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# Improving material selection in shopping centres through a parametric life cycle embodied flow and material cost analysis model

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## Abstract

Shopping centres are significant built assets and part of the urban fabric in most developed economies. Yet very few studies have conducted a life cycle assessment of shopping centres, despite them using significant amounts of energy and resources throughout their life cycle. This paper presents a parametric model that quantifies the life cycle embodied flow (LCEF) and material cost (LCMC) of Australian shopping centres to inform material selection. Different combinations of building materials and assemblies are identified with minimum LCEF and LCMC for 13 different shop categories typical in shopping centres. The parametric model is used to simulate a case study centre which tests and analyses over 8,820 scenarios and delivers benchmark values for the LCEF and LCMC of shopping centres. It shows that a typical centre using concrete and steel, average embodied flow intensities are 14.2 GJ/m$^2$ and 830 kg$CO_2$e/m$^2$. It further demonstrates recurrent embodied flow, which is currently disregarded, is significant and represents up to 56% of the LCEF of a shopping centre over a period of 50 years. Results show that specific assembly combinations could achieve up to 32% LCEF reductions

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while saving up to 17% on material costs. Foundations and roof structure are identified as the most crucial of building elements for reducing embodied flow in the centre structure. This paper contributes to the embodied environmental impact assessment efforts and the energy-cost nexus by facilitating the appraisal and demonstrating broader societal impacts in making the built environment more economically and environmentally sustainable.

## Highlights

1. The model quantifies life cycle (LC) embodied environmental flows and cost of shopping centres.
2. LC embodied energy (LCEE), GHG emissions and cost intensities for 3 shop categories within shopping centres are proposed.
3. Average LCEE of a shopping centre using steel and concrete is 14 GJ/m² of which 56% are recurrent.
4. Specific assembly combinations could achieve up to 32% LCEE and 17% cost reductions.
5. Foundation and roof structure are the most critical assemblies for reducing embodied flows.

## Keywords

Australia; embodied energy flow; life cycle costing; material selection; object-oriented programming; shopping centres.

## Word Count

8757 words

## List of Abbreviations

| | |
|---|---|
| GHG | Greenhouse gas |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| NASA | National Aeronautics and Space Administration |
| WGBC | World Green Building Council |
| LCEE | Life cycle embodied energy |
| LCEF | Life cycle embodied flow |
| LCMC | Life cycle material cost |
| LCEGHGE | Life cycle embodied greenhouse gas emission |
| BOQ | Bills of quantities |
| OOP | Object-oriented programming |
| IEE | Initial embodied energy |
| REE | Recurrent embodied energy |
| RF | Refurbishment frequency |

## 1. Introduction

Climate change driven by anthropogenic GHG emissions from burning of fossil fuels is having observable effects on the environment with changing ecosystems, increasing surface temperatures, melting ice and other effects [1, 2]. The IEA [3] declared that 36% of total energy use and 39% of total GHG emissions are attributed to the building and construction sector globally. Reducing life cycle energy and GHG emissions in buildings is thus crucial to mitigating climate change [3, 4]. Operational energy use in buildings has exhibited a downward trend since 2000 because of the increasing use of energy efficiency measures and renewable energy sources used in buildings [3, 5, 6]. However, the positive impact caused due to these measures has been negated by the increasing embodied energy of building materials [3, 7-9]. As a result, many studies have highlighted the adverse environmental effects associated with embodied environmental flows and also have identified possible approaches to reducing those effects [5, 10-13]. The majority of these studies have focussed on residential and commercial office buildings, with the retail property sector relatively slow to adopt and embrace sustainability, both from a research and industry perspective [14-16].

Shopping centres are the most significant component of the retail property sector and an essential element in contemporary cities. Throughout their building life cycle, shopping centres experience several refurbishments and renovations [17-19]. Frequent fit-out modifications occur in order to stay abreast of current trends in consumer preferences and maintain an attractive business presence [20-23]. Additionally, due to the fixed term nature of their lease periods, tenant turnover also results in frequent refurbishments and renovations in shop fit-outs [24, 25]. Lease lengths in Australia are typically five years for speciality tenants and 20 years for anchor tenants [26]. If tenant leases are established for shorter periods or defaulted, renovations and refurbishments could occur even more frequently, increasing the investor's life cycle costs and material flows [27].

The refurbishment frequency of shopping centres is thus considered exceptionally high, with replacements every 2 to 10 years [25]. As a result, building materials used in shopping centres often experience premature replacements contributing to the depletion of natural resources [25, 28, 29]. These material replacements, which are due to economic, functional or social obsolescence [30-32], represent recurrent embodied flows (REF) and recurrent costs [12]. These increased REF result in higher life cycle embodied energy (LCEE) use and life cycle costs (LCC) [33]. However, there are currently only a limited number of studies focused on assessing life cycle embodied flows and the cost of shopping centres globally. Moreover, none have considered the shopping centre as a whole.

Informed material selection has been identified as an effective approach to reduce life cycle embodied flows of buildings [34, 35]. In addition, environmentally responsive material selection has been identified as a multi-criteria decision where cost also performs a critical role [36-41]. Identifying materials and assemblies that reduce both embodied flows and cost can enlighten decisions regarding material selection [42, 43]. These are imperative to improve the environmental performance of shopping centres as a building asset.

Shopping centres are being developed rapidly in Australia as they provide convenient, comfortable and accessible shopping opportunities for the communities they serve [44]. Despite increasing online retailing [45-47], evidence suggests that customers still have a preference for instore shopping and the associated opportunities such as socialising, exercising and refreshments [48-50]. As a result, shopping centres are reinventing and reforming into community spaces rather than just delivering retail shopping which require special features and characteristics to attract customers [44, 47, 49]. Therefore, it is vital to understand and assess embodied environmental impacts of Australian shopping centres, and to pursue more environmentally responsive building materials and assemblies for their design and construction, that can mitigate adverse effects. Learning from Australian shopping centres can also help inform shopping centres in other parts of the world.

### 1.1. Aim and scope

This research addresses the knowledge gap on LCEF and LCC assessments of shopping centres. The ultimate goal is to assess life cycle embodied energy and material cost and identify combinations of building materials and assemblies with minimum embodied energy and material cost for shopping centre design and construction in Australia. To achieve this goal, the study employs a bottom-up model allowing for the rapid analysis of thousands of scenarios to identify combinations of building materials and assemblies to minimise environmental effects and improve environmental performance in the built environment.

The study is novel as it adds to the body of knowledge on the topic of life cycle embodied environmental flows and material cost assessment of shopping centres as a building asset, which is understudied. It further documents the assessment of embodied energy and material cost of typical Australian shopping centres and identifies building materials and assemblies that lead to potential embodied energy reductions with minimal material cost increments. This study provides an understanding on the LCEE and LCMC of typical Australian shopping centres and how different shop types contribute towards these. It uses the comprehensive hybrid life cycle inventory technique to quantify embodied flows, which has not been done before. As such it provides new findings and data at very granular level which currently does not exist in the scarce scientific literature on the life cycle assessment of shopping centres. Findings can enable embodied energy assessments of similar projects and evaluation of the embodied environmental flows of alternative designs. The assembly combinations identified by the model will assist decision-makers such as architects, designers, engineers, quantity surveyors, builders and others, in sustainable material selection without compromising material costs. This also offers a platform for policy makers within the government, authorities, councils, and others, for evaluating the implications of material selection for shopping centres in Australia. In addition, the model itself is robust and usable in assessing any other building asset with minor modifications.

## 2. Existing studies on the embodied flows and cost of shopping centres

Only a limited number of studies have assessed the embodied flows of retail buildings. The term 'retail building' here involves any retail built-form from a small retail fit-out to a large shopping centre. Only three relevant studies were found; one in Canada, one in the United Kingdom and another one in China, which have considered embodied environmental flows in a retail building. These are outlined in Table 1.

Table 1: Studies on the embodied flow of retail centres

| **Study** | **Building type** | **Location** | **Gross floor area** | **Embodied flow** | | **Life cycle inventory technique** |
|---|---|---|---|---|---|---|
| | | | | **Initial** | **Recurrent** | |
| *Fridley, Zheng [51]* | Shopping centre | China | N/A | 10 GJ/m$^2$ | Not calculated | Process analysis |
| *Fieldson and Rai [25]* | Retail fit-out (Department stores) | United Kingdom | 5000 m$^2$ | 0.04 $tCO_2e/m^2$ | Not calculated | Process analysis |
| *Van Ooteghem and Xu [52]* | Retail | Canada | 586 m$^2$ | 8.95 GJ/m$^2$ | | Process analysis |

[53] found that a shopping centre's initial embodied energy intensity in China was 10 GJ/m$^2$, which was the highest value of all commercial buildings investigated. Investigating the GHG emissions of a

department store fit-out in the UK, [25] found that the use of timber-based products and materials that are less processed, along with the elimination of suspended ceilings can substantially reduce embodied GHG emissions over the life cycle. [52], however, found that the development of a retail building in Canada using steel building structure led to significant embodied energy savings in comparison to alternative scenarios of timber and hot rolled steel structures. The difference in roof systems was cited as the main reason for the variation, where the pre-engineered steel scenario used a commercial standing steel roof, but the others used a 4-ply built-up asphalt roof system with higher embodied energy.

These studies, therefore, indicate that retail building structures become more embodied energy efficient with the use of pre-engineered steel systems. In addition, fit-outs are more energy efficient when timber-based and natural products are used. However, none of the existing studies conducted assessments at the shopping centre level by including all shops and common areas. Due to the frequent refurbishments that occur in speciality shops and common areas, it is vital to perform a more comprehensive assessment to identify the embodied environmental impacts of shopping centres and to evaluate potential emission reductions approaches.

In conclusion, all existing studies rely on process analysis for their life cycle inventory which is problematic. Process LCIs systematically underestimates embodied environmental flows due to inherent truncation error [54, 55]. Studies relying on the more comprehensive hybrid LCI [54, 56] are needed to provide a more comprehensive assessment of embodied environmental flows in shopping centres. Hybrid LCIs have been demonstrated to produce embodied environmental flows figures up to 2-4 times higher than process LCIs, at a whole building level [5, 57]. This demonstrates there is a gap in knowledge regarding life cycle embodied flows and cost assessment for shopping centres. In particular, how embodied environmental flows and cost data can be used for in material selection decision-making.

In light of the above, this study provides the most detailed and comprehensive life cycle embodied energy, GHG emissions and cost analysis of shopping centres to date using a Python-based bottom-up model. The parametric model enables rapid analysis of thousands of scenarios to assist decision making on material selection for shopping centres. The research design is presented in the next section.

# 3. Material and methods

## 3.1. Modelling the life cycle embodied energy, greenhouse gas emissions and material cost of Australian shopping centres

The study followed the steps presented in Figure 1 to address the research aim. The review of the prevailing literature demonstrated a gap for life cycle assessment and life cycle cost analysis of shopping centres. It further showed that the currently available academic and commercial tools for selecting environmentally sensitive building materials demonstrated a gap for shopping centres, addressing their unique refurbishment frequencies. Hence, we incorporated two main research methods to achieve the aim, namely a case study method and a mathematical and parametric life cycle assessment.

