

Development of a Machine Learning Sustainability Cost Estimation Model in the Facilities
Management Sector

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the Facilities Management Sector

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Summary: Facilities Management includes the service and use phase of the full life cycle of assets of a variety of building types. Sustainability is an increasingly critical business driver for Facilities Management. Therefore, the cost estimation of the value of the impact of sustainability drivers on facilities management contracts is now critical to improve. This research uses a narrative review to identify and define costs or cost drivers related to sustainability and exemplify Life Cycle Costing models. The development of the methodology and its validation is informed through an exploratory case study with a Facilities Management company. The findings are used to inform further work in development of novel sustainability cost estimating methods.

Word Account: 6797

1. Introduction

1.1 Background

Many of the themes of Sustainability focus on the engineering and technological challenges related to the sustainability and global warming challenge. However, there is minimal research directed at the Cost Engineering challenge in industry and specifically the cost estimating requirement. The Association of Cost Engineers Community of Practice in Cost Estimating (AcostE CoP Body of Knowledge document 2023) indicates there is a cost estimating requirement for Net Zero planning and sustainability challenges. In other words, the cost benefit analysis and full life cycle costing for sustainability is being given to cost engineers in industry to carry out. Therefore, it is now critical and timely that research develops a novel cost estimating process to be used in Business Case development supporting sustainability and aligned with sustainability standards and regulations.

In addition, there is an emerging opportunity to use improved contemporary Artificial Intelligence and machine learning methods in cost forecasting, cost estimating and cost modelling (Zhou, Etemadi and Mardon, 2022). There has been previous research into applications of soft computing including neural networks and fuzzy logic. However, these have been in mainly non-sustainability related applications and also limited in the type of AI being used. The advent of novel data sources and developments in AI around deep learning and hybrid methods, provides an opportunity to innovate in cost modelling methods by synthesizing data sources and also developing novel architectures including several methods.

This project engages with a large global company in Facilities Management with a focus on the use phase of the full life cycle of assets, in asset management, and hence the cost estimating of Environmental Social Governance (ESG) is a main business driver.

The project was carried out over 6 weeks with weekly steering meetings with the Global Cost Estimating Manager. A literature analysis of specific areas of cost engineering was carried out. A cost model was developed and tested with a sustainability related data source and the use of machine learning techniques.

1.2 Aims and Objectives

The central aim of the research is to conduct an exploratory case study into developing a sustainability cost estimating methodology in a global facilities management business. To accomplish this aim, it is essential to: i) develop informed decision making and long-term strategic planning by accurate and efficient cost estimates, ii) manage budgets by identifying and defining sustainability related costs or cost drivers, iii) improve compliance and reporting by a robust estimating methodology appropriate for various sustainability regulations and reporting standards, iv) identify and assess financial risks associated with environmental, social and governance impacts, v) facilitate new

efficiencies and cost savings by applying machine learning algorithms.

Therefore, this research has put forward three research questions below as specific gaps to be filled:

1. What are costs or cost drivers related to sustainability in global facilities management and which data sources are appropriate for collecting sustainability cost data?
2. What current cost estimating methodologies are used in global facilities management, and how can these methodologies be adapted or improved to better incorporate sustainability considerations?
3. How can machine learning models be trained and validated using available data sources and what are the potential benefits and limitations of using machine learning for sustainability cost estimation?

To solve these research questions, the research has set up the following objectives:

1. Identify cost drivers and data sources to develop cost estimates in a global facilities management company;
2. Identify a novel cost estimating methodology for sustainability costs in a global facilities management company;
3. Develop and test a machine learning cost modelling method as part of the novel cost estimating methodology.

1.3 Contents

1. Section 1 is an introduction to this research, presenting the basic research background, setting up aims and objectives and structuring the full paper;
2. Section 2 is a literature review that identifies sustainability-related costs and cost drivers in preparation for the cost estimation model, providing examples of cost models in asset management and pointing out research gaps;
3. Section 3 is research methodology which contains a comparative machine learning model of 1 Dimensional Convolutional Neural Networks and Multilayer Perceptron and also designs a series of steps to estimate sustainability following the logic of classical cost estimation;
4. Section 4 is presentation as well as analysis of results, exhibiting model results and conducting further discussion;
5. Section 5 is a research conclusion on the full paper with review on completion of research objectives, feedback and future work to further this research.

Besides, Fig 1 also briefly illustrates the research structure as below.

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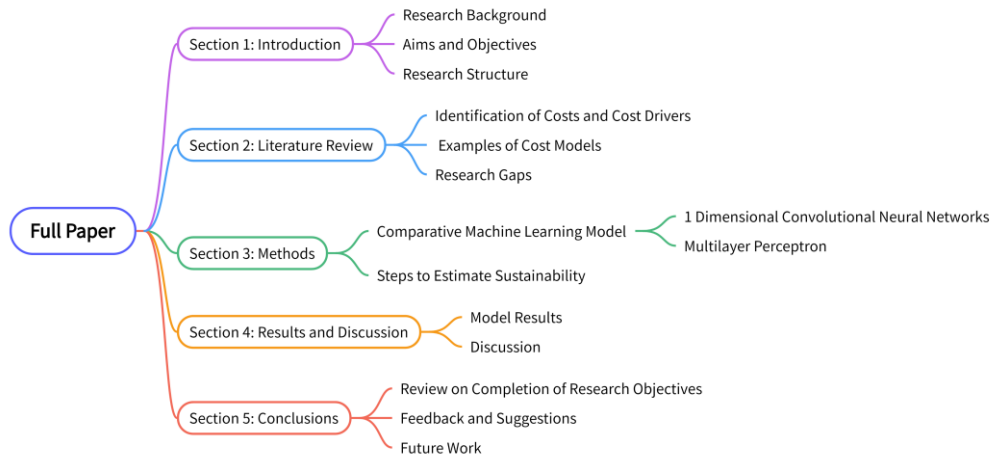


Fig 1 Research Structure

2. Literature Review

2.1 Development Process of Cost Estimation

Cost estimating is a process where financial and other means of resources required to deliver a whole project within a specific scope and schedule are measured (Infrastructure and Projects Authority, 2021). However, traditional methods usually make a crude and minimal concentration on sustainability for they lack relevant data and indicators to measure the impact of sustainability. To be more specific, sustainability involves multiple aspects, including environmental, social and economic factors, which need to be considered and measured in an integrated manner, which can be relatively complex and difficult to collect and analyse (Türkay et.al, 2016).

