,897	37	104,498,832	44	119,607,418	33	148,538,880	42	−19
Fabric & decoration	72,181,305	18	126,108,372	48	96,077,145	40	98,122,274	19	129,241,728	37	−24
Cleaning & external works	67,521,825	17	20,880,938	8	25,011,804	10	37,804,856	22	63,645,120	18	−41
Repairs and replacement	106,906,170	27	17,270,006	7	14,403,546	6	46,193,241	26	12,434,688	4	271
Total O & M Costs	**2,248,415,820**	**100**	**1,584,540,191**	**100**	**1,430,259,990**	**100**	**1,754,405,334**	**100**	**2,248,569,792**	**100**	**−22**
Costs per m ^{2}	**497,988**		**415,999**		**400,970**		**442,585**		**557,681**		**−21**

to saving in fabric and decoration cost of GBs compared to traditional building.

4.3. Residual value

The environmental pollution is less in respect of demolition and disposal of GBs, where environmental friendly materials are used. Therefore, it was assumed that at the end of life-cycle, GBs have more residual value than traditional buildings. The PV of the residual was calculated at the end of life cycle of each building and normalized to cost per m^2 and per head. Table 6 presents the comparison of residual value between green and traditional buildings.

4.4. LCC of green Vs. Traditional buildings

The NPV was derived by summing up the PVs of construction, operation, maintenance costs and residual value in each building. Table 7 illustrates a detailed comparison of LCC of green and traditional buildings.

Table 6
Residual Value of Green and Traditional Buildings.

Residual Value	GB 1	GB 2	GB3	Avg. GB	CB
Cost (LKR)	(1,426,740)	(689,429)	(581,421)	(899,197)	(774,144)
Cost per Unit Area (LKR/m ^{2})	(3 1 6)	(1 8 1)	(1 6 3)	(3 1 2)	(1 9 2)

As presented in Table 7, the main cost components of construction, operation cost, maintenance costs and residual value contribute to approximately 15%, 70%, 15%, and less than 1% respectively to life cycle cost of GBs while the respective elements in the traditional building contribute approximately 10%, 76%, 14%, and less than 1%. The comparison of the elemental cost contribution of these two types of buildings indicate that construction cost and residual value of GBs are 29% and 16% higher than traditional building respectively.

In terms of operation and maintenance GBs contribute to substantial savings of 23% and 15% respectively. This results in green industrial buildings contributing to total life cycle cost saving of 17% in Sri Lanka.

4.5. Sensitivity analysis

To test the uncertainty of variables considered for LCC analysis, sensitivity analysis was performed for the possible alternative discount rates of 1 to 9% and for analysis periods of 30 to 50 years. Fig. 1 illustrates the LCC variation of each selected building for these alternative discount rates.

In general, the LCC decreases when the discount rate increases. As seen from Fig. 1, the LCC of the selected green and traditional buildings decreases and the difference between the LCC of green and traditional buildings also decreases with increase in discount rates. Consequently, the LCC of green and traditional buildings can be equal and there could be a zero difference at any discount rate. Even though at

Table 7
LCC Comparison between Green and Traditional Buildings.

Costs Elements	Cost (LKR)										Saving
	GB 1	%	GB 2	%	GB 3	%	Avg. GB	%	CB	%	
Construction	**320,890,080**	**12**	**305,889,363**	**16**	**289,218,354**	**17**	**305,332,599**	**15**	**236,674,368**	**10**	**29**
Building Works	260,050,455	10	225,732,767	12	217,118,354	13	234,300,525	11	189,758,016	8	23
LEED Certification	23,103,255	1	35,427,509	2	25,000,000	1	27,843,588	1	–	–	–
Other Costs	15,093,645	1	26,483,977	1	30,000,000	2	23,859,207	1	29,082,816	1	−18
Facilitating Works	22,642,725	1	18,245,110	1	17,100,000	1	19,329,278	1	17,833,536	1	8
Operation	**1,845,880,995**	**72**	**1,321,882,978**	**70**	**1,190,268,663**	**69**	**1,452,677,545**	**71**	**1,894,709,376**	**76**	**–23**
Utilities	929,579,805	36	573,921,075	30	467,587,329	27	657,029,403	32	934,166,016	38	−30
Administrative Cost	750,799,350	29	403,567,359	21	417,806,277	24	524,057,662	25	512,705,088	21	2
Other Costs (insurance and taxes)	165,501,840	6	344,394,544	18	304,875,057	18	271,590,480	13	447,838,272	18	−39
Maintenance	**402,534,825**	**16**	**262,657,213**	**14**	**239,991,327**	**14**	**301,727,788**	**15**	**353,860,416**	**14**	**– 15**
Services	155,925,525	6	98,397,897	5	104,498,832	6	119,607,418	6	148,538,880	6	−19
Fabric & decoration	72,181,305	3	126,108,372	7	96,077,145	6	98,122,274	5	129,241,728	5	−24
Cleaning & external works	67,521,825	3	20,880,938	1	25,011,804	1	37,804,856	2	63,645,120	3	−41
Repairs and replacement	106,906,170	4	17,270,006	1	14,403,546	1	46,193,241	2	12,434,688	1	271
Residual Value	**−1,426,740**	**0.06**	**−689,429**	**0.04**	**−581,421**	**0.03**	**−899,197**	**0.04**	**−774,144**	**0.03**	**16**
NPV (LCC)	**2,567,879,160**	**100**	**1,889,740,125**	**100**	**1,718,896,923**	**100**	**2,058,838,736**	**100**	**2,484,470,016**	**100**	**−17**
NPV (LCC) per m2	**568,744**		**496,125**		**481,889**		**519,428**		**616,188**		**−16**
NPV (LCC) per head	**1,945,363**		**1,349,814**		**1,312,135**		**1,532,634**		**1,854,082**		**−17**