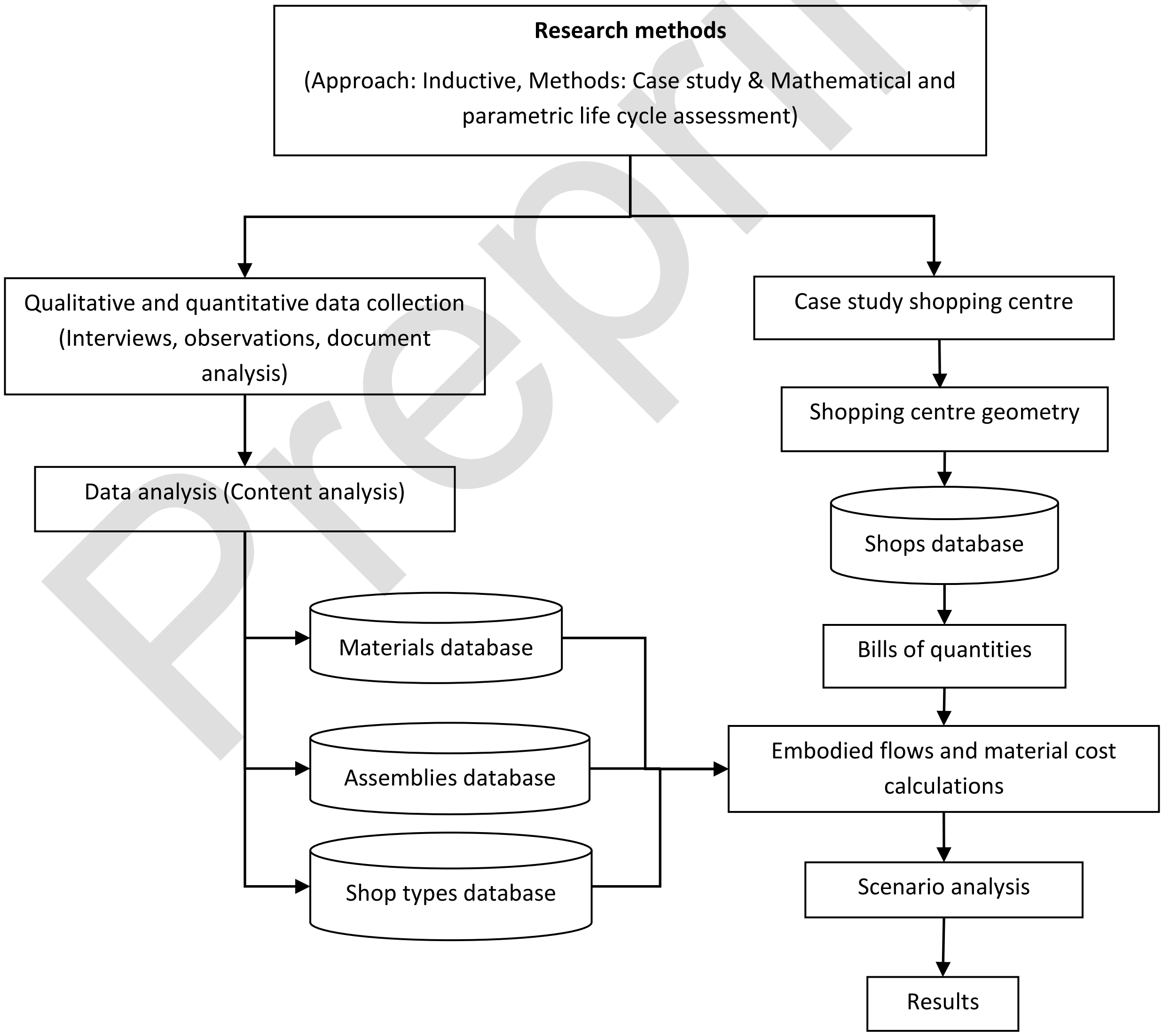


Figure 1: Research design

A mathematical model is used to quantify LCEF (LCEE and LCEGHG emissions) and LCMC of different building materials combinations for case study buildings. LCEF and LCMC calculations of shopping centres are complex tasks due to building sizes and the use of extensive amounts of different building materials and assemblies. Calculation processes demand a range of data inputs of materials and assemblies and their respective quantities, along with other data intensive matrix calculations.

A key requirement of the model was to conduct scenario analysis, where the embodied environmental flows and material cost of different assembly combinations are assessed and compared rapidly. The model architecture required resilience and flexibility. The model development approach was, therefore, selected critically considering the identified requirements. Accordingly, object-oriented programming was selected as the modelling approach for developing the mathematical model. Among several other programming paradigms in Python that can be adapted, such as imperative, functional, procedural, and object-oriented [58-60], the latter was identified as the most suitable concerning the requirements stated above due to its pragmatic nature.

The study used a case study for data collection and the application of the object-oriented model. The case study was used to set the business as usual (BAU) scenario of Australian shopping centres in terms of material selection and assess LCEF and LCC. A single-storey subregional shopping centre that represented the 'typical' Australian shopping centres [61] was selected as the case study to model and simulate different scenarios.

The case study method incorporates both qualitative and quantitative data collection in the research; hence a mixed-method approach was adopted [62]. Qualitative data was collected through semi-structured interviews, document analysis and on-site observations. Semi-structured interviews were selected to gather qualitative data on materials and assembly types as well as a to validate the data on refurbishment frequencies of shop types gathered from published articles. The interviewees included professionals involved in shopping centre developments, management bodies and shopping centre managers themselves. Qualitative data, including building materials, their specifications and construction assemblies, were directly used as inputs to the model. Quantitative data was also collected through interview findings, document analysis, and observations. Even though quantitative values were directly used, qualitative data needed to be converted to quantitative format to be used in the model. For example, different building materials were provided with unique identification numbers used in model calculations. The model was tested using the case study, and the results generated were then analysed. As such, the semi-structured interviews conducted were not analysed deeply since the responses were not expressions of extensive opinions but direct data points that could be used as input in the model. For instance, interview questions gathered data on refurbishment frequencies of shop types and types of replacement materials used in shop fitouts, which were directly used as data inputs to the model. Therefore, an in-depth content analysis was not required of the interview responses but only a preliminary screening was conducted.

### 3.2. Developing an object-oriented program in Python

The mathematical model relies on object-oriented programming in Python to carry out life cycle embodied flows and material cost assessments and to identify combinations of building assemblies for different shop types in shopping centres. OOP is a programming paradigm organised around "objects" and data [60]. Objects with different attributes and methods are classified under different classes [58]. The development of the model comprised two stages; (1) databases and (2) computing core development. The paper defines four classes as *Material*, *Assembly*, *Shop* and *ShoppingCentre* in the computing core. The model uses the methods and attributes of these classes to create objects of *Materials*, *Assemblies, Shops* and *ShoppingCentres* using input data.

Data inputs included types of building materials and assemblies, embodied energy coefficients (from the EPiC database by [63], service life values [64] of materials, and refurbishment frequency values of shops [25, 26]. Table 2 outlines the qualitative and quantitative data collected through different means and sources. Data were collected using various techniques, including semi-structured interviews, observations on site, desktop studies, literature findings and project document analysis. Semi-structured interviews were carried out with shopping centre developers and management bodies. Twenty subregional shopping centres were visited to gather further data on types of building materials and assemblies used.

Table 2: Data requirements and their sources

| Data type | Source | Description | Implementation |
|---|---|---|---|
| ***Quantitative data*** | | | |
| Embodied energy coefficients | EPiC database [63] | Open access database of embodied flows coefficients for construction materials | A numerical attribute of a material object |
| Embodied GHG emission coefficient | EPiC database [63] | Open access database of embodied flows | A numerical attribute of a material object |

| | | | |
|---|---|---|---|
| | | coefficients for construction materials | |
| Material prices | Rawlinson's cost guide, material supplier details | Cost data published by industry | A numerical attribute of a material object |
| Refurbishment frequencies | Maintenance schedules of case study buildings, semi-structured interview with subregional shopping centre management, tenant leases, existing studies | | A numerical attribute of a shop object |
| Service life values | [64], existing studies | | A numerical attribute of an assembly object |
| ***Qualitative data*** | | | |
| **Materials and assemblies** | Existing studies, semi-structured interviews, project documents, other published data | | Converted to a numerical attribute by assigning unique IDs as material and assembly objects |

These inputs were stored as quantitative data in five different databases, namely *Materials*, *Assemblies*, *Shops_catalogue*, *Shops* and *Shopping_centres*. The *Materials* database stores data inputs of materials (i.e. brick, mortar, block) that are used in shopping centre construction in Australia. Data fields include material ID, material name, embodied energy coefficient, embodied greenhouse gas coefficient, service life values, and several others. The construction *Assemblies* database contains details on different assemblies (i.e.110 mm brick wall, 140 mm block wall) through basic fields as assembly ID, assembly name, assembly type and assembly service life values. Assemblies are defined under eleven types based on the [65] elemental categories as *foundation, roof structure, columns, structural wall*, *internal wall, window, lintel, floor finish, wall finish, ceiling finish* and *waterproofing*. More than 60 construction assemblies were categorised under these types. The *Assemblies* database also contains materials and respective quantities that go into a unit quantity of each assembly. *Assemblies* database is provided in open access[2].

Data on different types of shops in shopping centres were stored in the *Shops_catalogue* database. In Australian shopping centres, 13 different types of shops were identified, including *supermarkets* and *discount department stores* as *anchor shops,* and *specialty shops* include *clothing, café and restaurant, health and beauty,* and *services*. These are defined in the typical tenancy mix of shopping centres in

[2] https://doi.org/10.6084/m9.figshare.19930022.v1

Shopping Centre Council of Australia. In the *Shops_catalogue* database, these shop types are defined with the combinations of assemblies used in the business-as-usual scenario of the shop design and construction, along with shop refurbishment frequencies.

A shopping centre usually consists of two parts: 1) centre structure and 2) internal layout. The *centre structure* is the core building of all structural elements (i.e. *foundation, roof, columns, structural wall*). The internal layout contains all fit-out designs of *anchor shops, specialty shops* and *common areas*. All these are considered as shop types for modelling purposes. *Specialty shops* are defined to have *internal walls, floor finishes, wall finishes* and *ceiling finishes*, but *anchor shops* have *structural walls*, instead of *internal walls* since they have a longer life span.

The *Shop* database contains data inputs of shop geometries. All shops in the case study shopping centre were included in the *Shops* database with basic geometries. Shops are modelled using a 'shoe-box' approach, as presented in Figure 2. Accordingly, a shop is considered as a box with a length (l), width (w) and height (h) and in some cases a span. These parameters are combined to generate bills of quantities.

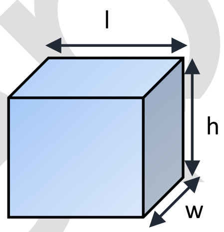


Figure 2: Shoe-box scenario used in the object-oriented model to define shop geometries

In the *Shop* class, bills of quantities are created using the basic geometry of parametric shop designs. This process is critical since the quantification of building elements can affect the findings of the study. Furthermore, this automated BOQ generation enables rapid quantification and adds flexibility to the model. Any modifications to the parametric shops in the *Shops* database can easily be adjusted in the *Shop* objects through the automated BOQ generation. The calculation of the quantities of building elements which are considered as assembly types, is undertaken using the equations presented in Table 3.

