Assessment of life cycle embodied energy and material cost in Australian shopping centres: Implications for material selection

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ABSTRACT

Shopping centres are the fastest-growing retail space in Australia driven principally by population growth and urban sprawl. A shopping centre undergoes frequent renovations and refurbishments during its life cycle for several reasons. These can include the need to increase foot traffic, improve sales and fixed term leasing periods of retail spaces. The refurbishment frequency of retail shops in shopping centres is exceptional compared to other commercial property assets, with refurbishments every 2 to 10 years. Consequently, building materials in shopping centres experience premature replacements due to economic, functional and social obsolescence. This overexploitation of resources ultimately increases the embodied energy and greenhouse gas emissions in shopping centres. Yet despite this, there is a lack of knowledge on embodied environmental impact of shopping centres in Australia, which constitutes a significant obstacle in achieving improved sustainability.

This thesis presents assessments of embodied energy and GHG emissions of shopping centres by developing an object-oriented model with three case study applications. Subregional shopping centres were selected as cases because they represent the largest share of shopping centre floor space (planned and existing) in Australia.

The embodied environmental effects of a building are predominantly governed by the materials and assemblies employed in its structure, envelope, and finishes. To minimise embodied effects, it is essential to select building materials with better environmental performances, which might increase life cycle cost. Hence, the object-oriented model prioritises both embodied energy and material cost to identify viable material and assembly solutions.

The model assessed and compared 8,820 assembly combinations across 16 different shop types in selected shopping centres. Results demonstrate that the estimated life cycle embodied energy and material cost of a typical single-storey subregional shopping centre are estimated to be around 485 TJ and AU$ 38 million as of 2019, respectively. Recurrent embodied energy is 45% of the total embodied energy, leading to an annual value of 193.15 MJ/m^2, which is significantly higher in comparison to other building assets. The largest contributing shop type for life cycle embodied energy and material cost is the centre structure. Results reveal that informed use of current building materials and assemblies (i.e. engineered timber structures, fly ash cement in concrete, cork and other timber based products) significantly reduce embodied energy and emissions (up to 43%) and deliver material cost savings (up to 17%) in comparison to the business as usual scenario. The introduction of a carbon tax is also identified as an effective mechanism to encourage the selection of materials yielding a reduction of embodied energy and GHG emissions. The research outcomes demonstrate that the premature replacements of building materials and assemblies in shopping centres have a significant effect on their embodied energy demand and this varies significantly by shop types.

The contributions of this study will allow building designers and other project participants to evaluate material selection decisions while enabling policy makers to develop regulations and guidelines that compel or encourage the selection of materials and assemblies with improved environmental performances. This research contributes to mitigating adverse environmental effects of the built environment.

DECLARATION

I declare that,

- this thesis presents only my original work towards the PhD except where indicated,
- it does not contain any materials previously published or written by another individual except where due acknowledgement has been made in the text,
- the thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Signed : ---

Kumudu Kaushalya Weththasinghe

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"I almost wish I hadn't

gone down that rabbit-hole

– and yet – and yet –

it's rather curious, you know,

this sort of life!"

- *Alice*

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Terms

BOQ	-	Bills of quantities
CBD	-	Central business district
CC	-	Capital cost
CIU	-	Cost-in-use
EEC	-	Embodied energy coefficient
GBCA	-	Green Building Council of Australia
GHG	-	Greenhouse gas
GLA	-	Gross lettable area
GLAR	-	Gross lettable area retail
ICSC	-	International Council of Shopping Centres
IEE	-	Initial embodied energy
LCEE	-	Life cycle embodied energy
LCEGHGE	-	Life cycle embodied greenhouse gas emissions
LCI	-	Life cycle inventory
LCMC	-	Life cycle material cost
LCMCWT	-	Life cycle material cost with carbon tax
OOP	-	Object-oriented programming
PCA	-	Property Council of Australia
PCC	-	Pearson's correlation coefficient
QS	-	Quantity surveyor
REE	-	Recurrent embodied energy
RF	-	Refurbishment frequency
RR	-	Replacement rate
SCCA	-	Shopping Centre Council of Australia
UML	-	Unified modelling language
WGBC	-	World Green Building Council
WSM	-	Weighted sum method

1 INTRODUCTION

1.1 BACKGROUND

The built environment is crucial for the economic and social advancement of any nation (Ng, Zou, Chan, & Chan, 2017; Wang, Xue, Yang, Luo, & Zhao, 2019). Regardless, due to exploitation of natural resources and generation of pollutants, the built environment is identified as an environmental liability (Andersson, 2019; Bribián, Capilla, & Usón, 2011; Krausmann, Schandl, Eisenmenger, Giljum, & Jackson, 2017; Ng et al., 2017; Röck et al., 2020; Teh, Wiedmann, Crawford, & Xing, 2019). The International Energy Agency (IEA) (2019) revealed that the built environment accounts for 36% of the final total energy use and 39% of total greenhouse gas (GHG) emissions globally. Building materials and their manufacturing processes represent 11% of global GHG emissions (Guo et al., 2019; IEA, 2019), of which Australia is one of the highest contributors on per capita basis (Department of Agriculture Water and the Environment, 2019). Energy intensities have exhibited a downward trend since 2000 because of the increasing use of energy efficiency measures and renewable energy sources used in buildings (IEA, 2019; Marszal et al., 2011; White, 2016; Zakaria, 2008). However, the positive impact caused due to these measures has been affected by the increasing energy intensities of building material manufacturing processes (IEA, 2019; WGBC, 2019a).

The demand for raw materials for construction purposes has increased by 40% since the 1980s (Krausmann et al., 2017). But many studies have been conducted highlighting the adverse environmental impacts associated with manufacturing of building materials (Bansal, Singh, & Sawhney, 2014; Bhochhibhoya et al., 2017; Bribián et al., 2011; Crawford & Treloar, 2005; Horvath, 2004; Inyim, Zhu, & Orabi, 2016; Krausmann et al., 2009; Treloar & Crawford, 2010). Many researchers have investigated possible methods of quantifying and reducing these impacts (Bribián et al., 2011; Crawford, 2011; De Klijn-Chevalerias & Javed, 2017; Ding, 2008; Dixit, 2019; Government of South Australia, 2017; Melià, Ruggieri, Sabbadini, & Dotelli, 2014; Napolano et al., 2016; Öztaş, 2015; Papadopoulos & Giama, 2007; Stephan & Stephan, 2016; Thormark, 2006). The majority of these studies have stressed the significance of residential and commercial office building assets in Australia. However, the retail property sector has been relatively slow to adopt and embrace sustainability, both from a research and industry perspective (Tang, Lai, & Cheng, 2016; Yudelson, 2009). Hence, more research attention should concentrate on the embodied environmental impacts of the Australian retail property sector to achieve the expected growth in sustainability within the built environment.