Nowadays, cost estimation related to sustainability is increasingly valued as a significant business driver for three main reasons. First, Environmental sustainability is critical to human health and well-being. Ekins and Zenghelis (2021) discuss and emphasize that a healthy planet is vital to human health, while an unhealthy planet is detrimental to human health. Environmental issues such as climate change, biodiversity loss and resource depletion pose significant risks and costs to human societies and economies. Secondly, sustainability implementation requires comprehensive consideration of economic, environmental and social factors. Traditional cost estimation methods tend to focus on economic benefits and ignore environmental and social impacts, such as greenhouse gas emissions, water usage, labour practices, and uncertainties in Key Performance Indicators of Life Cycle Costing. However, as awareness of sustainability increases, a growing body of research shows that sustainability implementation is critical to economic growth, resource management and social practices such as “Net Zero by 2050” (International Energy Agency, 2021). By conducting sustainability-related cost estimates, the economic benefits of sustainable development strategies can be better understood and assessed, providing improved information to decision-makers and advancing the achievement of sustainable development goals (Vorisek and Yu, 2020). Thirdly, Sustainability-related cost

estimates can help shape new markets and business opportunities (Ekins and Zenghelis, 2021). With increased environmental awareness and the development of sustainable technologies, more and more companies and organisations are focusing on seeking sustainability business opportunities. However, they are confronted with technical challenges due to few previous data or experience in volume production (Vaezi *et al.*, 2013). By conducting sustainability-related cost estimation, the potential for creating economic value in the field of sustainability can be revealed, facilitating innovation in new technologies and behavioural models to drive the transformation of the economy and the achievement of sustainable development, which also caters for goals from the 26th Conference of the Parties (Mountford *et al.*, 2021). It is now critical to link cost estimating and sustainability in the right way during the full life cycle to inform business planning.

Some sustainability business drivers such as Low Carbon and Net Zero are progressively protected by legislation and new standards like PAS 2080, a significant part of the cost estimating requirement. PAS 2080 is a carbon management standard that provides a framework to manage carbon for organizations delivering projects and programs across buildings and infrastructure specifying requirements for the management of whole life carbon in buildings and infrastructure, in the provision, operation, use, and end-of-life stages.

2.2 Literature Review Search Strategy

The following literature review search strategy was used to develop the work and inform the exploratory case study. There is an inclusion of specialized cost estimating sources.

1. Keywords related to sustainability and cost engineering are defined as follows: Sustainability; Key Performance Indicator; driver; barrier; cost driver; Green Supply Chain Management; Pharmaceutical Production.
2. Search using academic search engines (e.g. Google Scholar, PubMed, IEEE Xplore, etc.). The following filters are set:
 - ◆ Year of publication: restrict to recent ten years (2013-2023) to ensure access to the most recent research, however, guidelines and baselines can be free from this restriction.
 - ◆ Type of literature: select JCR Q1 journal articles and industry reports in terms of sustainability and cost engineering.
 - ◆ Key authors or institutions: ICEAA (International Cost Estimating and Analysis Association) and AACE (Association for the Advancement of Cost Engineering) articles.
3. Check the websites of professional organizations such as ICEAA (International Cost Estimating and Analysis Association) and AACE (Association for the Advancement of Cost Engineering) to find publications, reports or journals related to sustainability cost publications, reports or research resources related to sustainability costing.

4. Browse the proceedings of relevant academic conferences, such as the annual conferences of ICEAA and AACE, for the latest research findings and industry trends.
5. Refer to industry reports, government reports or policy documents related to sustainability, carbon emissions and cost estimation to identify costs or cost drivers, and select datasets from government as data sources.

2.3 Nature of Review and Limitations

This report includes an exploratory review on sustainability and cost estimation with qualitative analysis. In this paper, it concentrates on what previous research has contributed to and what current research gaps await more efforts. However, it cannot avoid the following limitations.

1. **Inconclusive results:** This review offers a qualitative approach to data collection, which is highly subjective and complex. As a result, the results can be difficult to interpret and may not provide conclusive results.
2. **Sampling problem:** This review makes use of a small number of respondents, which opens up the risk of sampling bias and the consequent reduction in reliability and validity.
3. **Lack of standardised analysis:** It lacks standardized analysis, which can make it difficult to compare results across studies.

2.4 Definitions of Sustainability Cost or Sustainability Related Cost

Sustainability cost or sustainability-related cost are defined as costs associated with activities or projects that aim to promote sustainable development (Foroutan Mirhosseini *et al.*, 2022). These costs may include expenses related to environmental protection, social responsibility, and economic viability. The following examples are listed to illustrate specific costs for sustainability.

1. **Initial Investments:** Implementing sustainable practices often requires upfront investments in technologies, equipment, infrastructure, and employee training. For example, installing energy-efficient systems, renewable energy generation facilities, or waste management infrastructure may involve significant initial costs (Ekins and Zenghelis, 2021).
2. **Operational Expenses:** Sustainable practices may lead to increased operational expenses in the short term. For instance, using renewable energy sources may have higher upfront costs compared to conventional energy sources. Similarly, implementing sustainable supply chain practices, such as sourcing from certified suppliers or conducting audits, may involve additional expenses (Gielen et.al, 2019).
3. **Resource Efficiency and Cost Savings:** One of the main drivers for sustainability is the potential for cost savings through improved resource efficiency. Sustainable practices can reduce energy consumption, water usage, and waste generation, leading to long-term cost savings. For example, energy-efficient technologies can lower utility bills, and waste reduction programs can minimize disposal costs (Ekins and Zenghelis, 2021).