Table 3: Equations used to generate bills of quantities of shops in the model

| Assembly Type | Unit | Equation |
|---|---|---|
| Foundation | $m^2$ | $QFD_S = l_S \times w_S$ |

| | | |
|---|---|---|
| Columns | m² | $QCL_S = \frac{w_S}{s_S} \times \frac{l_S}{s_S} \times h_S$ |
| Roof structure | m² | $QRS_S = QFD_S$ |
| Structural wall – Centre structure | m² | $QSW_{CS} = \left(l_{S_{cs}} + w_{S_{cs}}\right) 2 \times h_{S_{cs}} - \left(0.1 \times l_{S_{cs}} \times w_{S_{cs}}\right)$ |
| Structural wall - Anchor | m² | $QSW_S = \left(l_{S_A} + w_{S_A}\right) \times h_{S_A} - \left(0.1 \times l_{S_A} \times w_{S_A}\right)$ |
| Internal wall | m² | $QIW_S = (l_S + w_S) \times h_S - (0.1 \times l_S \times w_S)$ |
| Window | m² | $QWI_S = (0.1 \times l_S \times w_S)$ |
| Lintel | m | $QLI_S = (QWI_S / h_S)$ |
| Wall finish - External | m² | $QWF_S = (l_S + w_S) \times 2 \times h_S - (0.1 \times l_S \times w_S)$ |
| Wall finish – Internal | m² | $QWF_S = (l_S + 2w_S) \times h_S - (0.1 \times l_S \times w_S)$ |
| Ceiling finish | m² | $QCF_S = l_S \times w_S$ |
| Floor finish | m² | $QFF_S = l_S \times w_S$ |
| Waterproofing | m² | $QWP_S = l_S \times w_S$ |

*$QFD_S$= Quantity of foundation in shop s; $QCL_S$= Quantity of columns in shop s; $QRS_S$= Quantity of roof structure in shop, s; $QSW_{CS}$= Quantity of structural wall in centre structure; $QSW_S$= Quantity of structural wall in anchor shop; $QIW_S$= Quantity of internal wall in shop s; $QWI_S$= Quantity of windows in shop s; $QLI_S$= Quantity of lintels in shop s; $QWF_S$= Quantity of wall finish in shop s; $QCF_S$= Quantity of ceiling finish in shop s; $QFF_S$= Quantity of floor finish in shop s; $QWP_S$= Quantity of waterproofing in shop s; $l_S$= Length of shop s; $w_S$= Width of shop s; $h_S$= Height of shop s.*

The next function of the *Shop* class is to quantify the life cycle embodied flows and material costs of the shops. The following section presents the estimation process.

### 3.3. Quantification of life cycle embodied energy, embodied greenhouse gas emissions and material cost

The embodied flow at the building material level can be estimated using three life cycle inventory analysis approaches, namely: process analysis, input-output analysis and hybrid analysis., Prior studies have found that embodied flow intensities derived using input-output-based hybrid analysis provide the largest coverage of system boundaries and are identified as the most comprehensive values that can be obtained at a material level [54, 66, 67]. Therefore, this study uses material EFC from the EPiC database developed by [63], based on an input-output-based hybrid analysis, to quantify the LCEF of shopping centres. These coefficients are developed for building materials used in Australia and are thus more specific to the research context. As time is an influential factor in the calculation of material energy coefficients and reliability of data, the EPiC database by Crawford et al. (2019) was considered the most suitable for this study. This was because it was the most recently developed database and the only database of hybrid embodied flow coefficients for construction materials globally. The initial embodied flow (IEF) and recurrent embodied flow (REF) of materials and assemblies used in shopping centres were calculated based on these hybrid EFC to determine LCEF. Materials that do not have exact EFC were assigned with proxy figures based on a similar material [68]. Recurrent embodied flow was calculated considering service life, durability and maintenance requirements of the materials and assemblies using the replacement rate of assembly equation in Table 4. Replacement rate of materials and assemblies was determined based on the service life value of the assembly and refurbishment frequency of the shop types. It was considered extremely significant for LCEF and LCMC calculations as they have a direct impact on the embodied flow and material cost figures over the life span of a shopping centre.

The estimation of LCMC of a building consists of the information of capital cost, expected service life, costs of maintenance required, demolition or dismantling, and removal costs. Present values of the future costs were considered as cost-in-use to account for the time value of money. These future costs were therefore converted to present value for calculation purposes using the net present value approach. NPV is an economic evolution analysis method that demonstrates the benefits or expenses by discounting the investments to present value [69]. This method is proven to be very useful when determining long-term profitability. Future cash flows over the time horizon were adjusted using a discount rate using the present value formula. The discount rate for calculation was derived depending on time value of money and financial risks associated. In previous studies, the discount rate has been derived based on factors such as inflation, cost of capital, time value of money, and investment opportunities [70, 71]. The discount rate for this study was determined based on the real interest rate of the Reserve Bank of Australia in 2020. Real interest rate was used to remove the effects of inflation as the equation accounts for real price escalation. The NPV formula was used at different building levels to calculate material financial flows at different periods. The real price escalation rate accounts for price escalation of building materials in the future. Cost-in-use calculations of the shops also used replacement rate of materials and assemblies for comparison purposes.

Equations used for quantifying embodied environmental flows and material costs of the shopping centre are presented in Table 4.

Table 4: Equations used for life cycle embodied flow and material cost estimation

| Measurement | Equation |
|---|---|
| Life cycle embodied flow of the shopping centre | $LCEF_{s,a}^{SC} = \sum_{s=1}^{S}\sum_{a=1}^{A} IEF_{a,s,sc} + \sum_{s=1}^{S}\sum_{a=1}^{A} REF_{a,s,sc}$ |
| Initial embodied flow of the shopping centre | $IEF_{s,a}^{SC} = \sum_{s=1}^{S}\sum_{a=1}^{A}\sum_{m=1}^{M} EFC_m \times Q_{m,a} \times Q_{a,s} \times WF_a$ |

| | |
|---|---|
| Recurrent embodied flow of the shopping centre | $REF_{s,a}^{\mathrm{SC}} = \sum_{s=1}^{S}\sum_{a=1}^{A}\sum_{m=1}^{M} RR_a \times EFC_m \times Q_{m,a} \times Q_{a,s} \times WF_a$ |
| Replacement rate of an assembly in a shop | $RR_{a,s} = \left\{\left\lceil \frac{POA}{SL_{a,s}} - 1 \right\rceil \Leftrightarrow \left\lceil \frac{POA}{SL_{a,s}} - 1 \right\rceil \leq RF_s \right\}$ OR <br> $RR_{a,s} = \left\{ RF_s \Leftrightarrow \left\lceil \frac{POA}{SL_{a,s}} \right\rceil > RF_s \right\}$ |
| Life cycle material cost of the shopping centre | $LCMC_{s,a}^{\mathrm{SC}} = \sum_{s=1}^{S}\sum_{a=1}^{A} CC_{a,s,sc} + \sum_{s=1}^{S}\sum_{a=1}^{A} CIU_{a,s,sc}$ |
| Capital cost of the shopping centre | $CC_{s,a}^{\mathrm{SC}} = \sum_{s=1}^{S}\sum_{a=1}^{A}\sum_{m=1}^{M} (Q_{m,a} \times UP_m \times Q_{a,s} \times WF_a)$ |
| Cost in use of the shopping centre | $CIU_{s,a}^{\mathrm{SC}} = \sum_{s=1}^{S}\sum_{a=1}^{A} ( Q_{m,a} \times UP_m \times Q_{a,s} \times WF_a \times \sum_{i=1}^{I} \left[ \frac{(1+g)^{(i-1)}}{(1+r)^{i}} \right])$ |

*$LCEF_{s,a}^{SC}$= Life cycle embodied flow of the shopping centre sc, (e.g. in GJ for energy); $IEF_{s,a}^{SC}$= Initial embodied flow of assembly a, in shop s in the shopping centre sc, (e.g. in GJ for energy); $REF_{s,a}^{SC}$= Recurrent embodied flow of assembly a, in shop s in the shopping centre sc,, (e.g. in GJ for energy); $EFC_m$= Embodied flow coefficient of material m, in assembly a, (e.g. in GJ/ functional unit for energy); $Q_{m,a}$= Quantity of material m in unit quantity of assembly a, in functional units (e.g. kg of steel); $Q_{a,s}$= Quantity of assembly a, in shop s in functional units (e.g. $m^2$ for flooring); $WF_a$= Wastage factor of assembly a; $RR_{a,s}$= Replacement rate of assembly a in shop s; $POA$= Period of analysis of shopping centre in years; $SL_{a,s}$= Service life of assembly a, in shop s in years; $RF_s$= Refurbishment frequency of shop s in years; $LCMC_{s,a}^{SC}$= Life cycle material cost of shopping centre sc, in currency units; $CC_{s,a}^{SC}$= Capital cost of assembly a, in shop s, in shopping centre sc, in currency units; $CIU_{s,a}^{SC}$= Cost in use of assembly a, in shop s, in shopping centre sc, in currency units; $UP_m$= Unit price of material m, in currency units/ functional unit (e.g. AUD/kg for steel); $g$= Real price escalation rate at 1.9%; $r$= Real interest rate at 3.304%; $i$= Replacement years (e.g. 5,10,…,45, if replacement rate is 5).*

The next section presents the details of the selected case study shopping centre.

## 3.4. Case study shopping centre

The case study research method provides the ability to study and analyse the building as a single integrated unit [72, 73]. This method is used when a holistic, in-depth analysis of a particular matter is required [74]. This paper examines the Australian shopping centres, where the researcher had no control over the relevant behaviours and data collected through observations on-site, document analysis, and interviews. Hence, the selection of the case study method in this study can be justified. This paper adopts a single case study approach as its main research method as the system that is studied (embodied flows on a shopping centre) is common, but data is difficult to obtain due to commercial confidentiality, making the case study critical and indicatory in nature, as described by [62]. In addition, the focus of the study is relatively novel and there are no existing datasets, containing consistent information on a large sample of the population (i.e. large shopping centres) to be readily used. When adopting a single case study approach, the case needs to be chosen carefully to be representative of the population that needs to be studied in order to maximise the external validity (extrapolation) of the results [62, 75]. In this case, the population studied comprises subregional shopping centres in Victoria, Australia.

The selected case study is a single storey subregional shopping centre representing the majority of the average Australian shopping centres based on the gross lettable area[3] [76]. They currently represent the largest share of Australian shopping spaces (5,246,278 $m^2$) representing 21% of the shopping centre floor space, and a broad pipeline of projects are planned to be constructed within the next few years [76, 77]. Single storey subregional shopping centres represent more than 80% of their total [76], hence selected for this study. The selection was primarily based on the benchmarks defined in Table 5. The benchmark values were calculated based on all subregional shopping centres in Victoria [76]. The composition of speciality shops in internal layout in the centres needed to follow the Shopping Centre Council of Australia's typical tenant mix. The statistical parameter 'median' of benchmark values was selected instead of 'mean' for selection purposes since it is robust against outliers and also provides a more realistic representation of the data set across a skewed distribution.