1.2 PROBLEM STATEMENT

Shopping centres are the most significant component of the retail property sector and an essential element in contemporary cities. Since the first shopping centre in

Australia was built in 1957, the characteristics, requirements and services provided by these have changed due to the dynamics of customer behaviour (SCCA, 2019). Shopping centres have evolved as community places where people congregate and comprise recreational facilities to enjoy, and places to meet, eat and shop (Urbis, 2015). This nature of the use of shopping centres along with demographic growth has increased the number of new centres and expanded existing developments to attract customers (JLL, 2019). Over the years, shopping centres have grown significantly in Australia, a testament to the defensive nature of these investments, even during the financial recession of 2007-08 (Urbis, 2015). The magnitude of this asset is evident from the retail property investment transactions in shopping centres in Australia, which accounted for AU$ 8.1 billion in 2018 (JLL, 2019).

Shopping centres in Australia can be classified into five main categories, namely, central business district (CBD) centres, regional, subregional, neighbourhood, and other (JLL, 2019). They account for 26.5 million m^2 of gross lettable area (GLA), representing approximately 46% of the total retail floor space in Australia (ICSC, 2019). This massive floor space represents 106 m^2 per 100 persons in Australia, making it the third largest country worldwide, in terms of GLA (PCA, 2019). Albeit these massive floorspace developments, shopping centres have been slow in adoption of sustainability measured in their construction and operation in comparison to other commercial property assets (Buxton, Goodman, & Moloney, 2016; Yudelson, 2009).

Throughout the building life cycle, shopping centres use significant amounts of energy and resources and emit substantial amounts of GHG (Juaidi, AlFaris, Montoya, & Manzano-Agugliaro, 2016; Máté, 2012; Reed & Wilkinson, 2011). This is due to several reasons including extended operational hours, large enclosed structures requiring constant heating or cooling, and frequent refurbishments.

Shopping centres typically experience several refurbishments and renovations during different stages of their life cycle (Coleman, 2007). The accelerated development and maturity stages, which see frequent tenant turnover, are identified as the most crucial in this aspect (Lowry, 1997). These continuous upgrades and maintenance are an essential part of shopping centres to attract customers and tenants and to sustain foot traffic (Aktas, 2012; Anselmsson, 2016; Hayles, 2015; Kocaili, 2010). Aesthetics is a primary requirement of retail designs, which is used as a primary driver to attract customers. Retailers, therefore, attempt to stay abreast of current trends in consumer preferences and maintain attractive business profiles through frequent modifications to the fit-outs.

Additionally, tenant turnover, due to the fixed term nature of their lease periods, also causes frequent refurbishments and renovations in shop fit-outs (Anderson & Mesher, 2019; Fieldson & Rai, 2009). Lease lengths are typically 5 years for speciality tenants and 20 years for anchor tenants (The Parliament of Victoria, 2003). If tenant leases are established for shorter periods or defaulted, renovations and refurbishments could occur even more frequently, increasing the life cycle costs for the investor, as well as increasing the use of natural resources.

The refurbishment frequency of shopping centres is thus considered exceptional, with replacements in every 2 to 10 years (Fieldson & Rai, 2009). As a result of these frequent refurbishments, building materials used in shopping centres experience premature replacements causing excessive use of natural resources (Fieldson & Rai, 2009; Lewry & Suttie, 2017). As a result of the increased use of building materials due to economic, functional or social obsolescence (Holtzhausen, 2007; Sarja, 2005), the share of recurrent embodied energy (REE)[1], becomes crucial in shopping centres. This increased REE eventually results in higher life cycle embodied energy (LCEE)[2] use. However, current research indicates a paucity of knowledge on LCEE assessment of shopping centres in Australia, which is a significant obstacle in achieving improved sustainability.

Materials and assemblies are the primary causes of embodied energy in a building, and by extension, are vital in LCEE reduction (Kim & Rigdon, 1998). The selection of environmentally sensitive materials, however, is believed to increase project expenditure, as the cost of materials at the initial construction stage can make up to 20% to 30% of the overall project cost (Ross, López-Alcalá, & Small III, 2007). Therefore, cost has been identified as one of the most significant barriers to sustainable material selection (Akadiri, 2015; Ametepey, Aigbavboa, & Ansah, 2015; Griffin, Knowles, Theodoropoulos, & Allen, 2010; Máté, 2013; Williams & Dair, 2007). The life cycle material costs (LCMC)[3] are significant in material selection decision. Making an inappropriate selection of materials can lead to excessive LCMC and LCEE (Castro-Lacouture, Sefair, Flórez, & Medaglia, 2009). Hence, it is essential to identify materials and assemblies that reduce embodied energy and material cost in shopping centres that can enlighten material selection decisions.

The use of environmentally sensitive building materials and assemblies are encouraged, or even obligatory, through regulations and policies in many countries (Carbon Pricing Leadership Coalition & International Finance Corporation, 2019). The enforcement of a carbon tax is acknowledged as one of the most effective approaches to sustainability in many countries, that could advance the construction industry towards carbon neutrality over time (Andersson, 2019; Laes, Mayeres, Renders, Valkering, & Verbeke, 2018; Metcalf, 2018; Murray & Rivers, 2015). The enforcement of the carbon tax in Australia, in 2012, led to a significant decline in GHG emissions, though the tax was later repealed in 2014 (Wong, Lacarruba, & Bray, 2013; Wong & Zapantis, 2013). Evidence suggests that emissions resumed growth after 2014 (Department of Agriculture Water and the Environment, 2019). Therefore, it is crucial to evaluate the implications of a carbon tax on building material selection as it may effect

[1] The energy embodied in materials and assemblies used to refurbish and renovate a building over its life cycle (Dixit, 2013)

[2] LCEE is a combination of initial and recurrent embodied energy, and demolition energy of a building (Ramesh, Prakash, & Shukla, 2010)

[3] Capital, recurrent and demolition costs of building materials and assemblies

behavioural changes in stakeholders involved in shopping centre development projects.

The selection of environmentally sensitive materials and assemblies is recognised as a critical process trading off different factors including structural adequacy, cost and quality (Akadiri, Olomolaiye, & Chinyio, 2013; Čuláková, Vilčeková, Katunská, & Burdová, 2013; Govindan, Shankar, & Kannan, 2016; Ogunkah & Yang, 2012). Several studies have been conducted to identify possible approaches to assist this process including multi-criteria decision methods, software tools and selection charts (Akadiri et al., 2013; Castro-Lacouture et al., 2009; Kazemi, Homayouni, & Jahangiri, 2015; Mousavi-Nasab & Sotoudeh-Anvari, 2018; Peças, Ribeiro, Silva, & Henriques, 2013; Prendeville, O'Connor, & Palmer, 2014; Seo, Tucker, & Ambrose, 2007). These approaches do not specifically address the distinctive nature of shopping centres as a building asset, and their unique refurbishment frequencies. Thus, it is imperative to develop an approach which can assess LCEE and LCMC of different material choices and identify solutions with potential savings in comparison to typical shopping centre constructions.