4. **Regulatory Compliance:** Non-compliance with environmental regulations or failure to meet sustainability standards can result in penalties and legal consequences, leading to potential financial losses. Investing in sustainability can help organizations avoid these costs and ensure compliance with regulations (Platform on Sustainable Finance, 2022).
5. **Reputation and Brand Value:** Adopting sustainable practices can enhance an organization's reputation and brand value, which can have financial implications. Consumers are increasingly favouring sustainable brands, and organizations that align with sustainability values may attract more customers and gain a competitive edge, resulting in increased revenue and market share (Eliot Partnership, 2022).
6. **Access to Capital and Investment:** Sustainability-focused organizations often have greater access to funding and investment opportunities. Many investors, including venture capitalists, impact investors, and sustainable finance institutions, prioritize organizations with strong sustainability performance, opening doors to potential capital injections and financial support (HM Government, 2023).
7. **Insurance and Risk Management:** Addressing sustainability risks can reduce insurance premiums and mitigate financial risks. For example, implementing measures to prevent environmental accidents or ensuring supply chain resilience can minimize potential financial losses associated with disruptions, reputational damage, or legal liabilities (European Insurance and Occupational Pensions Authority, 2022).
8. **Long-Term Financial Performance:** Incorporating sustainability into business strategies can enhance long-term financial performance and resilience. Sustainability-driven organizations may experience increased profitability, improved investor confidence, and better access to markets, leading to sustainable growth and competitive advantage (Organization for Economic Co-operation and Development, 2020).

2.5 Definitions of Cost Driver

Cost Drivers are the direct cause of a business expense. A cost driver is any activity that triggers a cost of something else. Previous scholars also give different definitions of cost drivers in various terms. For instance, Corporate Finance Institute (2019) defines a cost driver as a factor that creates or drives the cost of an activity and explains how cost drivers are used in activity-based costing while Franklin et al (2022) describe cost drivers as factors that cause a business to incur costs and provides examples of cost drivers for different types of costs. An example of this could be how the amount of water your office uses in a month determines the price of your water bill. The units of water are the cost drivers, and the water bill is the cost. This concept demonstrates that all activities require the consumption of resources, and as people complete work activities, there is an associated resource cost for each activity. The following examples are listed to illustrate specific cost drivers for sustainability.

1. **Technology and Infrastructure:** The choice of sustainable technologies and infrastructure plays a significant role in determining costs. Upfront investments in renewable energy systems, energy-efficient equipment, waste management

infrastructure, and sustainable transportation solutions can impact the overall costs of sustainability initiatives (Ekins and Zenghelis, 2021).

2. **Scale and Scope of Operations:** The size and complexity of an organization's operations can affect the costs of sustainability. Larger organizations or those with extensive supply chains may require more resources and investments to implement sustainable practices across various sites or locations (Govindan et.al, 2021). For instance, between 2005 and 2015, Wal-Mart worked to quadruple the efficiency of their fleet by deploying improved truck loading, driver training, and cutting-edge technologies. By the end of 2014, they had significantly increased fuel economy from the baseline in 2005 by almost 87%. Through these improvements, 15,000 metric tonnes of CO2 emissions were prevented, and the year's savings came to little under \$11 million (Whelan and Fink, 2016).
3. **Training and Education:** Building a culture of sustainability requires investing in employee training and education. Costs associated with sustainability-related training programs, workshops, and awareness campaigns can be significant, especially when aiming to engage and empower a large workforce (Organization for Economic Co-operation and Development, 2020).
4. **Supply Chain Considerations:** Integrating sustainability into the supply chain can involve additional costs. This may include assessing and auditing suppliers for sustainability performance, implementing sustainable sourcing practices, and managing supplier relationships to ensure compliance with ethical and environmental standards (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, 2017).
5. **Performance Measurement and Reporting:** Tracking and reporting sustainability performance requires dedicated resources and tools. Organizations may need to invest in software systems, data collection processes, sustainability reporting frameworks, and expertise to effectively measure, monitor, and report on their sustainability efforts (European Federation of Financial Analysts Societies, 2009).
6. **Risk Management:** Addressing sustainability risks and ensuring resilience can involve costs. Implementing measures to mitigate risks associated with climate change, supply chain disruptions, regulatory non-compliance, or reputational damage may require additional investments in risk assessment, contingency planning, and insurance coverage (European Central Bank, 2022).
7. **Stakeholder Engagement:** Meaningful stakeholder engagement is essential for successful sustainability initiatives. Costs associated with stakeholder consultations, surveys, engagement platforms, and communication channels need to be considered when planning sustainability strategies (GOV.UK, 2016).
8. **Innovation and Research:** Developing and implementing innovative solutions and practices for sustainability often requires research and development (R&D) investments. Organizations that aim to be at the forefront of sustainability may incur costs related to exploring and piloting new technologies, materials, or business models (The UCL Green Innovation Policy Commission, 2021).
9. **External Consultants and Expertise:** Organizations may seek external expertise

to design and implement sustainability strategies effectively. Engaging sustainability consultants, auditors, or advisors can add to the overall costs, but their specialized knowledge and guidance can help organizations navigate complex sustainability challenges (Financial Conduct Authority, 2021).

2.6 Definition of Sustainability Key Performance Indicator

Key Performance Indicator refers to a set of quantifiable measurements used to gauge a company's overall long-term performance. KPIs specifically help determine a company's strategic, financial, and operational achievements, especially compared to those of other businesses within the same sector. The following examples are listed to illustrate specific key performance indicators for sustainability.