Table 5: Case study profile

| **Criteria** | **Median of benchmark values** | **Case study values** | **Relative difference** |
|---|---|---|---|
| No of anchor tenants | 3 | 3 | 0% |
| Anchor tenants-Gross lettable area retail ($m^2$) | 11,660.00 | 12,100.00 | +4% |
| No of specialty stores | 49 | 47 | -4% |
| Specialty- Gross lettable area retail ($m^2$) | 6,381.00 | 5,802.00 | -9% |
| Total Centre- Gross lettable area retail ($m^2$) | 17,490.00 | 20,250.00 | +16% |
| Total Centre- Gross lettable area ($m^2$) | 18,426.00 | 22,498.00 | +22% |
| Specialty proportion | 34.44% | 39.00% | +13% |
| Anchor proportion | 63.00% | 60.00% | -5% |
| Cinemas | No | No | No difference |
| Centre type | Enclosed | Enclosed | No difference |
| Ventilation | Fully airconditioned | Fully airconditioned | No difference |
| Enclosed car bays | No | No | No difference |
| Tenant mix | | | |
| Anchor | | | |
| Supermarket | 32.00% | 28.15% | -12% |
| Discount department store | 28.00% | 31.60% | +13% |

[3] The floor space contained within a tenancy at each floor level as per Method of Measurement for Lettable Area published by Property Council of Australia.

| | | | |
|---|---|---|---|
| Specialty | | | |
| Clothing | 4.00% | 2.00% | -50% |
| Food supplies | 5.50% | 7.38% | +34% |
| Household | 5.25% | 11.54% | +120% |
| Multimedia and electronics | 1.25% | N/A | N/A |
| Gymnasium | 1.50% | 2.01% | +34% |
| Leisure and entertainment | 2.75% | 0.46% | -83% |
| Health and beauty | 1.50% | 4.80% | +220% |
| Coffee and restaurant | 2.50% | 4.71% | +88% |
| Other retail | 2.50% | 0.10% | -96% |
| Shoes | 1.25% | 0.52% | -58% |
| Services | 12.00% | 6.73% | -44% |

The selected case is located approximately 27 km west of Melbourne's central business district, in Tarneit (climate zone 6: mild temperature) [78]. The actual floor plan of the case study shopping centre is presented in Figure 3. However, simplified shop designs were used for modelling purposes, as discussed in Section 3.1.

The next section discusses the details on scenario modelling.


Figure 3: Case study shopping centre floor plan

## 3.5. Scenario modelling

As explained in Section 3.2, assemblies of different types are combined to construct a shop. Different shop combinations are generated for all shop types using the assemblies defined in the *Assemblies* database. The assembly combinations of the shop variations are used to determine the combinations minimising LCEE, LCEGHGE and LCMC. A shop level analysis is carried out as scenario modelling consisting of five different scenarios, hereinafter referred to as; *minimum life cycle embodied energy (LCEE)*, *minimum life cycle embodied GHG emissions (LCEGHGE), minimum life cycle material cost (LCMC)*, and *optimal* (which minimises both LCEF and LCMC equally) and comparing them with the *business as usual (BAU)* scenario (which is the most typical assembly combination used in construction) defined in the *Shops_catalogue* database. More than 8000 material combinations were considered for the analysis.

## 3.6. Data availability

We strongly believe in data transparency and the reproducibility of results. As per best practice recommendations from the field of Industrial Ecology [79], we made all relevant supporting data available through Figshare[4], as a citable document.

These data include:

- The database of assemblies;
- The embodied flow and material cost intensities of different shop categories in an Australian shopping centre; and
- Other relevant data.

# 4. Results

This section presents the results obtained under the five scenarios of the *business as usual (BAU)*, *minimum LCEE, minimum LCEGHGE, minimum LCMC* and the *optimal* of different shop categories and the shopping centre. The analysis is presented at the shop level and at the whole shopping centre level.

[4] https://doi.org/10.6084/m9.figshare.19930022.v1

## 4.1. Centre structure results

The *centre structure* or the building shell is the largest shop type in the shopping centre, as defined in the model. The *centre structure* comprises all structural assembly types (*foundation, column,* and *roof structure*), some envelope assembly types (*structural wall, window,* and *lintel*), and only a single finishes assembly type (*wall finish*). The period of analysis is 50 years, and no refurbishments are assumed to the structure during that time. The shoe-box model is 240 m in length, 88 m wide, 10 m high and has a structural span of 9 m. This results in a total gross lettable area of 22,498 $m^2$. The model compared about 720 material combinations, including the BAU combination of concrete slab-on-grade foundation with general purpose Portland cement, steel columns, steel roof structure with Colourbond roof sheets, precast concrete panel walls, metal framed glass windows, steel lintels and sheet metal cladding structural wall finish.

Table 6 presents the embodied environmental flows and material costs for the *centre structure* across different scenarios discussed in Section 3.5.

Table 6: Comparison of life cycle embodied energy, embodied GHG emissions and material cost across different scenarios of the centre structure

| Criteria | Business as usual | Minimum life cycle embodied energy | Minimum life cycle embodied GHG emissions | Minimum life cycle material cost | Optimal |
|---|---|---|---|---|---|
| Initial embodied energy ('000 GJ) | 105.6 | 97.2 (-8%) | 97.2 (-8%) | 100.1 (-5%) | 98.4 (-7%) |
| Recurrent embodied energy ('000 GJ) | 8.1 | 7.9 (-2%) | 7.9 (-2%) | 8.1 (0%) | 7.9 (-2%) |
| Life cycle embodied energy ('000 GJ) | 113.7 | 105.0 (-8%) | 105.0 (-8%) | 108.1 (-5%) | 106.3 (-7%) |
| Capital cost (million AUD) | 21.6 | 21.6 (0%) | 21.6 (0%) | 21.2 (-2%) | 21.3 (-1%) |
| Cost in use (million AUD) | 0.3 | 0.3 (0%) | 0.3 (0%) | 0.3 (0%) | 0.3 (0%) |
| Life cycle material cost (million AUD) | 21.9 | 21.9 (0%) | 21.9 (0%) | 21.5 (-2%) | 21.7 (-1%) |
| Life cycle embodied greenhouse gas emission (tonne $CO_2e$) | 6,682 | 6,175 (-8%) | 6,175 (-8%) | 6,356 (-5%) | 6,246 (-7%) |

Figure 4 shows that the IEE represents a larger share of LCEE (*93%*) across all scenarios. This is because the *centre structure* is assumed to have a refurbishment frequency of 50 years, and the service life values of most structural assemblies used in the *centre structure* typically exceed the refurbishment frequency resulting in lower REE. A similar observation can be made on the capital cost contribution, which represents around 99% of the LCMC across all scenarios.

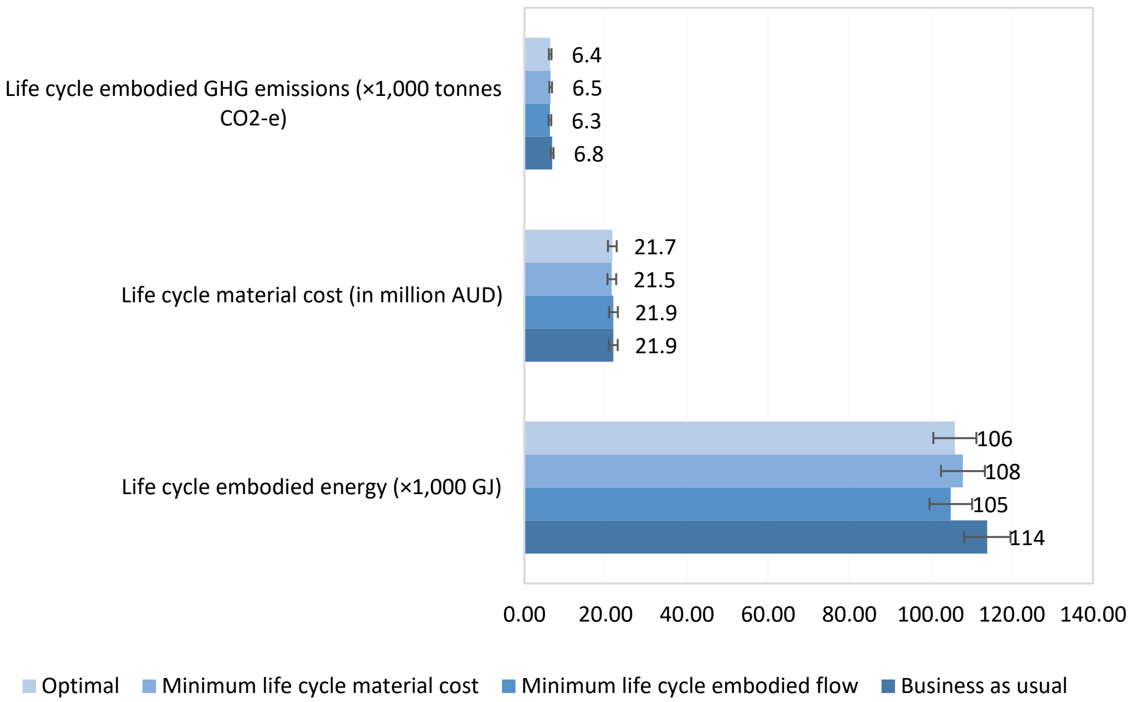


Figure 4: Life cycle embodied energy, embodied greenhouse gas emissions and material cost distribution across centre structure scenarios



The *BAU* scenario is identified as a generic *centre structure* design in Australia. The IEE intensity of the scenario is 4.7 GJ/m$^2$, whereas the CC intensity is 959 AUD/m$^2$. Percentage contributions of IEE of the *BAU* scenario show that the *roof structure (63%)* is responsible for the largest share of IEE followed by *foundation (22%)*. IEE contributions of other assembly types are significantly lower and, when combined, are responsible for around 15% of the total. The CC contributions also follow a similar pattern where the *roof structure (78%)* has the highest contribution, followed by *foundation (10%)* and *structural wall (8%)*. The CIU and REE of the *centre structure* is significantly low when compared to IEE and CC because only the *finishes* assemblies are replaced over the period of analysis. The REE is 0.4 GJ/m$^2$, and the CIU is 14 AUD /m$^2$. Hence the LCEE, LCEGHGE and LCMC intensities of the *centre structure* are quantified as 5.1 GJ/m$^2$, 0.3 tonne$CO_2$e/m$^2$ and 973 AUD/m$^2$, respectively, dominated by initial inputs.

The LCEE intensity of the *minimum LCEE* scenario is 4.7 GJ/m², which is an 8% reduction from the *BAU* scenario. However, the LCMC intensity is slightly higher *(<+1%)*, which is estimated at 974 AUD/m². The *minimum LCMC* scenario has an LCEE intensity of 4.8 GJ/m² and an LCMC of 957 AUD/m². Compared to the *BAU* scenario, LCEE shows a 5% reduction, whereas LCMC shows only a 2% reduction. Therefore, it can be stated that the *minimum LCMC* assembly combination is a better solution than the *BAU* scenario in both LCEE and LCMC aspects. The *optimal* scenario leads to LCEE savings *(-7%)* when compared to the *BAU* scenario as well as LCMC *(-1%).* However, when compared to the *minimum LCEE* scenario, the savings are reversed, where LCEE is increased and LCMC is reduced *(<1%)*. The results conclude that in the shopping centre structure there is very little variations and scope for improvements in terms of material selection.

### 4.2. Anchor shop results

The analysis for *anchor shops* is carried out for a *discount department store* representing the shop category. It consists of a single envelope assembly type (*structural wall*) and all finishes assembly types (*wall finish, floor finish, ceiling finish*). The refurbishment frequency is taken as 20 years. The shoe-box model is 93 m in length, 58 m wide, and 8 m high. This results in a total gross lettable area of 5,394 m².

The summary comparison of the LCEE, LCEGHGE and LCMC is presented in the table below. The model compared 149 variations, including the BAU scenario of precast concrete panel walls, plasterboard lining with paint on timber frame ceiling, porcelain floor tiles and water-based paint cement mortar screed with white putty wall finish.