Accordingly, this research addresses the knowledge gap on LCEE and LCMC assessments of Australian shopping centres and use the implications to identify combinations of building materials and assemblies which minimise their adverse environmental impacts and contributes to achieving sustainability in the built environment.

1.3 RESEARCH AIM AND OBJECTIVES

1.3.1 Aim of the research

This research aims 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.

1.3.2 Research objectives

In order to achieve the aim of this research, the following objectives were developed.

1. To review typical and alternative building materials and assemblies used in shopping centres in Australia
2. To assess life cycle embodied energy and material cost of shopping centres in Australia
3. To examine the relationship between material selection, life cycle embodied energy and material cost of shopping centres in Australia
4. To investigate the impact of carbon tax enforcement on potential behavioural changes of material selection decisions of shopping centres in Australia

5. To propose combinations of materials and assemblies, with minimum life cycle embodied energy and material cost at varying replacement frequencies for different shops in shopping centres in Australia

1.4 RESEARCH SCOPE AND LIMITATIONS

This research focuses on the assessment of embodied energy and material cost during life cycle and using implications for material selection decision making of shopping centres in Australia. It employs three single-storey subregional shopping centres in Victoria, Australia as case studies. Of all the shopping centre categories, subregional centres are the most significant in Australia in terms of floor space (JLL, 2019), and almost 80% of these are single-storey centres (PCA, 2019). Therefore, this study uses single-storey subregional shopping centres as case studies.

The development of databases of various building materials and assemblies used in shopping centre construction is a crucial aspect of this research. The building materials and assembly data are obtained from existing literature, project document analysis, on-site observations and suppliers' information and demonstrate the most representative of those used in Australian shopping centres.

The assessments of LCEE and LCMC are carried out for the case studies focusing only on three building layers, namely: 'structure', 'skin' and 'space plan', as highlighted in Figure 1.1.

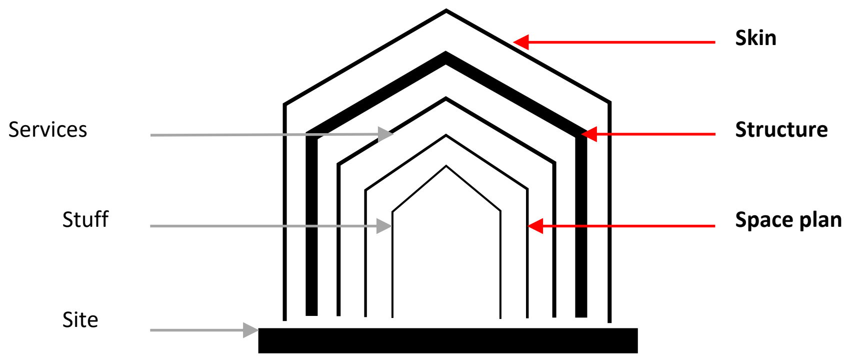

Figure 1.1: Shearing layers of change of a building throughout the life cycle

Source: Brand (1995)

These layers are based on the concept of shearing layers of change, introduced by architect Frank Duffy, and further elaborated by Brand (1995). This concept identifies transformations of different layers in a building over its lifespan. These three layers are typically the most changing layers of a building over the life cycle and therefore can be identified as the most crucial for reducing the embodied energy and material cost of shopping centres. Although 'stuff' is also identified as a continuously changing layer, representing internal fittings such as furniture, shelving, etc., it is not categorised as a component of building materials and assemblies and is not considered in this study. Any external structures of a shopping centre such as parking, shading or landscaping are also beyond the scope of this study.

This study assesses only LCEE and LCMC of shopping centres. While operational energy and operational costs are important from a sustainability perspective, they have not been considered within the scope of this research. They can be regarded as external to the study (Figure 1.2) given the aim of this research is to assess LCEE and LCMC in shopping centres and use the implications for material selection decision making.

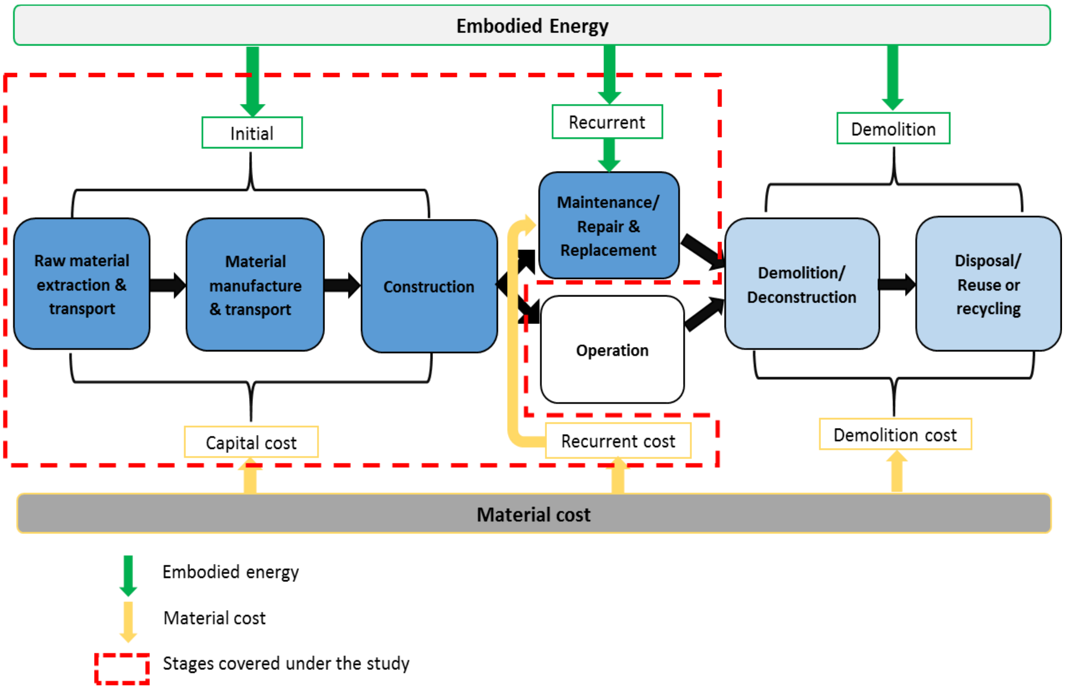

Figure 1.2: Building life cycle stages and system boundaries involved in the study based on EN15978

Source: Altered from Crawford (2011)

The energy associated with demolition and disposal stages are also beyond the scope of the research so are not quantified. However, they are referred to within Chapter 8, by identifying it as a possible area for extension in the model. Financial flows of shopping centres include only the capital cost (CC) and cost-in-use (CIU) of building materials. Recurrent costs of building materials and assemblies at the use phase are accounted as CIU. Demolition costs are disregarded in the LCMC assessment, yet possible means of cost recovery through recycling and reuse of building materials at the end of their first life, are provided in the discussion.