1. **Carbon footprint:** Measures the total greenhouse gas emissions associated with an organization's activities, including direct and indirect emissions. It helps assess the environmental impact and effectiveness of emission reduction strategies (Müller et.al, 2020).
2. **Energy consumption:** Tracks the amount of energy consumed by an organization or facility. It provides insights into energy efficiency initiatives and the potential for reducing energy usage (Somu and Ramamritham, 2021).
3. **Water usage:** Measures the amount of water consumed by an organization and its operations. Monitoring water usage helps identify opportunities for conservation and sustainable water management practices (Nie et.al, 2020).
4. **Waste generation and recycling rates:** Measures the quantity of waste generated by an organization and the percentage that is diverted from landfills through recycling, composting, or other sustainable waste management practices (Ferdous et.al, 2021).
5. **Social impact:** Evaluates the positive or negative effects an organization has on society, including employee well-being, community development, human rights, and diversity and inclusion. It may involve indicators such as employee satisfaction, community engagement, or labour standards (Fernandes et.al, 2023).
6. **Supplier sustainability:** Assesses the sustainability performance of suppliers and their adherence to ethical and environmental standards. It helps ensure that an organization's supply chain aligns with sustainability goals and promotes responsible practices (Khan et.al, 2023).
7. **Product life cycle assessment:** Measures the environmental impact of a product or service throughout its entire life cycle, including raw material extraction, production, distribution, use, and disposal. It helps identify areas for improvement and guide sustainable product design and development (Bishop et.al, 2021).
8. **Economic performance:** Includes financial indicators that consider the economic viability of sustainability initiatives. These may include return on investment (ROI), cost savings from resource efficiency measures, or revenue generated from sustainable products or services (Souza et.al, 2022).
9. **Biodiversity conservation:** Focuses on preserving and restoring ecosystems and protecting biodiversity. Indicators may include the number of protected areas, species conservation efforts, or the integration of biodiversity considerations into

business operations (Ober and Pinkse, 2022).

10. **Stakeholder engagement:** Measures the level of engagement and collaboration with stakeholders, such as customers, employees, communities, and investors, in sustainability initiatives. It assesses the effectiveness of communication, involvement, and responsiveness to stakeholder concerns (Lu et.al, 2023).

2.7 Examples of Sustainability Related Cost Models and Cost Estimates in the Asset Management Literature

Haugbølle and Raffnsøe (2019) discuss the life cycle costs of sustainable office buildings in Denmark, with a focus on the main cost drivers and their implications for authorities, clients, and building professionals in the building industry, which provides a notable contribution to the academic understanding of the significance of different cost drivers as well as the practical implementation of life cycle costing. The costs are calculated by the net present value (NPV) method.

$$NPV = \sum_{i=1}^n \frac{\text{Cash Flow}_i}{(1 + r)^i} - \text{Initial Investment}$$

In this equation, Cash Flow is the sum of money spent and money earned on the investment or project for a given period; n is the number of periods of time; r is the discount rate.

The data sources for the study were 21 office building projects from 2013-2017, which were part of the sustainable certification scheme DGNB. The inputs for the cost calculations included actual construction costs from the project accounts and calculated running costs based on industry standards and assumptions. The outputs were the life cycle costs of the office buildings over a 50-year period, broken down into different cost drivers such as construction costs, running costs, and cleaning costs.

Notably, the paper suggests redirecting the effort towards other more prominent cost drivers like cleaning and technical installations.

The level of uncertainty in the study is addressed through several limitations and challenges. One limitation is the lack of reliable data, especially for running costs which had to be calculated based on assumptions. Another challenge is the weak implementation of whole life costing principles in building projects, which hinders the accuracy of the cost calculations. Additionally, the study acknowledges that the calculated energy consumption may differ from the actual energy consumption in buildings due to factors like user behaviour and the concept of service. Despite these uncertainties, the study provides valuable insights into the significance of different cost drivers and the practical implementation of life cycle costing in sustainable building design.

The Life Cycle Cost (LCC) model used in the paper is based on a more detailed, specific, and industry-supported set of calculation assumptions than is usual for life cycle costing

studies. The model takes into account the main cost drivers of sustainable office buildings, including energy costs, water supply costs, cleaning costs, technical installation costs, and applied finish costs. The model shows that the life cycle costs for cleaning are higher than the supply costs for energy and water combined, with cleaning costs making up approximately one-fifth of the life cycle costs and utility costs for energy and water combined making up approximately two-fifths of the life cycle costs, which suggests that authorities, clients, and building professionals need to redirect their attention towards other more important cost drivers to avoid making costly, erroneous decisions based on false assumptions of relevant cost drivers.

2.8 Analysis of Cost Drivers

There are different levels of cost estimate that relate to early or latter stages of the full life cycle and therefore the amount of information available to the cost estimator (Altavilla and Montagna, 2019). High level estimates are made early in the design stages where conceptual and specification level information is available, and costs are uncertain. On the contrary detailed level cost estimates include more detailed activity and resource profiles for the full life cycle.

2.8.1 High-Level Cost Estimate Level

1. **Design and Planning:** The sustainable design features and planning decisions made early in the project can impact the overall cost estimate. Factors such as energy efficiency, water conservation, and material selection need to be considered (Nie et.al, 2020).
2. **Green Building Certifications:** Pursuing green building certifications, such as LEED (Leadership in Energy and Environmental Design) or BREEAM (Building Research Establishment Environmental Assessment Method), can involve additional costs related to certification fees, documentation, and compliance with specific requirements (Fontana, 2019).
3. **Life Cycle Cost Analysis:** Performing a life cycle cost analysis helps evaluate the long-term costs and benefits of sustainable design choices. This analysis considers factors like energy consumption, maintenance costs, and operational efficiency (Haugbølle and Raffnsøe, 2019).
4. **Energy Efficiency Measures:** Incorporating energy-efficient systems and equipment, such as LED lighting, efficient HVAC systems, and renewable energy technologies, can impact the cost estimate. While these measures may have higher upfront costs, they can result in long-term energy savings (Wu et.al, 2019).

2.8.2 Detailed Cost Estimate Level

1. **Material Selection:** Choosing sustainable and eco-friendly materials, such as recycled content products or locally sourced materials, can affect the detailed cost estimate. These materials may have different price points or availability compared to conventional options (Silva et.al, 2017).
2. **Waste Management:** Implementing waste management strategies, including recycling and waste diversion plans, may involve additional costs for waste sorting,

disposal, or recycling facilities (Ferdous et.al, 2021).