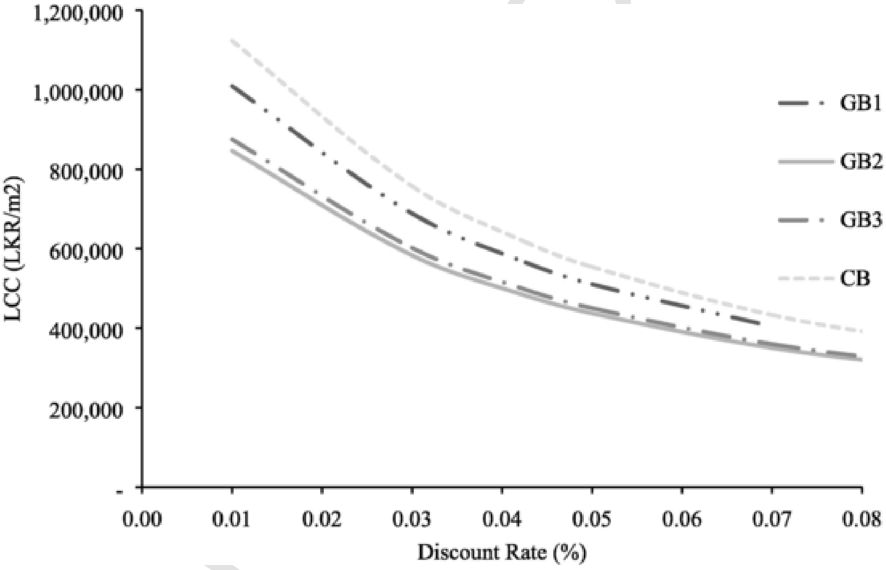

Fig. 1. LCC vs Discount Rates.

the highest possible real interest rate (7%) recorded by the Central Bank of Sri Lanka, 16% of the difference is visible in the LCC of green and traditional buildings. Thence, in all these circumstances the GBs are more economical compared to traditional buildings.

Likewise, the LCC of each building was recalculated for varying life cycle analysis periods and the results are depicted in Fig. 2.

As shown in Fig. 2, the LCC of GBs is less than traditional buildings for all considered life cycle years between 30 and 50 years. Furthermore, an equal difference in LCC between green and traditional buildings is visible for the alternative analysis periods.

5. Findings and discussion

GBs hold a substantial place in the sustainable construction that incorporates the environmental leadership, economic efficiency and social wellbeing. With the view of improving the adoption of green technologies in industrial buildings in Sri Lanka, this study aimed to compare the life-cycle costs (LCC) of green and traditional industrial buildings and establish the potential LCC savings over the higher initial cost of green technologies.

The analysis results indicate that the construction cost of gold-certified green industrial buildings is 29% higher than that of traditional buildings. This finding is considerably higher than the percentage highlighted in the global and local contexts by the previous studies [1,2,11,15,17] concerning the construction cost of green office, residential, healthcare and school buildings. Further, the increased construction cost is due to the incorporation of both active and passive GB technologies in to the seleted GBs and specially due to the most of the active GB technologies. Therefore, this supports the findings in previous studies [21,26,38]. Active technologies such as solar water heating system, servo motors, evaporative cooling, adjustable diffusers, waterless urinals, and mechanical water treatment systems contributed to increased construction costs, while contributing for operational costs savings interms of electricy and water utilites. It is worth noting that