1.5 SIGNIFICANCE OF THE RESEARCH

Shopping centres are being developed rapidly in Australia as they provide convenient, comfortable and accessible shopping opportunities for the communities they serve (SCCA, 2019). Despite increasing online retailing (JLL, 2019; Peterson, 2017; Rao, 2020), evidence suggest that customers still have a preference for instore shopping and the associated opportunities such as socialising, exercising and refreshments (Lee, Sener, Mokhtarian, & Handy, 2017). 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 (Rao, 2020; SCCA, 2019). Therefore, it is imperative to understand 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.

This thesis adds to the body of knowledge on the topic of life cycle embodied impact and material cost assessments of shopping centres as a building asset. It 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. The relationships between gross lettable area and embodied energy, and GLA and material cost of shopping centres are investigated. The implications of a carbon tax reintroduction are also evaluated. This study provides an understanding on the LCEE and LCMC of typical Australian shopping centres and how different shop types contribute towards these rectifying the research gap. Findings will enable embodied energy assessments of similar projects and evaluation of the embodied environmental impacts 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. Informed material selection decisions will lead to embodied energy and emissions reductions in shopping centres. The identification of relationships between GLA, embodied energy and material cost provides an insight into GLA optimisation while minimising embodied effects and costs along other market factors. 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 resilient and usable in assessing any other building asset with slight modifications.

1.6 THESIS STRUCTURE

This thesis is structured in accordance with Table 1.1.

Table 1.1: Structure of the thesis

Chapter Number	Title	Objective/s addressed	Description
Chapter 1	Introduction		The *Introduction* chapter provides an overview of the study, stating the research gap, aim, objectives, scope, significance of the research and the thesis structure.
Chapter 2	Shopping centres as a building asset	Objective 1	*Shopping centres as a building asset* chapter reviews the development of shopping centres and identifies the significance of refurbishment frequency.
Chapter 3	Building materials, embodied energy and cost	Objective 1	*Building materials, embodied energy and cost* chapter provides a literature synthesis on material selection, embodied energy and material cost concepts. Establishes the relationship between material selection, life cycle embodied energy and material cost identifying the significance of material selection decision for shopping centres.
Chapter 4	Research method	Objective 1, 2, 3, 4	*Research method* chapter describes the research method used in the study in more detail. Selection of case studies and data sources are discussed. The use of the object-oriented approach for the development of the mathematical model is reviewed.
Chapter 5	Case studies profiles	Objective 1, 2, 3, 4	*Case studies profiles* chapter reviews the selected case study shopping centres. It further identifies the types of data collected from case studies and their use in the mathematical model.
Chapter 6	Object-oriented model development	Objective 2, 3, 4	*Object-oriented model development* chapter describes the features of the mathematical model and different steps in the model development process. The different approaches used to quantify embodied energy and material cost are described alongside the algorithms used and their applications.
Chapter 7	Results and analysis	Objective 2, 3, 4, 5	*Results and analysis* chapter presents the results of the case studies obtained from the model and provides the basis for the discussion.
Chapter 8	Discussion	Objective 2, 3, 4, 5	*Discussion* chapter provides the interpretation of the results analysed in *Results and analysis*. The applications of the model are discussed, along with its limitations and potential improvements.
Chapter 9	Conclusion		*Conclusion* chapter delivers the conclusions of the research, articulates the research contribution, and identifies the potential future research areas simulated by this research.

2 SHOPPING CENTRES AS A BUILDING ASSET

2.1 INTRODUCTION

Shopping is a primary anthropological activity, which is inevitable for virtually every individual in contemporary society. It is a necessity for all, and for many, a manner of recreation and a channel for social interaction (Beddington, 1991; Das & Varshneya, 2017). For a shopper, it is a relaxation, and a leisure pursuit, which is a repetitive cycle and thus requires comfort, convenience and ease of access (Calvo-Porral, Lévy-Mangín, & Jean-Pierre, 2018; Jarvenpaa & Todd, 1996). For the retailer, it is a function of providing the merchandises demanded by the consumers at an acceptable price retaining an acceptable profit margin at diverse demographics locations (Jones, 2005; Vinod, 2005). Hence, an appropriate shopping atmosphere that generates interest is essential to both retailers and shoppers. A shopping area should create the aura of eagerness, vivacity and competitiveness together with the sense of familiarity, security and confidence. Homogeneous designs in shopping areas, tedium and uniformity are the worst attributes that need to be eliminated in retailing to increase the trading potential (Jones, 2005). The financial performance or the sales activities of a retailer are directly affected by the foot traffic, identified as the '*the presence of people moving around a facility or passing by*' (Perdikaki, Kesavan, & Swaminathan, 2012). Thus, retailers attempt various approaches to draw new customers as well as to retain the existing ones (Chebat, Michon, Haj-Salem, & Oliveira, 2014). Every shop fit-out is therefore essential to create a positive impact - with unique shop fronts, signage, and shop planning from the entrance to the exit used to lure the shoppers (Coleman, 2007). Shop envelopes, or the shopping environment is, therefore, an inevitable element in retailing. Moreover, shopping facilities are an integral element and a critical part of planned urban forms in any economy (Goodman & Coiacetto, 2009). Retail centres are a part of the built form that provides a service as well as a public space for the communities. Shopping environment or retail centres are, therefore, significant in the culture and face of any city (Goodman & Coiacetto, 2012).

The aim of this chapter is to offer an understanding of the concept of shopping centres in Australia. The chapter begins with a brief historical overview, including definitions and notations used for different forms of shopping centres. The life cycle stages of a shopping centre identifying the significance of refurbishment frequency and the excessive use of energy and resources are discussed. Sustainable development of shopping centres in Australia is reviewed recognising the trends in adverse environmental effect mitigations associated with the use phase. Finally, the necessity of shopping centres to consider sustainability in terms of resource use and embodied energy is outlined.

2.2 HISTORICAL DEVELOPMENT OF SHOPPING CENTRES

The shopping centre industry contains various forms of innovative shopping centres around the world, from the massive South China mall with 660,000 m^2 of gross lettable area to some small neighbourhood centres with GLA less than 10,000 m^2. The co-location of shops away from the traditional high street started in the 19^{th} century with historic arcade shopping centres.

The world's first shopping centre is considered to be the Galleria Vittorio Emanuele II which was developed in 1877, in Milan, Italy. This four-storey double arcade shopping mall still operates today and is one of Italy's most famous tourist attractions. Westminster arcade is noted as the first shopping arcade in the United States, with Royal arcade, in Melbourne, Australia, Burlington arcade in the United Kingdom noted as some of the world's oldest arcade shopping centres.