3. **Water Conservation:** Incorporating water-efficient fixtures, rainwater harvesting systems, or graywater reuse systems can impact the detailed cost estimate. The costs associated with these systems, such as installation, plumbing modifications, or storage tanks, need to be considered (Nie et.al, 2020).
4. **Indoor Environmental Quality:** Integrating features that enhance indoor air quality, such as low-VOC (volatile organic compound) paints, proper ventilation systems, or natural daylighting, may have cost implications related to material selection, installation, and maintenance (Megahed and Ghoneim, 2021).
5. **Green Infrastructure:** Implementing green infrastructure elements like green roofs, permeable pavements, or rain gardens can impact the cost estimate. These features often require additional design considerations, installation techniques, and maintenance efforts (Nieuwenhuijsen, 2021).

2.9 Research Gap

There is minimal research which develops a cost engineering solution to sustainability cost estimating in global facilities management companies. Islam, Nazifa and Mohamed (2019) put forward a problem that construction companies struggle with reliable cost management and face rising demands for sustainable projects, but there is a lack of research on the cost risk associated with sustainability in construction projects. Besides, Millin (2014) exemplified that facilities management companies in the Gulf Cooperation Council region have low sustainability maturity and often fail to identify risk to their businesses, indicating a need for guidance and performance improvement in sustainability aspects. Górecki and Díaz-Madroño (2020) conducted a literature review and survey on facilities management research trends, indicating that there is no consensus on the sustainability principles needed for maximal benefits in the built environment, suggesting a research gap in understanding the specific sustainability principles required for facilities management.

On the other hand, there is limited research on analysing the most important cost drivers and types of sustainability costs in different organizations (Connolly *et al.*, 2019). However, some scholars have made contribution by identifying various cost drivers and types of sustainability costs in specific contexts. For instance, Lozano and Haartman (2017) focused on the total costs of roadway transportation in North America, including non-market environmental and social costs. Park *et al.* (2009) developed a Sustainability Price framework to include social and environmental costs in the price of goods, with a focus on climate change and poverty. Saeed and Kersten (2019) conducted a systematic literature review to identify and analyse drivers of sustainable supply chain management, with regulatory and market pressures being the most prevailing drivers for implementing sustainability practices. Nevertheless, the cost estimating requirement for global facilities management companies with sustainability as a cost driver has not been fully analysed. There is no coherent best practice cost estimating methodology which includes novel sustainability data sources and machine learning methods able to meet the new estimating requirement.

3. Methods

3.1 Research Design

The research methodology consists of several steps in developing and testing a novel sustainability cost estimating methodology as shown briefly in Fig 2.

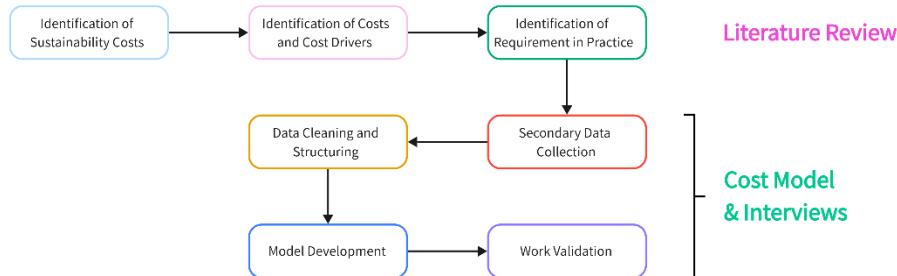


Fig 2 Research Design

1. Identify the main best practice elements of a cost estimating process for sustainability costs as shown in Section 2.2;
2. Identify costs and cost drivers that are important for developing potential data sets to be used in sustainability cost modelling.
3. Identify a cost estimating requirement with the cost estimating manager of the company. A series of 6 steering meetings have contributed to defining an estimating requirement. The estimating requirement has informed the development of the cost estimating methodology and machine learning cost models.
4. Collect secondary data from the public domain useful for the estimating requirement and the machine learning cost models.
5. Identify and structure a cost data set with a cost estimating manager. In particular a planned sustainability Key Performance Indicator (KPI) was developed to be predicted by the machine learning models.
6. Develop two machine learning cost models from the data set. In particular a convolutional neural network and a multi-layer perceptron have been used in a comparative analysis of their effectiveness.
7. Validate the work with industry and academic experts through feedback.

3.2 Resource Description

Heating and energy use in buildings contribute to around 40% of the UK's energy consumption and carbon emissions. The Department for Levelling Up, Housing & Communities (2023) provides data for buildings with issued energy certificates in England and Wales updated by September 2020 (Available at: https://epc.opendatacommunities.org/docs/guidance#glossary_domestic). After data cleaning, 8995 detailed units of data for buildings and their sustainable impacts are selected to feed the cost analysis (inputs are "New Build Benchmark", "Existing Stock Benchmark", "Floor Area", "Standard Emissions", "Target Emissions", "Typical Emissions" "Building Emissions").

3.3 Introduction to Models

As for research on this Project, six inputs including: “New Build Benchmark”, “Existing Stock Benchmark”, “Floor Area”, “Standard Emissions”, “Target Emissions”, and “Typical Emissions” are fed to the cost analysis and finally the outputs, “Predicted Emission”, are generated and compared with the practical value of “Building Emissions”. Convolutional Neural Networks (hereafter abbreviated as “Conv 1D”) and Multi-layer Perceptron Network (hereafter abbreviated as “MLP”) are applied as comparative models to predict emissions.

3.3.1 Conv 1D Model

Convolutional Neural Networks are a classical type of artificial neural networks and a basic Deep Learning method. Generally, common convolution kernels are measured in two dimensions to accommodate length and width of pictures, but they also can be measured in a single dimension when Convolutional Neural Networks are applied to time-series forecasting and cost estimating. Besides, Conv 1D can train swifter in comparison with other Deep Learning techniques as it can conduct parallel computation (Shiva Verma, 2019).

3.3.2 Multilayer Perceptron (MLP) Model

MLP is made up of several layers of linked nodes, or neurons that receive inputs, apply weights to those inputs, and pass the weighted sum through an activation function to produce an output. MLP networks may be trained using backpropagation, a popular supervised learning technique, and are frequently used for tasks like classification and regression. Similarly, MLP is expert at regression and estimation (Banoula, 2021).