Table 7: Comparison of life cycle embodied energy, embodied GHG emissions and material cost across different scenarios of the anchor shop (discount department store)

| Criteria | Business as usual | Minimum life cycle embodied energy | Minimum life cycle embodied GHG emissions | Minimum life cycle material cost | Optimal |
|---|---|---|---|---|---|
| Initial embodied energy ('000 GJ) | 7.6 | 3.5 (-54%) | 3.5 (-54%) | 7.1 (-7%) | 7.6 (0%) |
| Recurrent embodied energy ('000 GJ) | 15.7 | 6.4 (-59%) | 6.4 (-59%) | 14.0 (-11%) | 15.7 (0%) |
| Life cycle embodied energy ('000 GJ) | 23.3 | 9.9 (-58%) | 9.9 (-58%) | 21.2 (-9%) | 23.3 (0%) |
| Capital cost (million AUD) | 0.9 | 1 (+11%) | 1 (+11%) | 0.7 (-22%) | 0.9 (0%) |
| Cost in use (million AUD) | 1 | 0.9 (-10%) | 0.9 (-10%) | 0.6 (-40%) | 1 (0%) |

| | | | | | |
|---|---|---|---|---|---|
| Life cycle material cost (million AUD) | 1.9 | 1.9 (0%) | 1.9 (0%) | 1.3 (-32%) | 1.9 (0%) |
| Life cycle embodied greenhouse gas emission (tonne $CO_2e$) | 1,366 | 584 (-57%) | 584 (-57%) | 1,243 (-9%) | 653 (-52%) |

In *anchor shops*, the REE and CIU represent a significant share of the LCEE and LCMC as their percentage contributions vary between 65-67% and 48-51%, respectively, across all scenarios.

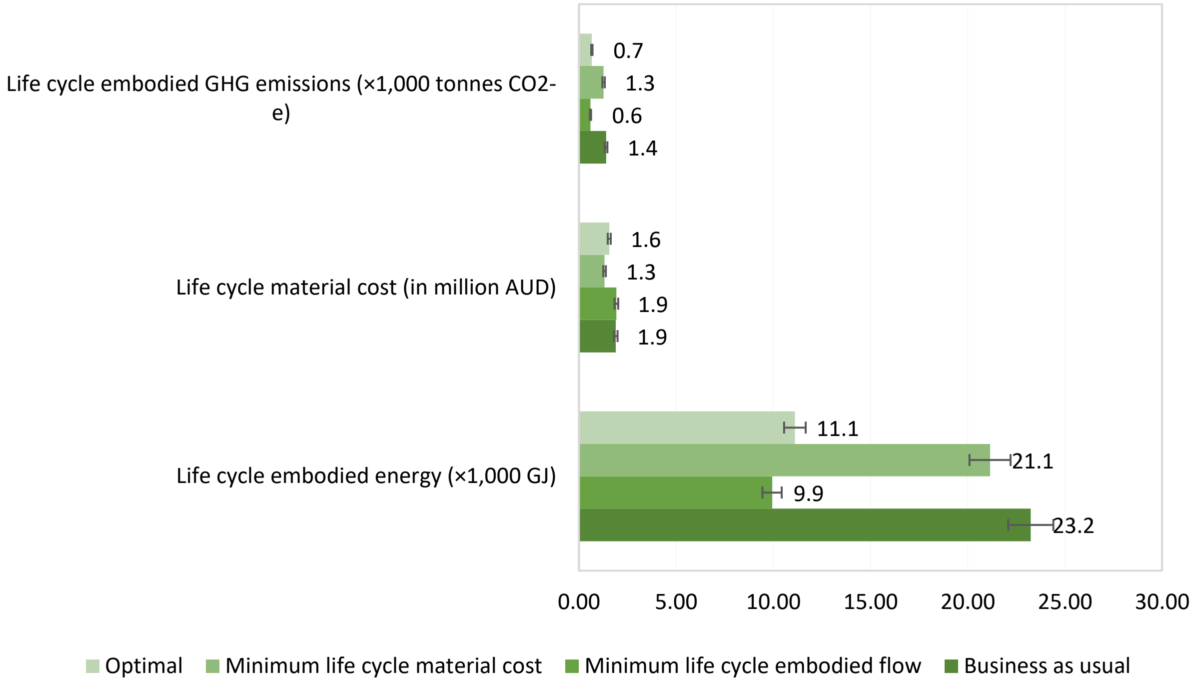


Figure 5: Life cycle embodied energy, embodied greenhouse gas emissions and material cost distribution across anchor shop scenarios

The LCEE intensity of the *BAU* scenario is 4.3 GJ/m$^2$, and the LCMC intensity is 351 AUD/m$^2$. The comparison of assembly types reveals that in the *BAU* scenario, *floor finish (54%)* contributes the most to LCEE followed by *ceiling finish (35%), wall finish (9%)* and *structural wall* (2%*)*. However, the LCMC distribution shows that *floor finish (47%)* is responsible for the largest contribution followed by *ceiling finish (30%), structural wall (14%)* and *wall finish (9%).*

The *minimum LCEE* and *minimum LCMC* scenarios show that LCEE and LCMC can be reduced by up to 57% and 30%, respectively, in comparison to the *BAU* scenario with the specified assembly combinations. The LCEE and LCMC of the *optimal* scenario have intensities of 2.1 GJ/m$^2$ and 289 AUD/m$^2$, respectively. The LCEE reduction and LCMC increment in the *optimal* scenario, in comparison to the *minimum LCMC* scenario, is caused by the change of the *floor finish* assembly from *ceramic tiling* to *terrazzo flooring,* which is environmentally responsive yet expensive. However, the assembly combination still results in 52% LCEE saving and 18% LCMC saving when compared to the *BAU* scenario. Results concluded that significant embodied flow and material cost reductions are possible for anchor shops with specific material combinations.

### 4.3. Specialty shop results

*Services* shop type is selected to represent the *specialty shops* since they account for the largest share of GLA of *specialty shops*. It consists of a single envelope assembly type (*internal wall*) and all finishes assembly types (*wall finish, floor finish, ceiling finish*). The refurbishment frequency is taken as 5 years. The shoe-box model is 20 m in length, 14 m wide, and 4 m high. This results in a total gross lettable area of 280 $m^2$. 1175 variations were considered including the BAU of steel stud wall, water-based paint on plasterboard, timber framed plasterboard ceiling and terracotta tiled flooring.

The comparison of LCEE, LCEGHGE and LCMC across the scenarios are presented in Table 8.

Table 8: Comparison of life cycle embodied energy, embodied GHG emissions and material cost across different scenarios of the specialty shop (services)

| Criteria | Business as usual | Minimum life cycle embodied energy | Minimum life cycle GHG emissions | Minimum life cycle material cost | Optimal |
|---|---|---|---|---|---|
| Initial embodied energy ('00 GJ) | 5.1 | 2.1 (-59%) | 2.1 (-59%) | 3 (-41%) | 2.5 (-51%) |
| Recurrent embodied energy ('00 GJ) | 45.9 | 18.9 (-59%) | 18.9 (-59%) | 27.4 (-40%) | 22.4 (-51%) |
| Life cycle embodied energy ('00 GJ) | 51 | 21 (-59%) | 21 (-59%) | 30.5 (-40%) | 24.9 (-51%) |
| Capital cost ('000 AUD) | 50 | 30 (-40%) | 30 (-40%) | 20 (-60%) | 30 (-40%) |
| Cost in use ('000 AUD) | 300 | 210 (-30%) | 210 (-30%) | 150 (-50%) | 170 (-43%) |
| Life cycle material cost ('000 AUD) | 350 | 240 (-31%) | 240 (-31%) | 170 (-51%) | 190 (-46%) |
| Life cycle embodied greenhouse gas emission (tonne $CO_2$e) | 299.51 | 123.54 (-59%) | 123.54 (-59%) | 179.18 (-40%) | 146.09 (-51%) |

Figure 6 demonstrates that across all scenarios, LCEE and LCMC are lower than in the *BAU* scenario. The comparisons reveal that the IEE and REE contributions from LCEE of *services* shops across scenarios are 10% and 90%, respectively. Similarly, CC represents 14% of the LCMC, whereas CIU is responsible for 86%. This pattern is identically followed across all *specialty shop* types with a refurbishment frequency of five years. This is because when assemblies are replaced in five-year recurrences, they do not require any additional replacement in between since in all selected assemblies expected service life values are higher than five years. Therefore, comparisons indicate that in terms of LCEE reductions in *specialty shops*, the operational phase is far more critical than the initial embodied energy. So, it is essential to give more attention to material selection during each recurrence, concerning life cycle environmental effects and costs.

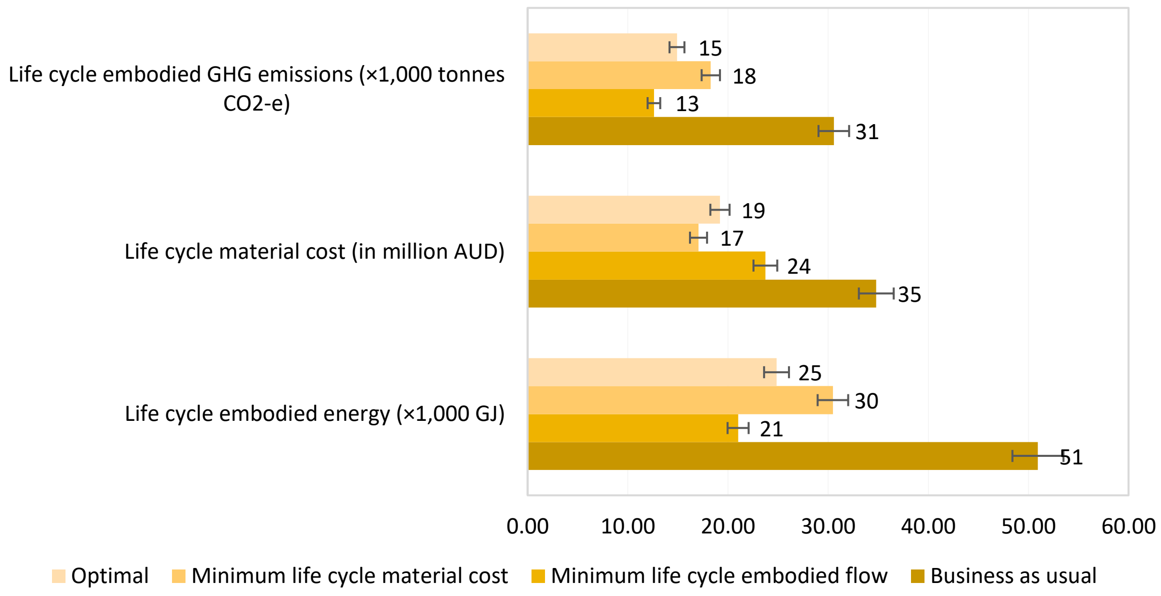


Figure 6: Life cycle embodied energy, embodied greenhouse gas emissions and material cost distribution across specialty shop scenarios

The *BAU* scenario results in an LCEE intensity of 18.2 GJ/m$^2$, and LCMC of 1,243 AUD/m$^2$. The LCEGHGE of the shop are measured as 1,070 kg$CO_2$e/m$^2$. The *BAU* scenario analysis shows that *floor finishes (61%)* dominate the LCEE followed by *ceiling finishes (28%)*, *wall finishes (6%)* and *internal wall (7%).* The LCMC distribution also takes somewhat a similar pattern led by *floor finishes (61%)* and *ceiling finishes (27%).*

The assembly configurations of the *minimum LCEE* and *minimum LCEE* scenarios lead to significant reductions of LCEE *(40-59%)* and LCMC *(32-51%)* when compared to the *BAU* scenario. The LCEE of the *optimal* scenario is 8.9 GJ/m$^2$, and LCMC is 686 AUD/m$^2$, resulting in 51% and 45% savings, respectively, in comparison to the *BAU* scenario.