The arcade shopping centres were typically located between two streets providing ease of public access. However, unlike the shopping centres in the 20^{th} century, they had not had car parking spaces surrounding the centre (Feinberg & Meoli, 1991). The development of shopping centres like the ones today started at the beginning of the 20^{th} century with the advent of the motor car.

The first modern shopping centres developed in the 1920s and have been referred to as strip malls, mini-malls or shopping plazas. They have been characterised as a collection of several shops located at a building with a shared parking space. The strip malls have typically been situated at major intersections in a city providing easy access to private vehicles. The first-ever unified shopping mall was the Country Club Plaza, developed in 1922 in Kansas city in the United States of America (Koolhaas, Chung, Inaba, & Leong, 2001). It has been identified as the forerunner of suburban shopping centres and designed as an integrated element of a substantial suburb as an alternative to a town centre (Crawford, 2002). The increased foot traffic in the Plaza led to new similar centres and the creation of a more sophisticated and attractive shopping experience (Coleman, 2007).

The 20^{th} century was considered a golden era for shopping centres (Hanchett, 1996). The population growth and concentration within the urban environment created a need for people to escape from the inner cities to the sprawling suburbs. Communities were attracted to the suburbs based on land availability and private vehicle ownership (Coleman, 2007). This dispersal of the population ultimately formed the requirement for malls or shopping centres, not only in the inner cities but further outside as well.

Two primary forms of modern shopping centres evolved at this time open-air centres and the mall, which had an enclosed walkway with shopfronts turned inside to face the interior space. Later a hybrid type developed, with the characteristics of both. In recent decades, however, the growth in the shopping centre industry has created other innovative forms to accommodate changing customer behaviour (Coleman, 2007).

Since then different economies have defined shopping centres in their own unique way and the next section provides further details of definitions and classifications of shopping centres in different countries.

2.3 DEFINITIONS AND CLASSIFICATIONS OF SHOPPING CENTRES

The International council of shopping centres (ICSC) defines a shopping centre as follows.

'A shopping centre is a group of retail and other commercial establishments that is planned, developed, owned and managed as a single property, typically with on-site parking provided' (ICSC, 2001, p. 1).

Based on the international definition, countries have adopted definitions which are compatible with the government regulations and legal framework in different geographies. Europe defines a shopping centre as '*a retail property that is planned, built and managed as a single entity, comprising units and "communal" areas with a minimum gross leasable area retail (GLAR: the total area a shopping centre leases to tenants including all selling spaces, storages and other miscellaneous spaces) of 5,000 square metres (m^2)' (Lambert, 2006, p. 1)*.

The definition for the Asia Pacific shopping centre is '*a group of retail and other commercial establishments that is planned, developed and managed as a single property, comprising commercial multi-branded rental units and common areas*' *(ICSC, 2001, p. 5)*.

Under these standard definitions, several types of shopping centres are available in the built environment, which can be classified under different names, based on pre-defined criteria.

A broader classification consists of two dominant categories of shopping centres as 'malls' and 'open-air centres'. Under each, several subcategories are available based on fundamental attributes of concept, size, acreage, types of anchor tenants[4], ratio of anchors and the size of trade areas (DeLisle, 2005). Based on these attributes, Table 2.1 outlines how the International Council of Shopping Centres (2001) classifies shopping centres in the United States.

Each category of shopping centres has a pattern of life of its own since they are not considered as just buildings. At present, shopping centres are regarded as lively forms of contemporary urban experience, which people never miss, whether they are placed in compressed cities or the subregions (Amendola, 2006). Each year after the construction of the centre is considered critical in its life cycle, as it needs to be integrated with the people to sustain in the competitive market.

[4] The tenant(s) within a shopping centre who make the centre economically viable for the landlord and the other tenants in the centre by being (one of) the primary draw(s) of customers to that centre (ICSC, 2001)

Table 2.1: The classification of the shopping centres in the United States

Type	Subtype	Concept	Gross lettable area (m²)
Malls	Regional centre	General merchandise, Fashion	37,000-74,500
	Superregional centre	Same as regional but with more variety	Over 74,500
Open-air centres	Neighbourhood centre	Convenience	3,000-14,000
	Community centre	General merchandise, Convenience	9,000-32,500
	Lifestyle centre	Entertainment, Upscale national chain speciality stores, Outdoor	14,000-46,500
	Power centre	Category dominant anchors, Few speciality stores	23,000-56,000
	Theme/festival centre	Leisure, Tourist oriented retail and service	7,500-23,000
	Outlet centre	Manufacturer's outlet stores	4,500-37,000

Source: International Council of Shopping Centres (2001)

2.4 THE LIFE CYCLE OF SHOPPING CENTRES

The study of the changes in the characteristics of a phenomenon over time is acknowledged as the life cycle concept (Audretsch & Feldman, 1996). According to Lowry (1997), this concept delivers a plausible explanation for the emergence and deterioration of various forms of shopping centres over the years. The life cycle of a shopping centre typically consists of four stages (Figure 2.1).

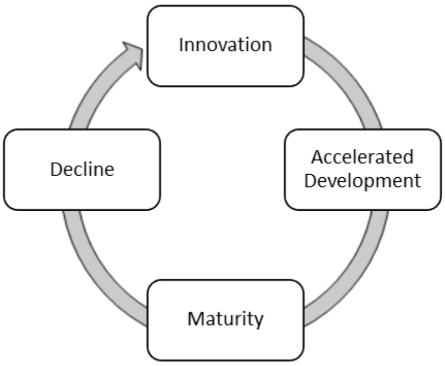

Figure 2.1: Stages of the life cycle of a typical shopping centre

Source: Adapted from (Lowry, 1997, p. 79)

The four stages of birth, growth, maturity and decline are distinguished using the characteristics of market factors, developer strategies, and tenant strategies. Market factors include the considerations of competition (number of competing centres), amount of foot traffic, rate of sales growth and vacancy rate. The strategies shopping centre developers consider are the developer's control over the centre, approaches used for advertising and promotional styles, renovations of the facility, attempts to lure new tenants, rental rates and the length of the lease.

Retailor/tenant strategies reflect the aspects of advertising and promotional activities used by individual tenants, exclusive sales and price reductions/discounts, varied product offerings, store design, layout and size, and the selection of store managers (Lowry, 1997). The change of the three main attributes, over the life cycle stages of a shopping centre, is demonstrated in Table 2.2.

The concern given to the three attributes, over the different life cycle stages of a shopping centre, differs, depending on the attention required, and the level of impact. Understanding the dynamics occurring through each stage can assist in responding to the critical changes, which affect the business profile of the shopping centre. These are presented in the following sub-sections.

2.4.1 Innovation Stage

Innovation is a more critical stage where uncertainty is higher regarding the market conditions of the shopping centre. If the centre is a new form, the market competition is less, as only a few similar nature centres are available. The customer attraction to a new environment is significantly high as it provides a different shopping experience that increases the foot traffic, which ultimately causes increased sales volumes. Other developers, observing the success and the financial performance of the centre, then start developing similar types of centres (Lowry, 1997; Rosendorf & Seidman, 1998).