3.4 Network Design

First, the input variables form into an initial matrix $\mathbb{R}^{n \times f}$, where $n = 8995$ represents the number of training data, and $f = 6$ stands for the number of features. Then it is transformed and activated by the “relu” function in three convolutional or dense layers. And three dimensions of intermediate data is “flattened out” in the flattened layer so that one dimension of outputs can be generated in the fully connected layer. More detailed processing can be viewed in the Fig 3 below.

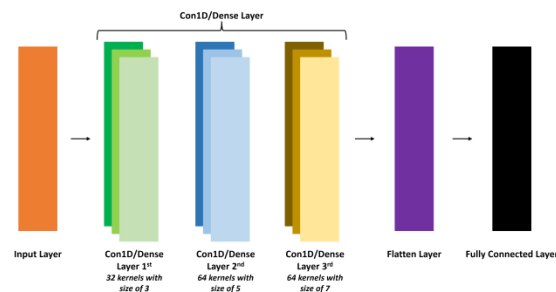


Fig 3 Network Structure Design

Besides, the 1D Convolutional Neural Networks and Multi-layer Perceptron Networks share the similar architecture comprising four layers as follows:

1. Input Layer: generate original inputs with fixed length;
2. Conv1D /Dense Layer: give weight of inputs and form into vectors and filters, apply non-linearity to the smoothed vector from convolutional or dense layer;
3. Flattened Layer: flat out three results from the former layer to one dimensional feature;
4. Fully Connected Layer: absorb representative input data that have experienced smoothing and non-linear transformation; activate representative output data to give weighted sum.

3.5 Steps for Sustainability Estimation

To develop a sustainability estimating process similar to a classical cost estimating process, it is possible to treat carbon emissions as a cost. The cost of carbon is a crucial metric for understanding the economic impacts of carbon emissions on the environment and society. The following is a step-by-step process for estimating the cost of emission:

3.5.1 Define the Cost of Emission

The social cost of carbon is the economic cost associated with the damages caused by emitting one additional ton of carbon dioxide into the atmosphere (Rickels, Meier and Quaas, 2023). In other words, it can be transformed from cost drivers to costs by some ways correlating carbon, e.g., carbon accounting system, activity-based costing, life cycle costing sensitivity analysis, and Monte Carlo simulation. Carbon emissions pose social impact on various aspects, such as agriculture, health, labour productivity, sea level rise, and energy consumption.

3.5.2 Gather Data and Information

To estimate the social cost of carbon, then relevant data and information are needed as follows.

- 1) Socioeconomic predictions: Information on population growth, economic growth, and manmade carbon emissions projections.
- 2) Climate projections: Data on how the climate will respond to emissions, including projections for sea level rise, temperature changes, and extreme weather events.
- 3) Benefits and costs: Data on how climate change affects different sectors, such as agriculture, energy use, and labour productivity, as well as the associated costs of adapting to climate change impacts.
- 4) Discount rate: The discount rate represents how society values present benefits compared to future benefits. It determines how much weight is given to future costs and benefits.

3.5.3 Use Integrated Assessment Models

Khabarov, Obersteiner and Smirnov (2022) concluded in a systems analysis of social cost of carbon that integrated assessment models are commonly used to calculate the cost of carbon. These models combine the gathered data and information to analyse the pathway through which emissions lead to climate change impacts, which in turn affect economic outcomes. Researchers typically simulate the climate's response to emissions

in the absence of policy changes and then augment the model to account for the increase in damage caused by emitting an extra ton of carbon dioxide, therefore, the difference in damages provides the social cost of carbon for a given period (Bhardwaj, Axsen and McCollum, 2021).

3.5.4 Consider Uncertainties

It is important to acknowledge that estimating the cost of carbon involves uncertainties, as there are numerous unquantifiable and uncertain climate impacts (Caesary, Kim and Myung Jin Nam, 2023). To exemplify this, Burke, Hsiang and Miguel (2015) conducted a meta-analysis, indicating that the potential costs of climate-induced human conflict, the effects of adaptation measures, and climate migration costs are challenging to precisely quantify. The models used inherently involve some level of political and moral judgment.

3.5.5 Regularly Update and Review the Estimates

The social cost of carbon is not a fixed value and can change over time due to advancements in climate science, changes in economic factors, and evolving policy landscapes (Fu *et al.*, 2023). As such, it is essential to regularly update and review the estimates using the most recent data and knowledge available. By following this process, policymakers and stakeholders can gain insights into the economic implications of carbon emissions and make informed decisions about climate policies. The social cost of carbon helps in evaluating the trade-offs between the costs of reducing emissions and the benefits of avoiding future damages to the environment and society (Rickels, Meier and Quaas, 2023). The aforementioned process is explained in the Fig 4.

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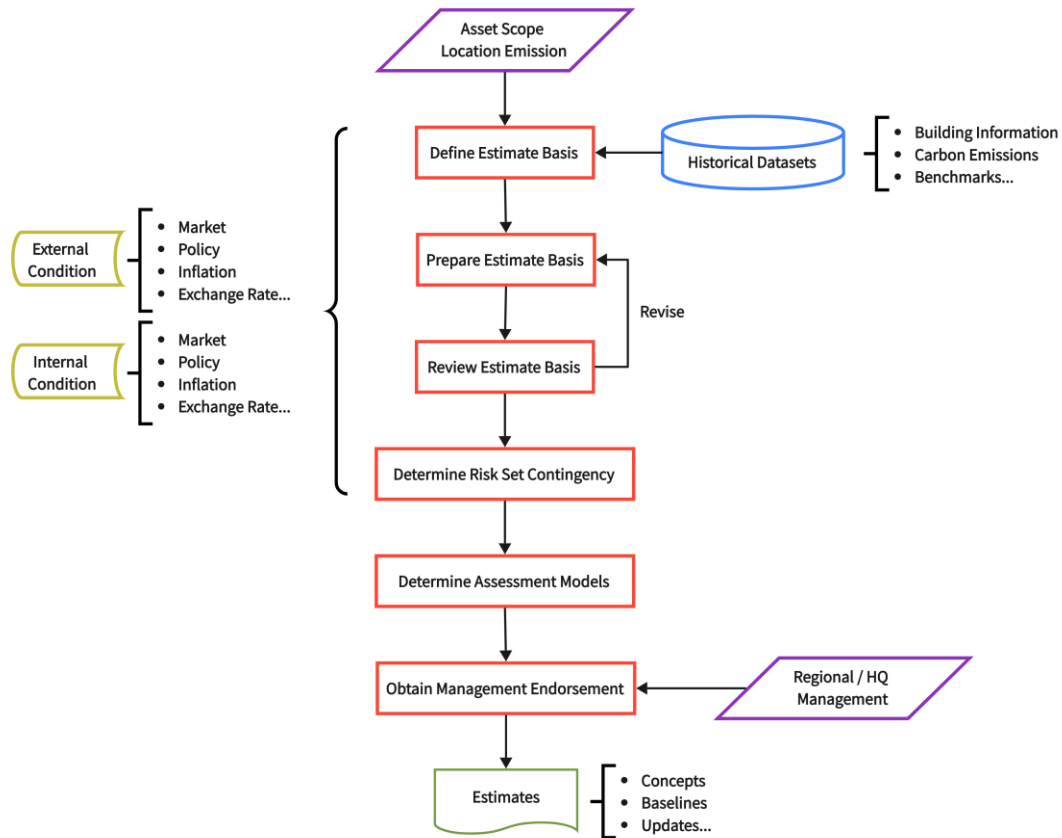