### 4.4. Whole shopping centre results

This section presents the scenario analysis of the case study shopping centre. The analysis incorporates the case study design with minor modifications to the building morphology as defined in Section 3. A total of 8,820 variations were considered by the model. Table 9 presents the profile of shop types.

Table 9: Profile of shop types in the shopping centre

| Shop type | No of shops | Gross lettable area (m$^2$) |
|---|---|---|
| Supermarket | 2 | 5,304 |
| Discount department store | 1 | 5,394 |
| Clothing | 3 | 401 |
| Food supplies | 7 | 1,290 |
| Household | 4 | 2,323 |
| Gymnasium | 1 | 400 |
| Leisure and entertainment | 1 | 90 |
| Health and beauty | 8 | 976 |
| Coffee and restaurant | 8 | 884 |
| Shoes | 1 | 112 |
| Services | 9 | 788 |

Table 10 presents the LCEE, LCMC and LCEGHGE values across the scenarios. The typical shopping centre or the *BAU* scenario is an aggregation of the *BAU* scenarios of all shop types defined in the model (*centre structure*, *anchor* and *speciality)*. However, it is assumed that shops belonging to the same type have an identical assembly combination in all scenarios. For instance, all three *clothing* shops in the shopping centre are assumed to have an identical assembly combination when any shopping centre scenario is generated.

Table 10: Comparison of life cycle embodied energy, embodied GHG emissions and material cost across different scenarios of the shopping centre

| Criteria | Business as usual | Minimum life cycle embodied energy | Minimum life cycle embodied greenhouse gas emissions | Minimum life cycle material cost | Optimal |
|---|---|---|---|---|---|
| Initial embodied energy (‘000 GJ) | 139.4 | 115.4 (-17%) | 115.4 (-17%) | 131.3 (-6%) | 118.0 (-15%) |
| Recurrent embodied energy (‘000 GJ) | 179.0 | 100.4 (-44%) | 100.4 (-44%) | 148.7 (-17%) | 107.7 (-40%) |
| Life cycle embodied energy (‘000 GJ) | 318.4 | 215.8 (-32%) | 215.8 (-32%) | 280.0 (-12%) | 225.7 (-29%) |

| | | | | | |
|---|---|---|---|---|---|
| Capital cost (million AUD) | 25.54 | 25.38 (-1%) | 25.38 (-1%) | 24.03 (-6%) | 24.44 (-4%) |
| Cost in use (million AUD) | 12.51 | 9.51 (-24%) | 9.51 (-24%) | 7.57 (-39%) | 8.53 (-32%) |
| Life cycle material cost (million AUD) | 38.05 | 34.89 (-8%) | 34.89 (-8%) | 31.60 (-17%) | 32.97 (-13%) |
| Life cycle embodied greenhouse gas emission (tonne $CO_2e$) | 18,714.8 | 12,684.7 (-32%) | 12,684.7 (-32%) | 16,456.3 (-12%) | 13,264.9 (-29%) |

Figure 7 displays the absolute values of LCEE, LCMC and LCEGHGE of the shopping centre scenarios comparatively.

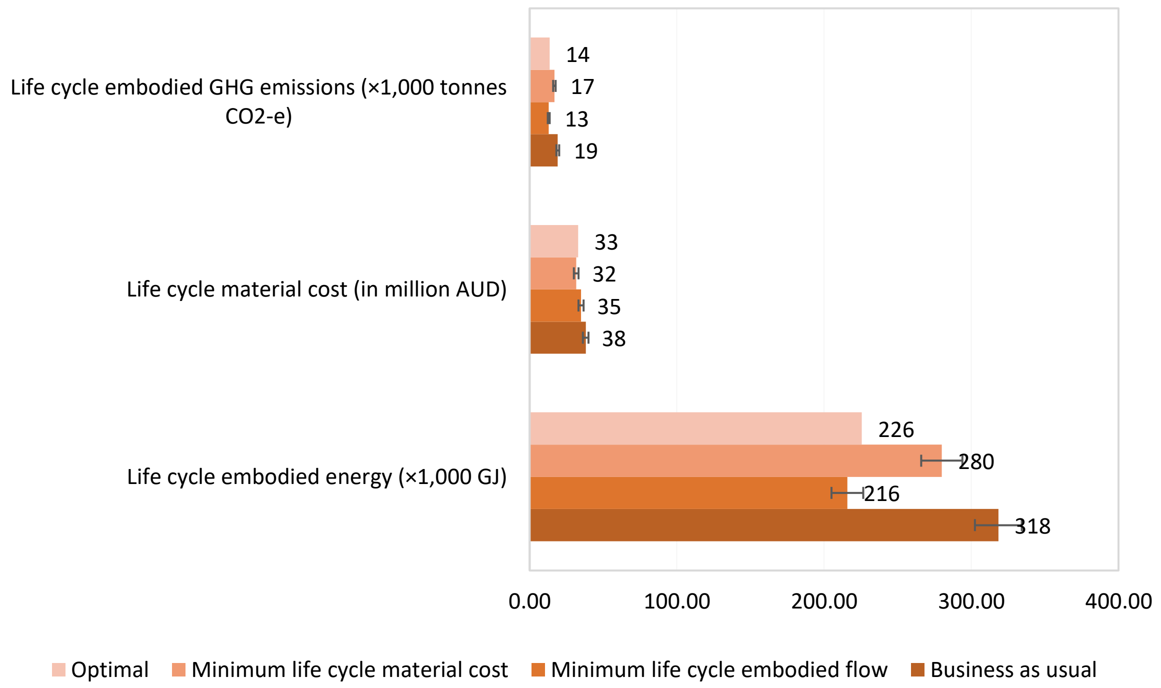


Figure 7: Comparison of life cycle embodied energy, embodied greenhouse gas emissions and life cycle material cost across shopping centre scenarios (absolute values)

The LCEE of the *BAU* scenario is 318,387.9 GJ, accounting for 14.2 GJ/m$^2$. REE represents 56% of LCEE, resulting in an annual value of more than 1% / (m$^2$.a).

Different types of shops account for various floor space percentages in a shopping centre, as shown in Table 9. Accordingly, LCEE, LCMC and LCEGHGE of these shops are also varied. The distributions, however, demonstrate that centre structure is responsible for more than 50% of all different parameters we are investigating, including LCEE, LCMC and LCEGHGE. *Household, supermarket, services* and *discount department stores* are identified as the next largest contributors of LCEE and LCEGHGE of the whole shopping centre. However, with regards to LCMC, *supermarket, common area* and *discount department store* are the most significant contributors.

Based on the floor space and selection of building assembly solutions, the percentage LCEE contribution of each shop type is different. Accordingly, in the *BAU* scenario, the LCEE of the *centre structure* accounts for 36% of the LCEE of the shopping centre, followed by *common area (10%), supermarket (9%), household (7%)* and *café and restaurant (7%)*. The smallest contribution towards LCEE is from *toilets and sanitary (~0%), shoes (~0%)* and *leisure and entertainment (~0%)* shops. The *centre structure* is the most significant in LCEE since modifying the assemblies in the *centre structure BAU* scenario with those of the *minimum LCEE* scenario solely can lead to 3% LCEE reduction of the whole shopping centre. Even though the *centre structure* seems dominant as a single entity, all other shops combined represent 64% of the total, making them far more significant.

The LCMC of the *BAU* scenario is 38 million AUD, where capital cost contributions represent 67%. The LCMC intensity of the shopping centre is 1,691 AUD/m$^2$. The LCMC composition by shop types consists of *centre structure* accounting for 57% of the total, followed by *supermarket (7%), common areas (7%), discount department store (5%)* and others. The shops with the least LCMC contributions are the same as before, including *toilets and sanitary areas (~0%)* followed by *leisure and entertainment (~0%)* and *shoes (1%)*.

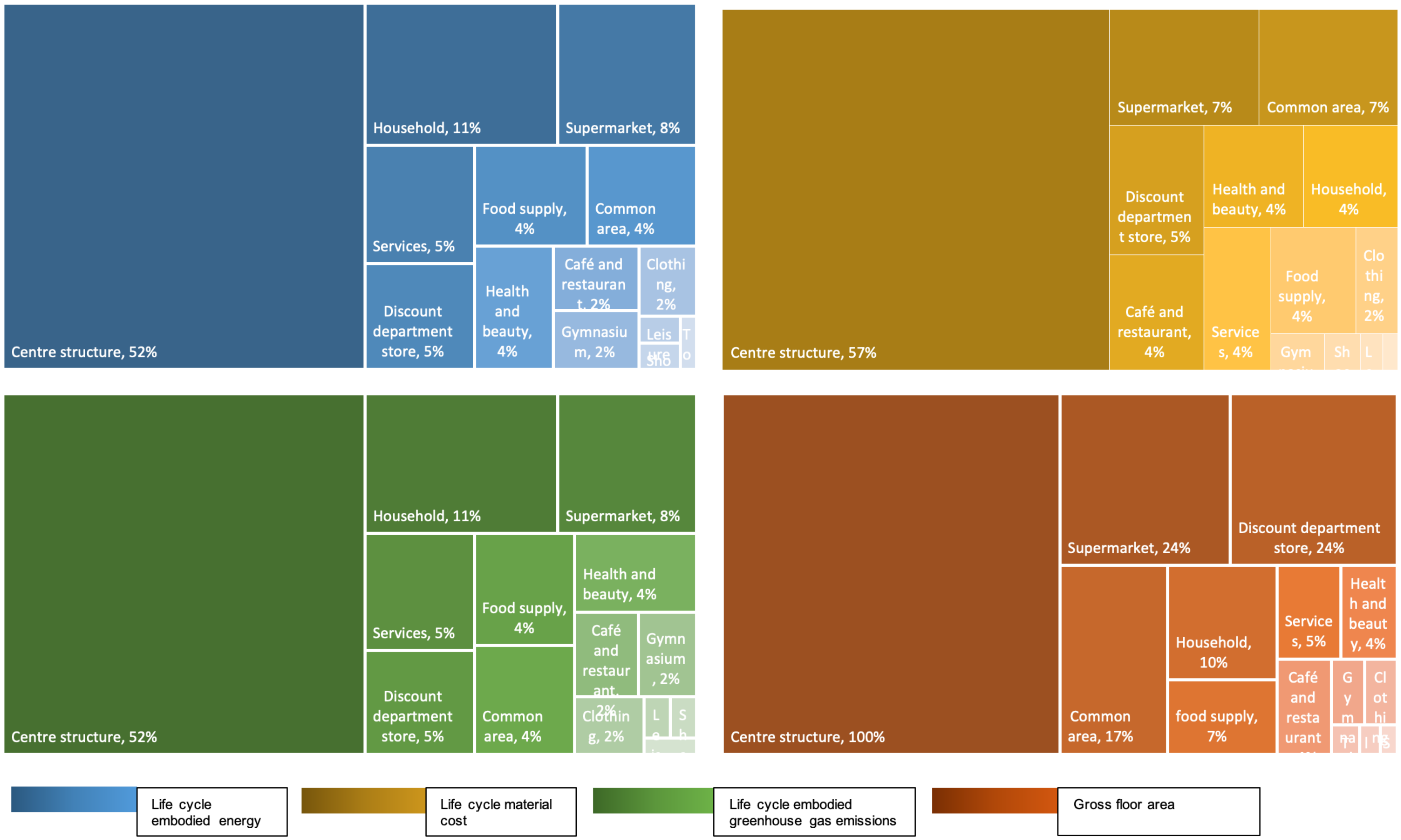


Figure 8: Life cycle embodied greenhouse gas emissions distribution across different shop types in the shopping centre business as usual scenario