Once the shopping centre starts performing, the developer monitors the operations of the centre, to obtain the most appropriate tenant mix for the centre, which is based on the customer demands and needs. Centre management implements various advertising and promotional approaches, to attract customers in the catchment and thus, support the retailers to increase the foot traffic. The main concern of the centre management is to retain the retail tenants with long term leases, at considerably higher rental rates (Coleman, 2007).

Retailers' most significant concern in the innovation stage is attracting customers to the shops (Nicoleta & Cristian, 2009). For that, they adopt various advertising methods and price promotions. An initial offering of a range of predetermined merchandise is used until the retailer can identify the needs of the market. The store layout and the design follow an existing, established store design and layout, to minimise additional operating problems. A competent manager with more entrepreneurial skills is, therefore required at this stage to adapt the store to the needs of the emerging market (Lowry, 1997).

2.4.2 Accelerated Development Stage

When a shopping centre reaches its accelerated development stage, the number of similar centres in the surrounding catchment area increases rapidly. Therefore, competition is growing as well. However, as the customers are aware of the offerings available at the centre, store traffic steadily increases. The familiarity of the centre and fulfilment of the customer needs that have been properly identified cause a growth in the sales.

Table 2.2: Change of attributes over the life cycle stages of a shopping centre

Attributes	Considerations	Stages of the life cycle			
		Innovation	**Accelerated development**	**Maturity**	**Decline**
Market factors	Competition/number of competing centres	Very few	Rapid growth	Many of similar	Many of similar and newer types
	Amount of foot traffic	Increases rapidly	Steadily increases	Stable	Steadily decreases
	Rate of sales growth	Very rapid	Rapid	Moderate to slow	Slow to negative
	Vacancy rate	Low	Very low	Moderate	High
	Control exerted by the developer	Extensive	Moderate	Extensive	Moderate
Shopping centre developer strategies	Advertising and promotional activities	Extensive	Moderate	Extensive	Moderate
	Renovations of the facility	None	Minor modifications	Maintenance of existing facilities	Neglect or extensive reformatting
	Attempts to lure new tenants	Extensive	Moderate	Moderate	Extensive
	Rental rates	High	High	Competitive	Low
	Length of lease	Long	Long	Moderate	Short
Retailor/ tenant strategies	Advertising and promotional activities	Extensive, to create awareness	Moderate, to draw greater interest	Extensive, to compete on price	Moderate, to remind of the sale price
	Special sales and price reductions or discounts	Few	Moderate	Extensive	Extensive
	Product offerings	Pre-planned variety and assortments	Variety and assortments to the market	Stable variety and assortments	Reduced variety and assortments
	Store design, layout and size	Prototype model	Adjusted to meet market demand	Stable size	Scaled-down
	Selection of store managers	Entrepreneurial	Aggressive	Professional	Caretaker

Source: Adapted from (Lowry, 1997, p. 79)

The visible growth in sales and foot traffic, attract more retailers to the centre, leasing the available spaces (Lowry, 1997; Nicoleta & Cristian, 2009).

After the innovation stage of the centre, the management control over the centre can be reduced. Advertising and promotional activities are also reduced as the centre has already established the clusters of customers, aimed at the innovation stage. As several years have passed since construction, minor modifications and alterations are needed to be undertaken to make the centre attractive to the customers and to maintain the standards of the retail tenants. By this time, as the tenants occupy most of the retailing spaces, the management does not have the pressure to attract new tenants. As a result of the increased occupancy rate and foot traffic, the developer has the power to increase the rental rates and the lease periods to gain more profit (Lowry, 1997; Rosendorf & Seidman, 1998).

The retailer’s efforts to attract customers through advertising can also be reduced as they have fine-tuned their customers and their needs. Nevertheless, due to the emerging competing centres, price-oriented sales events become more dominant. The experience gained during the innovation period allows a retailer to adjust its merchandises to meet customer needs. The impact of the store layout on sales volumes can be measured using specific productivity measures, such as sales per employee and sales per unit floor area. If the results are not satisfactory, shop retrofitting is undertaken with interior changes as well as space rearrangement. Even though the retailer had identified its potential customers by this time, and had established a niche in the market, the manager needs to continue being competitive and to create a solid base of customers for his business (Coleman, 2007; Lowry, 1997).

2.4.3 Maturity Stage

The main characteristic of the maturity stage is the availability of a higher number of centres of a similar form. The competition among centres is severe, and thus no further sales growth is available. Nonetheless, loyal customers who are familiar with the centre, visit the shops maintaining the foot traffic, but when leases expire, retailers tend to leave and join new centres. Thus, more significant renovations are required to retain the existing retailers as well as to maintain and attract customers. The renovations and refurbishments at the maturity stage cause excessive use of building materials. If the retail tenants tend to remain in the centre, they also require renovations and refurbishments to the shop fit-outs (Nicoleta & Cristian, 2009).

During this stage, extensive management control over the centre is necessary. The management needs to launch advertising and promotional activities together with the retailers, to strengthen the customer base. Since the tenants are reluctant to renew the leases and tend to leave, the centre management has the pressure of seeking new tenants. Due to tenants’ replacements in the centre, shop fit-outs depend on the requirements of the new tenants, planning to lease. As competing centres are also attempting to attract similar tenants, the management is forced to provide lower rentals and shorter lease periods to keep the centre occupied (Rosendorf & Seidman, 1998).

In the maturity stage, retailers also need to increase promotions and advertising to maintain foot traffic, which is challenged by the competing centres. These promotions are more focused on price cuts and sales events. A long-term retailer occupied in the centre for a considerable period understands its customer base and its needs. Furthermore, these retailers are aware of aspects such as implications of the shop design and layout on the foot traffic and sales. Thus, the store manager identifies the most competitive store design and layout. Based on these requirements, store fit-outs are modified. The professional skills and intelligence of the manager are, therefore, essential to understanding the changing market and the strategies to sustain in the business (Lowry, 1997).

2.4.4 Decline Stage

Severe competition from other centres of similar and/or newer types cause reduced foot traffic and sales volumes for the older centre. This centre with outdated building designs and facilities is not competitive enough to endure in the market among newer, more sophisticated designs. A significant transformation in the demographics of the customer base is also possible during this period, that can cause a huge loss to many tenants. As a result of these changes, tenants tend not to renew their leases, causing a vacancy problem (Nicoleta & Cristian, 2009).

The decline stage of a shopping centre can worsen where the owner or the management does not attempt to protect the centre, knowing it will not last long and thus devotes resources to other interests. Expensive advertising can also be skipped, as confidence that it will not make a significant change to the foot traffic falters. After identifying the centre has reached the decline stage, management is reluctant to invest more money into the maintenance of the centre and has more interest in disposing of the building. In some rare situations, centres are transformed into different types of buildings with different functions (Audretsch & Feldman, 1996). As a result of the minimal effort to attract tenants to the centre, lower renal rates and shorter leases, become essential.