Fig 4 Steps for Sustainability Cost Estimation

4. Results and Discussion

4.1 Model Results

This research separates first 80% data (7195 units) as training and rest of 20% data (1800 units) as test. The following figure compares predicted emissions-based models fed with training data and actual values in Conv1D and MLP models (Please view results in the Fig 5 and Fig 6). It can be seen clearly that predicted values can fit actual situations so both models are trained successfully. In other words, known information including areas, benchmarks and a series of expected emissions guided by UK government can be utilised to infer actual emissions from buildings.

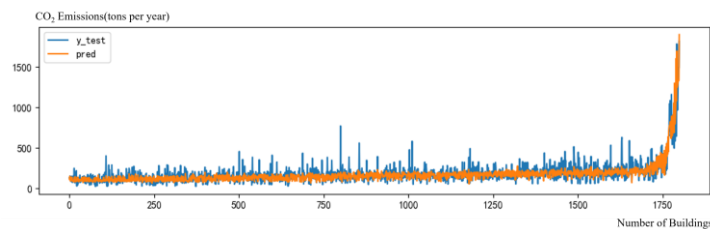


Fig 5 Predicted Results from Conv1D Model

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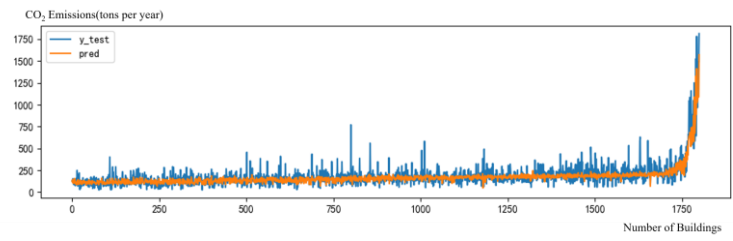


Fig 6 Predicted Results from MLP Model

Besides, buildings' emissions in text-based features including "Property Type", "Building Level", "Main Heating Fuel", "Building Environment" extracted from datasets of buildings in England and Wales are presented in the following Fig 7-10 (The Department for Levelling Up, Housing & Communities, 2023).

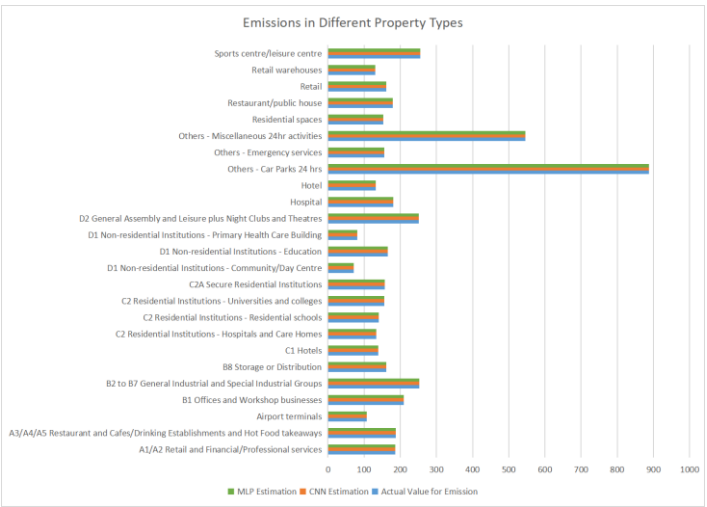


Fig 7 Comparative Results for "Property Type"

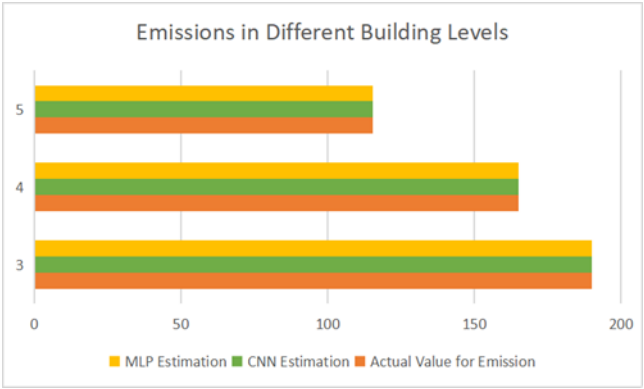


Fig 8 Comparative Results for "Building Level"

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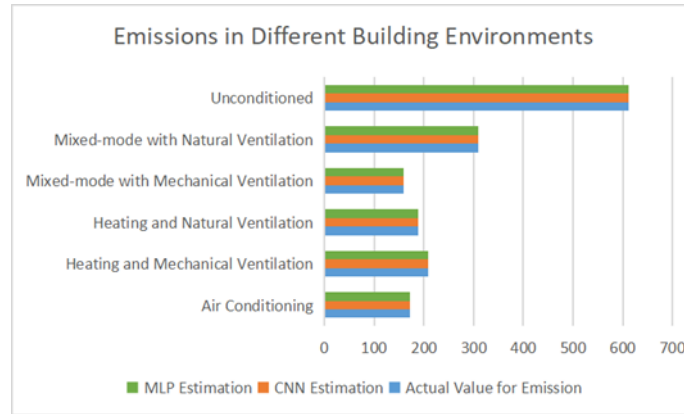