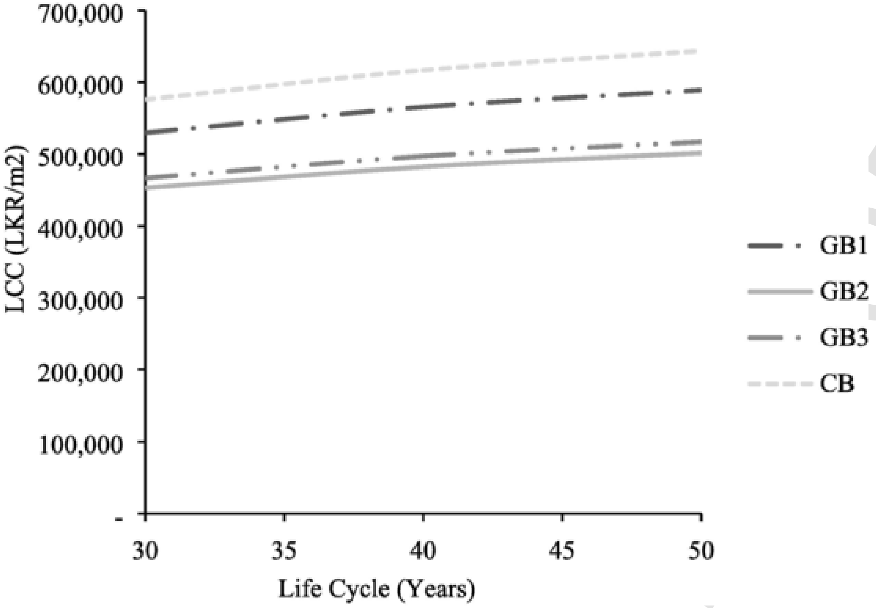

Fig. 2. LCC vs Life Cycle Periods.

the cost of building works which is responsible for 80% of the total construction cost is only 23% higher in GBs than trational building.

The current study found that the operation and maintenance of GBs result in 23% and 15% savings respectively and lead to an overall saving of 17%. Further, the operational cost saving is mainly contributed through utilities and administrative cost. The saving in both the elemental costs are attributed to technologies implemented in the GBs incorporated belong to energy & atmosphere (EA) and water efficiency (WE) sustainable features alternative transportation and construction of IAQ management plan. The respective technologies which were integrated are provided in Table 3. However, in the current study, the increase in administrative cost is partly attributed to the number of occupants (see Table 2) in the buildings. The part of the current study where the factors influencing the running cost elements indicated that the 'number of occupants' is second most variable after 'function of the building' which influences the operational administrative costs of a building. Thus, it can be concluded that the GBs contribute to energy savings as reflected in the utilities cost of the comparative LCC analysis. These findings are consistent with the findings of Dwaikat and Ali [6] which that estimated that GBs contribute 22% of contruction cost, 50% of operation cost, 27% of maintenance cost and 1% of endlife costs.

Further, the 15% savings in maintenance cost is attributed to its main constituents which are services maintenance and fabric & decoration. Although cleaning & external works contribute considerably to life cycle cost of both green and traditional buildings, they result in net savings of 41%. The saving in these costs are attributed technologies implemented under sustainable features as shown in Table 3 as well as differences in number of occupants are also a contributory factor.

A further scrutiny of cost elements in Table 7 shows that over 80% of LCC is contributed by utilities, administrative, buildings works and other costs (insurance and taxes) in both GBs and traditional buildings. The comparation of similar elements between green and traditonal buildings show that utilities (30%) and administrative cost (-2%) together result in 60% saving against the 23% additional cost of building works. This results in a net saving of 17% offered by green industrial buildings over traditional building in Sri Lanka.

6. Conclusions

This study performed a comparative analysis of the LCC of GBs and similar natured traditional industrial buildings. From the study findings, it was apparent that the cost of construction of green industrial buildings is about 29% more than traditional buildings while the GBs offer savings of 23% in operation and 15% in maintenance. However, GBs also incur additional cost of 16% in terms of residual value compared to traditional buildings. A close scuritny confirmed that the net savings in LCC of green industrial buildings would be 17%, mainly due to utilities, administrative and against building works which are significant LCC sub-elements. Furthermore, the results of sensitivity analysis performed for the possible alternative discount rates and analysis periods, subsequently concluded that green industrial buildings compared to traditional buildings provide cost savings over their physical life at certain discount rates. Further, the study has shown the specific green technologies which have contributed to green certification and life cycle cost savings of industrial manufacturing buildings. This would enhance the knowledge of green industrial investors on the applicable technologies and the resultant savings on the operational and maintenance cost against the initial investment committments. However, the current study used three GBs and one traditional building of the selected four GBs and two traditional buildings due to incompleteness and discrepancies between the data sets. Though the study has established the cost/saving differences between GBs and traditional building, given the due consideration to building characteristics, geography and performance data in selecting building cases, authors believe that to a little extent, the differences could be influenced by factors other than those considered. For example, cost of utilities, administration services maintenance, and cleaning could be influenced by services availability, resources availability, technology used, quality of materials & equipment used, durability of materials & equipment used, and workmanship, etc. Further, the current study has limited the analysis to collective impacts of green techologies implemented in the selected buildings, fails to recognise the effects of individual techonology.

Therefore, it is recommended the future studies to address these shortfalls to the possible extent in assessing the effects and thereby contribute to eliminate barriers in uptake of green developments.

Uncited references

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CRediT authorship contribution statement

Achini Shanika Weerasinghe: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Project administration. **Thanuja Ramachandra:**

Resources, Writing - review & editing, Supervision, Funding acquisition. **James O.B. Rotimi:** Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2021.110732.

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