Retailers in this stage are typically waiting until their leases expire to leave the centre. Advertising is undertaken to gain consumers’ attention and to remind retailers’ about availability at the centre. Substantial price reductions and sale events are frequent during this period to attract price-sensitive shoppers. No further improvements to the shop fit-outs are made, understanding it is a cost that will not be repaid and will do little to attract new customers. Due to the decreasing foot traffic, retailers tempt to reduce the offerings of merchandise and may also reduce the retail area. A caretaker is the appropriate type of store manager needed, as the retailer will close the shop, once the lease expires (Nicoleta & Cristian, 2009).

A shopping centre goes through all these stages throughout its life cycle. However, separating the stages clearly and identifying the boundaries is challenging. More detailed information is therefore needed to evaluate the life cycle stages of a shopping centre. The age of the centre, competition in the market, dynamics in shoppers' behaviour, and the marketplace are all determinants of the life cycle stage of a shopping centre. The accelerated development and the maturity stages are responsible for the majority of renovations and refurbishments in shopping centres. Thus, these two stages are identified as the most critical in terms of recurring use of building materials and assemblies.

2.5 SIGNIFICANCE OF THE USE PHASE OF SHOPPING CENTRES AS A BUILDING FORM

Shopping centres are an innovative form of retail property, which experience continuously changing design developments over their life cycle (Anderson & Mesher, 2019). The aim of the developers and designers of shopping centres is to create "an experience" that lure and attract customers to the "one-stop" large group of shops (Kocaili, 2010). The challenge, however, is creating emotions and relationships with the customers who are passionate about shopping, at the place they feel comfortable and safe (Gibbs, 2012). Hence, shopping centres need to be designed, developed and maintained continuously over its life cycle to achieve customer expectations. Preserving the shopping centre charm for customers is also crucial, for the financial performance of the centre, over the different stages of its life cycle (Lowry, 1997). As stated earlier, continuous renovations and refurbishments, are therefore seen as essential for the shopping centre particularly, during the accelerated growth stage and the maturity stage.

'Build it, and they will come' is not the concept of shopping centres, where once the building is constructed, the work is done (Lowry, 1997). The primary requirement of a shopping centre is to be competitive in design and the uniqueness in the shopping environment, which needs to change with time. Maintaining attractiveness of the property over the years is challenging, yet essential for shopping centres (Rosendorf & Seidman, 1998). Updating to the latest design trends and social requirements are the drivers of this competitiveness. Continuous renovations and refurbishments are therefore common in shopping centres, retrofitting shopping centre interiors along with changing design features and several other methods. Therefore, refurbishment frequency of shopping centres is considered exceptional in normal building terms, with replacements every 2 to 10 years to ensure the centre continues to entice customers (Aktas, 2012; Hayles, 2015; Kocaili, 2010). The renovations and refurbishments occur due to the dynamics in economic, social and functional requirements of the stakeholders engaged in the shopping centre.

At about the age of 15 years, shopping centres start to decline if proper renovation or retrofitting is not implemented (Coleman, 2007; Lowry, 1997; Nicoleta & Cristian, 2009). Customer attraction towards shopping centres can be explained through the "law of commercial gravity" (Huff, 1963), in which newer shopping centres with attractive features improve foot traffic. Surveys on customer spending behaviour reveal that customers with a similar pattern of shopping time and trips spend more money in centres where no competition is close than in places where competitive centres are within a 30 km radius (ICSC, 2001; Lambert, 2006). Over time a trend can be observed with new centres starting with more luxurious facilities, with both customers and retail tenants to them. Rental rates start to decrease slightly, as a result of the emerging retail vacancy rate and the increasing costs of maintenance and renovations. Therefore, the shopping centre renovation decision is made when the marginal costs of renovations are equal to the marginal loss of rental income (Wong & Norman, 1994).

Refurbishments can take various forms, including redesigned centre layouts and public spaces, modernised interior finishes and lighting, attractive signage and shopper circulation routes with increased tenant visibility (Feldman, 2004). It has been found that refurbishments in shopping centres have a direct impact on the property value increment, since enhanced functionality and changes in the tenant mix, reposition the centre in the competitive market (Bernhardt, Donthu, & Kennett, 2000; Chain Store Age, 1992; Van den Berg, Van Lomwel, & Van Ours, 2003). The decision on the optimal time for shopping centre renovation is difficult as it is based on several elements, namely, cost of renovation, time for renovation, the residual value of the property, expected net profit and obsolescence.

Salway (1986), as cited by Baum and Crosby (2014), conducted a study on the depreciation of commercial properties and revealed that the refurbishment frequency of shopping centres is typically in between 4 to 20 years. Moreover, shopping centres were identified as the building asset type with the most frequent renovations and refurbishments, based on the hypothesis of five year tenant leases (The Parliament of Victoria, 2003). Due to economic and social obsolescence in the dynamic markets, the decision on renovations and refurbishments becomes critical for the existence of the centres. Although frequent renovations are identified as essential for the shopping centres, too frequent renovations are believed inefficient (Chau, Wong, Leung, & Yiu, 2003).

Therefore, renovation or refurbishment frequency of a shopping centre is a critical attribute and can be a challenging decision to make. However, it has been identified that renovation or refurbishment of a shopping centre typically occurs between 2 to 10 years, taking into account tenant leases are granted typically for five years (Fieldson & Rai, 2009). It also indicates that if tenant leases are established for shorter periods, renovations and refurbishments could occur even more frequently, increasing the costs for the investor, as well as increasing the use of natural resources. These frequent renovations and refurbishments require significant amounts of construction resources for execution. The resources can involve considerable amounts of building materials and assemblies, which are mostly non-renewable, and thus shopping centres are considered less sustainable when considered alongside other forms of building assets.

2.6 SHOPPING CENTRES AND SUSTAINABILITY

Sustainability is the phenomena that acquires consideration of the needs of the present without compromising the ability of the future (Brundtland, 1987). Since the consideration of sustainability more than three decades ago, its imperious has been driven by a need to not disrupt technological and cultural developments (Kibert, 2016; Robichaud & Anantatmula, 2011). The construction industry, as an essential sector in most developed and developing economies, has also followed the movement in many forms of building and infrastructure asset developments (Govindan et al., 2016; Ogunde, Olaolu, Afolabi, Owolabi, & Ojelabi, 2017; Yin, Laing, Leon, & Mabon, 2018). The industry has achieved the milestones set by the legislation, with some considering how to best serve the communities. Both residential and commercial building developers have attempted to improve sustainability, by considering not only legislative requirements but future consequences (Graham & Warren-Myers, 2019; Laes et al., 2018; Sitek, 2018). In the commercial sector, the case for sustainable buildings has been recognised and appreciated, considering the economic, non-economic, tangible and intangible benefits of the sustainability concept (Aksamija, 2016; Aye, Bamford, Charters, & Robinson, 2000; Noller, 2005; Wang, Chang, & Nunn, 2010). However, irrespective of the sustainable growth among most of the sub-sectors in the built environment, the retail sector has not kept pace with achieving sustainability goals (Yudelson, 2009). This gap is caused by many social and economic challenges. The stakeholders involved in the retail asset development have different interests which are conflicting and may not be compatible with sustainable development (Yudelson, 2009).