Fig 9 Comparative Results for "Building Environment"

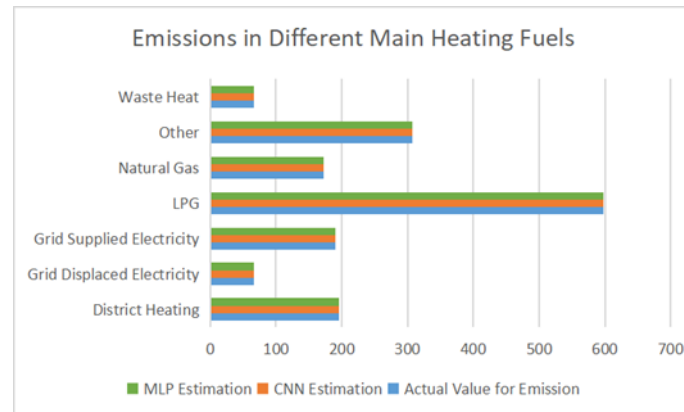


Fig 10 Comparative Results for "Main Heating Fuel"

4.2 Discussion

Based on the model results that have been mentioned previously, this research proceeds to conduct further and more comprehensive discussions as follows.

1. Among the various properties under consideration, it has been observed that social clubs, dwellings, and residential institutions emit the least amount of emissions. Conversely, libraries, museums, and galleries emit the most emissions. One potential explanation for this disparity is the notion that buildings where individuals move more frequently and swiftly have the capacity to mitigate negative impacts on the environment to a greater extent.
2. The measurement of Greenhouse Gas Emissions is deemed crucial in gauging sustainable performances based on specific benchmarks, encompassing emissions and areas, and ultimately mirroring the evaluation at the "Building Level". Nonetheless, upon closer inspection, it becomes apparent that there is no discernible discrepancy between the 3rd and 4th levels of buildings. However, the 5th level performs remarkably better in terms of sustainability. It can be seen clearly that high spec means of energy can be more sustainable such as water heat and biomass while coal and other means of fossil fuels emit most greenhouse gas, which shows the significance of energy transformation for buildings.
3. It is evident that energy sources characterized by high specifications, such as water heat and biomass, hold the potential to be more sustainable. Conversely, coal and

other forms of fossil fuels emit the highest levels of greenhouse gases, thus underscoring the criticality of energy transformation within the realm of buildings.

4. In a similar vein to heating fuels, it is observed that more advanced surroundings have the capacity to outperform their original counterparts. This observation further underscores the paramount importance of technological advancements in the realm of building development, particularly with regards to the creation of optimal building environments.

5. Conclusions

5.1 Review on Completion of Research Objectives

To be specific, this research has identified cost, costs drivers and KPI related to sustainability respectively in Section 2.4, 2.5 and 2.6. Furthermore, it conducts further analysis of cost drivers and classified them in high-level cost estimate level and detailed cost estimate level in Section 2.8. To build up a cost model, this research also has searched for data sources from Department for Levelling Up, Housing & Communities.

Besides, this research has learnt and analysed LCC methods to measure the total costs of sustainable office buildings in Denmark in Section 2.7. Grounded on this, this research has designed a basic series of steps for sustainability estimation in Section 3.5.

Last but not least, this research has built up Conv1D and MLP, two common machine learning models as contrast and applied them in sustainability cost estimation. Compared with practical values, this research has found that both models can be trained to make reasonable estimation in Section 4.1.

5.2 Feedback and Suggestions

1. In terms of the analysis of the life cycle, the existing data is not sufficiently comprehensive to account for the entire sustainability cost, as it solely focuses on the aspects of operation and maintenance, while neglecting the crucial considerations of installation and disposal. Consequently, it is more reasonable to explore the available data when considering the entire life span of buildings.
2. In the realm of sustainable development, it is crucial to engage in a holistic evaluation process that takes into account not only the measurement of emissions, but also the comprehensive analysis of various other key factors. Among these factors, one must consider the assessment of energy conservation efforts as well as the scrutiny of recycling and disposal practices. By broadening the scope of evaluation, organizations and policymakers can gain a more comprehensive understanding of sustainable performances and make informed decisions that contribute to the long-term viability of our planet.
3. The concept of sustainability is intricately intertwined with economic benefits. The cost of upgrading equipment and technology is an essential factor to be taken into account when calculating the return on investment. Furthermore, the returns resulting from the implementation of supportive policies and regulations should also be factored into the analysis.

5.3 Further Work

In total, this research has completed substantially three main research objectives. However, there is still room for development of sustainability cost estimating methodology in facilities management as follows.

Initially, this research has not adequately considered critical success factors in facilities management. However, there is a need to conduct thorough research on these factors and their impact on sustainability in cost estimating globally. It is essential for the unique challenges faced by different regions and industries. Therefore, the research should integrate critical success factors for facilities management.

Besides, there is still a need for Life-Cycle Cost Analysis enhancement. To be specific, Conv1D and MLP may not be precise if the duration real-time data increases. This research is planned to test Recurrent Neural Networks and Long Short-term Memory that can accommodate more dense data in the long term. Also, more factors given social and human aspects of sustainability, such as occupant health, well-being, productivity, and satisfaction, into the cost-benefit analysis should be considered as this research focuses on only carbon emissions from buildings.

Last but not least, it can be furthered by development of benchmarking tools and identification of best practices for sustainable cost estimating in facilities management as this research has only selected some elements of best practices in the cost estimating process. For example, some interesting best practices and standards for sustainable cost estimating can be adopted and promoted such as Life-Cycle-Cost Analysis Approach (CPG Corporation, 2022) and Facilities Management Cost Index (Werner, Jacoby and Grawert, 2022).

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