The difference in contributions of LCEE and LCMC of shop types can be due to several reasons such as the choice of materials and assemblies, refurbishment frequencies and their respective GLA, which will be discussed further in Section 5. Since percentage contributions of embodied energy and material costs can highly depend on the GLA proportions of the shop types, LCEE, LCMC and LCEGHGE intensities per unit area are also estimated at the shopping centre level. These intensities provide an understanding of shop types irrespective of their GLA (Figure 9). Accordingly, it can be observed that the *cafe and restaurant (24.4 GJ/m$^2$)* has the highest LCEE intensity, followed by *leisure and entertainment (20.0 GJ/m$^2$), services (19.3 GJ/m$^2$), shoes (19.2 GJ/m$^2$), clothing (19.2 GJ/m$^2$)* and others. The least effects are from *discount department stores (4.3 GJ/m$^2$), supermarkets (5.5 GJ/m$^2$),* and *common areas (8.8 GJ/m$^2$)*. The highest LCMC intensities are from *shoes (1,770 AUD/m$^2$)*, followed by *café and restaurant (1,749 AUD/m$^2$)*, *clothing (1,711 AUD/m$^2$), health and beauty (1,597 AUD/m$^2$)*, and others. The least are from *discount department stores (351 AUD/m$^2$)* and *supermarkets (502 AUD/m$^2$)*.

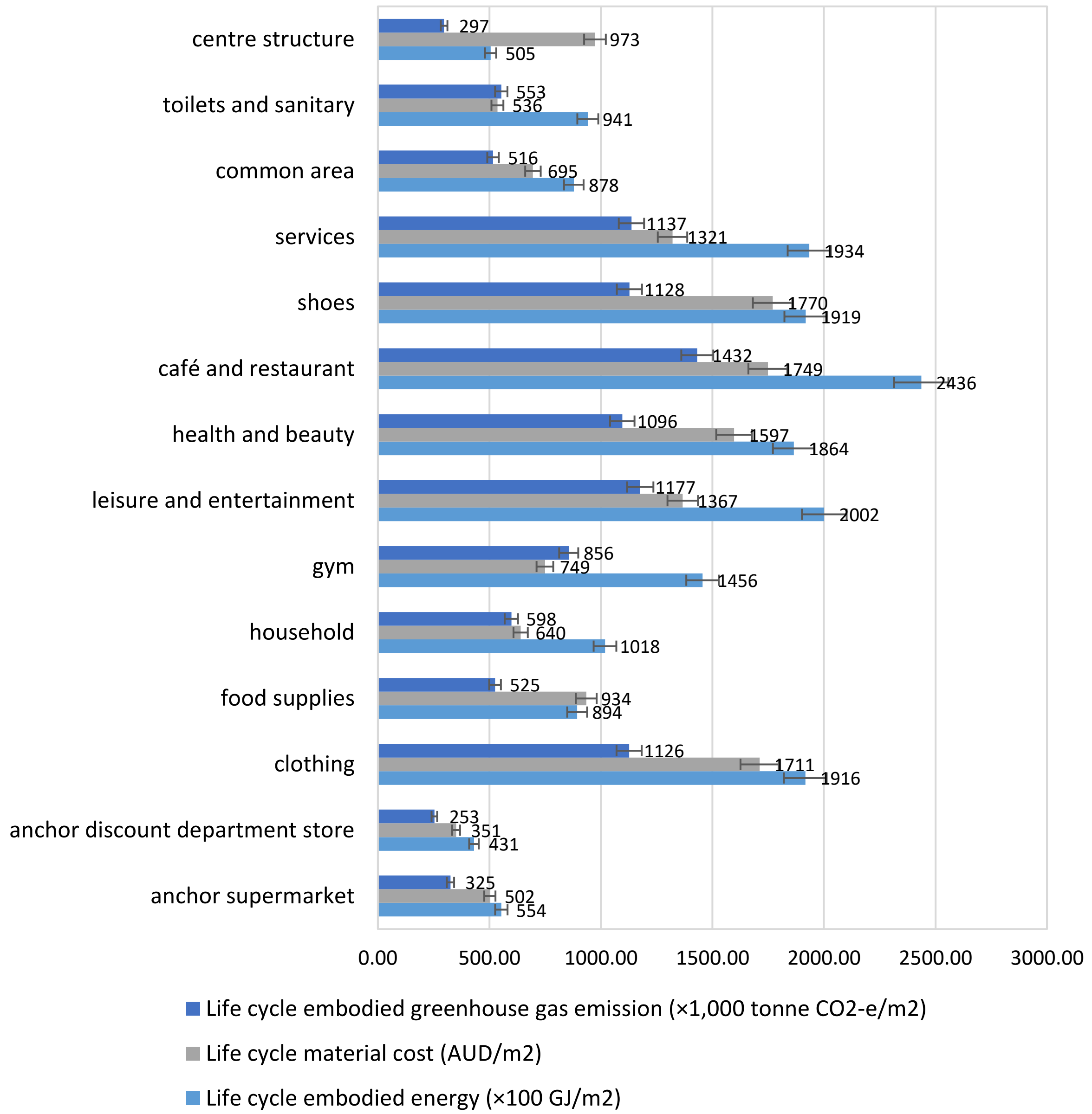


Figure 9: Life cycle embodied energy, embodied greenhouse gas emission, and material cost intensities of different shop types in the shopping centre business as usual scenario

By understanding the significance of LCEE in the *BAU* scenario, the model further identifies combinations of shops that can lead to embodied energy, GHG emissions and material cost reductions at a shopping centre level.

The *minimum LCEE* shopping centre scenario is an aggregation of shops with *minimum LCEE*. The LCEE of this scenario is 215,800 GJ, accounting for 9.6 GJ/m$^2$. This level of performance is a significant reduction when compared with the *BAU* scenario (14.2 GJ/m$^2$), leading to a drop of 32% in LCEE. The annual REE intensity of the shopping centre is 89.2 MJ/(m$^2$.a), which is a 44% reduction from the *BAU* scenario. The *minimum LCEE* scenario results in AUD 34.9 million for LCMC, which is also an 8% reduction from the *BAU* scenario. The LCMC intensity of the shopping centre is estimated as 1,551 AUD/$m^2$. The LCEGHGE intensity is 560 $kgCO_2e/m^2$. The findings suggest that the *minimum LCEE* scenario of the shopping centre can reduce both LCEE and LCMC. Yet, it is essential to maintain the shop fit-out replacements with similarly lower embodied energy assemblies at each recurrence.

When LCMC is minimised in the shopping centre, by aggregating the shops of *minimum LCMC*, the LCEE accounts for 280 TJ, resulting in an intensity of 12.44 GJ/$m^2$. IEE and REE contributions are 47% and 53%, respectively. The annual REE intensity of the *minimum LCMC* scenario is reduced by 17% when compared to the *BAU* scenario. The LCMC of this scenario is 1,404 AUD/$m^2$. The most significant observation is that even when *LCMC* minimisation is targeted, the solutions deliver a reduction in embodied environmental flows, in comparison to the *BAU* scenario.

The *optimal* shopping centre scenario in which both LCEE and LCMC are equally minimised is an accumulation of shops of *optimal* values. The LCEE intensity of the scenario is 10 GJ/$m^2$. The annual REE intensity is 95.7 MJ/($m^2$.a) or 0.96% /year, which is a 40% reduction from the *BAU* scenario, yet 7% increase from the *minimum LCEE* scenario. The LCMC of the scenario is valued as 1,465 AUD/$m^2$, reducing 13% from the *BAU* scenario, and LCEGHGE is estimated as 590 $kgCO_2e/m^2$.

The scenario analysis revealed that, at the whole shopping centre level, the shop types: *common area, supermarket,* and *household* are the most significant for LCEE reduction when absolute values are compared, but *leisure and entertainment* and *café and restaurant* become crucial when intensities are considered. These contradicting results are due to the disproportionate GLA distribution among different shop types in shopping centres. Therefore, it is important to evaluate the embodied energy effects using different functional units to identify the most significant shop types for reducing the adverse effects. This has already been observed for residential buildings by Stephan and Crawford (2016).

In the *BAU* scenario, it can be observed that *health and beauty*, *café and restaurant* and *clothing* shop types have the highest range of intensities in all variables. This considerable variance can be a result of the level of importance of the aesthetic appearance of shop types to attract customers. Typically, these shop types are very much attentive to the aesthetics of the shop, to increase foot traffic and sales. Making the shops more pleasing and aesthetically approachable is one of the key functions of these shop designs to create customer behavioural changes. Therefore, the shop designs can vary to a great extent using various building materials and assemblies, leading to a significant variance in the LCEE and LCMC.

Conversely, *centre structure*, *discount department store* and *supermarket* have the lowest range. These shop types have a smaller number of assembly combinations with limited selection. Furthermore, they are typically much less concerned about aesthetics compared to the specialty shops, as the additional attempts to attract customers by using sophisticated aesthetics is minimal. *Supermarkets* and *discount department stores* have a different business profile than the specialty retailers where customer attractions are increased through product price drops when necessary.

## 5. Discussion

### 5.1. Contributions

This paper shows that the construction of a typical Australian shopping centre using steel and concrete requires 318 TJ of embodied energy, generates 18,715 tonne $CO_2e$ of embodied greenhouse gas emissions and costs about AUD 38 million over 50 years of life. An interesting finding is that the REE of shopping centres is more significant than their IEE by 12%. Since the *centre structure* is responsible for more than 44% of the total LCEE, the internal shop fit-outs account for almost 56%. On an annual basis, REE represents more than 1% /($m^2$.a) of LCEE. Results also indicated that IEGHGE contributes 44% towards the LCEGHGE of the shopping centre while REGHGE accounts for the majority 56%. This demonstrates the significance of the recurrent embodied environmental flows of shop fit-outs of shopping centres in Australia.

Using specific intensities, the average LCEE of a single-storey shopping centre is 14.2 GJ/$m^2$, and the LCEGHGE intensity is 830 $kgCO_2e/m^2$ in the *BAU* scenario (where construction is dominated by steel and concrete). In the *BAU* scenario, the annual REE intensity of the shopping centre is 159 MJ/($m^2$.a). The annual REE of the *BAU* centre is almost 20% of the annual operational energy intensity of an enclosed shopping centre, including tenancies, estimated as around 984 MJ/($m^2$.a) in primary and secondary energy forms [80]. This indicates that the effects of continuous replacements of building materials and assemblies are significant in shopping centres. Furthermore, with the improvements in operational efficiency, the importance of embodied flows is increasing [7]. When LCEE is presented in terms of annual total embodied energy, it accounts for 283 MJ/($m^2$.a). This value shows that if LCEE is equally distributed across the 50-year life span, annual embodied energy represents at least 22% of the annual total energy use of the shopping centre.

However, shopping centre stakeholders are currently more focused on operational energy and emissions reductions as these can lead to monetary savings while achieving sustainability ratings of Green Star and NABERS. Despite the fact that there has been slow growth in relation to sustainability in shopping centres in Australia, concern on embodied environmental effects is still lacking. The paucity of knowledge on the embodied environmental flows is one of the main reasons for this lack of concern [7, 81]. However, a few leading developers are attempting to achieve Green Star Design and As-Built rating for their shopping centres through efficient use of materials, water, land, and ecology to reduce associated greenhouse gas emissions [61, 82, 83]. The findings of this study thus bridge the knowledge gap of embodied environmental flows assessment and provide awareness on environmentally sensitive and cost-effective building materials available in the current market. Albeit there is a “long road to go” in this sector, 'Australia has a real opportunity to become the world leader in shopping centre sustainability' [84] achieving life cycle environmental efficiency.

One of the significant outcomes of the study is delivering the currently unavailable embodied energy and embodied greenhouse gas emission intensities of different retail shop fit-outs. However, it must be noted that the results are subject to limitations due to the assumptions made throughout the modelling process. Nonetheless, the findings can be used as proxy values to assess retail shop fit-outs, shopping centre common areas, and the centre structure at the initial design stages to estimate the environmental effects and material costs. These can also be used as benchmarks to compare the shops' embodied energy use and GHG emissions.

The study reveals the combinations of building assemblies that lead to reduced LCEF and LCMC for different shop categories. It only presented the best assembly combination achieving the objective functions of the *centre structure, discount department store* and *services* shop due to the conciseness of the paper. However, the model delivered a series of different assembly combinations for shop types minimising LCEE and LCMC, which can be used as a basis for material selection decision making for different shops in shopping centres for future construction projects. The Python-based parametric model analysed more than 8800 scenarios rapidly to identify material combinations that achieve defined objective functions. The pragmatic nature of the model provided greater flexibility to accommodate any modifications and updates required with variances in data collection.

The *BAU* construction of the shopping centre structure is governed by concrete and steel where the *optimal* scenarios promote the use of *engineered timber* and *fly ash cement in concrete,* reducing 29% LCEE and 13% LCMC. The *anchor* shop category *(discount department store)* showed 52% LCEE reductions and 18% LCMC savings while using *plasterboard ceiling with paint on metal frame, insulated precast sandwich wall panels, terrazzo flooring with infill slab* and *cement mortar screed with white putty.* The *speciality* shop category (*services*) showed 51% LCEE reductions and 45% LCMC savings when designed using *plasterboard ceiling with paint on metal frame, cork board flooring, steel stud walls (welded)* and *water-based paint on plasterboard,* in comparison to the *BAU* scenario.

Refurbishment frequencies of the shops play a vital role in embodied environmental flows and must be integrated into material selection. Results indicated that changing the increments and decrements in refurbishment frequencies have different effects on the levels of impact in terms of LCEF and LCMC. When refurbishment frequencies are increased, the selection tends towards assemblies with higher service life values in order to reduce the number of assembly replacements that occur before the shop refurbishment. As expected, increasing the refurbishment frequencies result in LCEF and LCMC value reductions due to the decreased number of replacements.

Material combinations identified in this study are majorly applicable to developments in climate zone 6 across Australia but can be generalised to a national level. Interview findings revealed that the use of insulation materials and external finishes can vary for different locations across Australia. These differences are based on climate zones and due to thermal design requirements and energy efficiency provisions stated in National Construction Code. However, a majority of other building materials utilised in the centre structure and fit-outs were identified to be not that different from Victoria. Therefore, majority of the findings could be generalised to a national level with more detailed analyses required for insulation materials and external finishes for different climate zones.

An integrated sustainable design policy is essential to reduce on embodied environmental flows in shopping centres, through material selection. The Green Building Council of Australia developed the Green Star - retail centre design rating tool in 2008, which supports sustainable planning, design and construction of high-performance retail centres in Australia. This rating tool has since been the guideline to achieve sustainability goals in retail centre design and construction and has made a considerable impact on the retail sector [85]. Green star - retail centre design tool addresses the significance of life cycle assessment of materials to assess the sustainability of the building design. Hence, this study builds on the existing framework and provides more detailed knowledge to enhance it. The areas identified in this research present opportunities to improve the environmental performance of Australian shopping centre designs and achieve national sustainability goals.

In addition, behavioural changes are required from developers and designers involved in the project inception and design stages to consider the feasibility of using those solutions in the designs as value-added options and to educate clients and other project stakeholders. The Green star retail interior fit-out rating tool could be used by the centre management as a guide to assess the environmental sustainability of the shop fit-outs [82]. The involvement of the shopping centre management in retail tenants' business can be justified since the implications of individual shops ultimately have a significant effect on the adverse environmental performances of the shopping centre. Also, it is vital to raise the awareness of shop owners regarding the environmental implications of the shops and the necessity to mitigate them. The low LCEF and LCMC options identified by the model could then be appropriately engaged in the shopping centre construction process and throughout the life cycle.

### 5.2. Limitations and further research

This study suffers from certain limitations concerning assessments of embodied energy, material cost and embodied greenhouse gas emission, determining refurbishment frequency, and design of the shops and shopping centre to represent reality.

The quantification processes in the model use a simplified algorithm to define the replacement rate and the selection of building materials and assemblies at replacements. It would be better if the model could present realistic replacement rates using actual data of a single case study, rather than having generic replacement rates.

The assessments exclude end of life potential energy recovery and reuse. Nevertheless, it is fair to presume that this study provides an extensive evaluation of the entire shopping centre and provides a fair basis for the comparison of the impacts of the selection of building materials and assemblies based on embodied environmental flows and material cost. LCMC quantification also suffers from certain limitations, including the exclusion of labour cost, the reliability of material unit price data, the material replacements, and the exclusion of potential end-of-life material cost savings.

The cost data only represent the cost of material purchase and transportation to the site, including handling fees at delivery, and excluding the costs of labour and equipment for on-site material installation. The study uses this limitation to investigate materials consistently (in embodied environmental flows quantification also only material inputs are considered). However, this can hinder the results of the study. The inclusion of labour and equipment cost components would not influence the assembly solutions with minimising embodied environmental flows but could affect the assembly solutions minimising cost and the optimal solutions minimising both embodied environmental flows and cost. Therefore, we conducted a preliminary analysis to identify the effect of labour cost in unit costs of internal walls and wall finishes assemblies used in shopping centres. This analysis is only a first screening labour intensities using quantitative data published in Rawlinson's construction cost guide [86]. The comparison demonstrated that when labour cost on-site is included the cost of assemblies vary. However, the ranking of assemblies from the least expensive to the most expensive are similar for all internal wall assemblies with or without labour costs. It must be noted that even though the rankings are the same, the exact values of assembly costs vary significantly after aggregating labour costs. Nonetheless, this comparison shows that the inclusion of labour cost on-site will not affect the results obtained from the model at assembly level. It is important to perceive that labour costs vary from site to site based on geographic locations and thus using trade ratios will not necessarily provide a comprehensive understanding of the matter. Therefore, further studies are a must to understand how labour cost on-site can affect material selection decisions.

The shopping centre designs evaluated by the model are based on actual case study shopping centres in Australia. However, these cases are only representations in terms of use of building materials, tenant mix and the shopping centre layout. The case studies follow the shoe-box concept of design, where all shops and shopping centres are modelled as box-shaped designs as rectangles or squares. This simplification of the building morphology can affect the material cost and embodied environmental flow results. The databases of building materials and assemblies created in the study include the most common and embodied energy-efficient building materials and assemblies available in shopping centre construction in Australia. Several innovative materials and assemblies are incorporated to make the industry more aware of the environmental benefits of those materials and to encourage their use in shopping centres. However, the EPiC database does not include future building materials solutions that are less energy-intensive and more cost effective. This could be immediately addressed as data becomes available by updating the *Materials* and *Assemblies* databases accordingly to incorporate those potential solutions and executing the model to run scenarios and obtain the updated results.

The mathematical model relies heavily on data inputs from different databases to quantify the LCEF and LCMC of shopping centres. The uncertainty and variability of these data sets are asserted using the interval analysis approach. The case study shopping centres selected for the analysis in the model are single-storey subregional shopping centres in Victoria, Australia. These case studies represent the typical subregional shopping centre design and layout across Australia. Therefore, the results of the study can be generalised to other locations in Australia in a similar context with proper adjustments. The profile of case studies can be expanded to other categories of shopping centres, i.e. major regional, neighbourhood and others, and even other building forms to evaluate the impacts of LCEF and LCMC to assist in material selection decision making. It would be better to use more case studies to potentially identify other realistic implications of material and assembly selection on the LCEF and LCMC and to improve the robustness of the results. Furthermore, the use of different case studies across Australia would expand the *Materials* and *Assemblies* databases, increasing the usefulness of the model.

## 6. Conclusions

Australia has been a leader in climate change mitigation [87], yet, despite the proactive measures to mitigate the adverse impacts of the Australian built environment, shopping centres have not been given the required attention in the sustainability agenda.

This paper provides life cycle embodied energy, embodied greenhouse gas emissions and material cost assessments of Australian shopping centres for material selection, using a computer model applied to a case study. Results showed that the initial embodied flow (representing 56% of the total LCEF of a typical centre) of the shopping centre structure is the most significant to reduce adverse environmental effects associated with embodied environmental flows. Findings also demonstrate that specific assembly combinations could achieve up to 8% of life cycle embodied flow reductions and up to 2% material cost savings in the centre structure. Two categories of shops, namely anchor shops and speciality shops, have a life cycle embodied energy intensity between 2.2 $GJ/m^2$ – 8.2 $GJ/m^2$ and 11.4 $GJ/m^2$ – 50.9 $GJ/m^2$ based on the choice of assemblies. The recurrent embodied flow of anchor (up to 67% of the total) and speciality (up to 90% of the total) shop categories are far more significant than initial embodied flows. Results further suggested that specific assembly combinations could lead to life cycle embodied flow reductions of up to 52% for anchor shops and 51% for specialty shops, compared to the business-as-usual scenario while achieving life cycle material cost savings of up to 32% and 51% respectively. The findings of the study facilitate the selection of environmentally responsive building assemblies for shop categories in Australian shopping centres identifying their impacts towards life cycle embodied flows.

With more floor areas planned in the next few years, shopping centres need to focus more on embodied environmental flows reduction to mitigate adverse effects. Therefore, by incorporating the study's findings and taking necessary regulatory actions to drive developers towards lower embodied energy designs, Australian shopping centres could improve their environmental performance and help achieve emissions reductions and mitigate climate change while controlling cost.

## Author's contributions

KW: Conceptualisation, Methodology, Data collection, Model development, Analysis, Writing - original draft. AS: Conceptualisation, Model development, Supervision, Writing - review & editing. VF & PT: Supervision, Methodology, Writing - review & editing.

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## Appendix A

Table A.1: Bill of quantities of the shopping centre, by assembly type

| Assembly Type | Unit | Quantity |
|---|---|---|
| Foundation | $m^2$ | 21,120 |
| Columns | m | 2,700 |
| Roof structure | $m^2$ | 21,120 |
| Structural wall | $m^2$ | 6,258 |
| Internal wall | $m^2$ | 3,606 |
| Window | $m^2$ | 2,112 |
| Lintel | m | 211 |
| Wall finish – External | $m^2$ | 4,448 |
| Wall finish – Internal | $m^2$ | 15,944 |
| Ceiling finish | $m^2$ | 22,498 |
| Floor finish | $m^2$ | 22,498 |
| Waterproofing | $m^2$ | 154 |