Typically, a retail property development involves many stakeholders, who benefit from the property, such as the owner, the investor/s (who could be single entities or on multiple stockholders), the developer, the manager, the tenant and the customers (Aktas, 2012; AlWaer, Sibley, & Lewis, 2008). Therefore, the perspectives of all stakeholders affect the decision for implementing sustainability. If the stakeholders who ensure initial financial investments on developing sustainable features differ from the stakeholders who would benefit from them in the future are not agreed upon implementation becomes challenging (Dangana, 2013; Woitenko & Clark, 2007; Yudelson, 2009). Specifically, in shopping centres, the reluctance to trail sustainable developments (as with other property forms) is caused due to these conflicts of interests. However, by identifying the benefits of sustainability for all stakeholders' efforts can be put into place. Nevertheless, it is evident that sustainability certifications that exist for other buildings are not suitable for evaluating the retail properties. Therefore, specific sustainability rating tools need to be developed for retail building assets considering their unique performances, priorities and complexities.

Therefore, by recognising the unique nature of the retail building assets, well-regarded sustainability assessment organisations around the world, have developed separate assessment tools, which can be applied to retail property evaluation (Hampton & Clay, 2016; Yudelson, 2009). The United States, Australia and the United Kingdom have identified the importance of the issue and developed rating tools specifically for retail building assets while some other countries continue to use standard tools. Table 2.3 lists the available rating tools for retail building assets around the world.

Table 2.3: Currently available sustainability assessment tools for retail assets

Country	Sustainability rating tool	Tools for assessment of retail assets
United States	Leadership in Energy and Environmental Design (LEED)	LEED Retail: New construction
		LEED Retail: Commercial interiors
		LEED Retail: Operation and maintenance
Australia	Green Star	Green Star: Retail centre v1
		Green Star: Retail centre design v1
		Green Star: Shopping centre design PILOT
United Kingdom	Building Research Establishment's Environmental Assessment Method (BREEAM)	BREEAM: Retail

These rating tools were developed to assess the sustainability features of retail centres based on several assessment criteria. However, the majority of the assessment criteria for different assessment tools are similar, even though the scores and weights given are different. The assessment criteria of LEED Retail, Green Star Retail and BREEAM Retail are summarised in Table 2.4.

Table 2.4: Assessment criteria of different retail sustainability assessment tools

Assessment Criteria	LEED Retail	Green Star Retail	BREEAM Retail
Management	√	√	√
Indoor environment quality	√	√	√
Energy	√	√	√
Transport/Location	√	√	√
Water	√	√	√
Building materials	-	√	√
Land use and ecology	√	√	√
Emissions/Sustainable sites	√	√	√
Innovation	√	√	-
Regional priority	√	-	-
Waste	-	-	√

LEED: Leadership in energy and environmental design; BREEAM: Building research establishment's environmental assessment method

Source: Green Building Council Australia (2015)

Accordingly, it needs to be emphasised that any retail sustainability rating tool considers similar criteria for the assessment, which differing slightly in its content according to the priority context of the countries. However, in all the tools, energy, water and building materials are given priorities in scoring and weighing to emphasise the significance of these resources used in the construction of retail building assets. Reducing the energy use throughout the use phase is, therefore, the most critical challenge, as shopping centres and any other retail centres are heavy energy users, due to their extended operating hours and common illuminated areas. Building materials are given priority due to the continuous material replacements occur in shopping centres causing excessive use of natural resources over the building life cycle.

The development of sustainability rating tools led to a movement in adopting sustainability concepts for retail centres around the world. The first retail project that achieved LEED certification in the United States is the “Giant Eagle” supermarket located in the Brunswick town centre shopping plaza in Ohio in 2004. It implemented several approaches to develop an environmentally friendly centre aim at reducing the energy and water use, as well as resource use. The features initiated in the supermarket were typically the consideration of the sustainability measures of any retail centre.

The first shopping centre certified as BREEAM Excellent in the United Kingdom is “Cabot Circus” shopping centre in Bristol. It was a mixed-use development, which included different functional uses such as retailing, leisure, offices, housing, hotel and parking. The retail floor area of the project is almost 0.9 million m^2. Sustainability features implemented involved waste recycling, rainwater harvesting, roof gardens and operational energy reduction methods.

Japan also implemented the concept of “Eco Store” and opened the first sustainable shopping centre, “AEON Chikusa” in Nagoya city in 2005. The store employed a range of sustainability features including renewable energy use, energy efficient equipment installation and resource conservation. Since 2005, AEON has opened eight other eco-stores in Japan, all of which have received the comprehensive assessment system for building environmental efficiency (CASBEE) ratings.

Green Star Retail in Australia certified its first shopping centre, namely the “Orion Springfield” shopping centre, in 2008. The centre is a 6-star Green Star certified property which accommodates more than 100 retailers. The preliminary investments on green initiatives were recorded as AU$ 2.5 billion, in addition to the initial construction cost. However, the centre has experienced a significant energy savings over the years of operation which outweigh the initial implementation cost of the sustainable features and technologies (GBCA, 2020b).

The Green Star Retail rating tool identifies the priorities of energy, water, building materials and indoor environmental quality in retail centres through its scoring and weighing factors, as demonstrated in Table 2.5 (GBCA, 2015).

Table 2.5: Green Star: Retail centre v1 rating tool - Scores and weightings

Credit name	Number of points	Weighting
Management	15	10%
Indoor environment quality	14	12%
Energy	27	24%
Transport	12	8%
Water	23	19%
Building materials	22	10%
Land use and ecology	8	9%
Emissions	16	8%

Source: Green Building Council Australia (2015)

The total number of points received are weighted to obtain the total weighted points for the project. Based on the number of weighted points received, the project then qualifies as a Green Star certified project. Since the first certified project in 2008 to 2020, Green Star has certified 46 retail projects around Australia (GBCA, 2020b).

Therefore, while sustainability in shopping centres has been increasingly addressed internationally since 2004, this lags behind other building asset types. However, it would appear that shopping centres are more frequently adopting sustainability measures, with prominent examples available for others to follow (Tang et al., 2016; Thompson, 2007).

A number of drivers are pushing the industry towards sustainability, including competition among other retailers, legislative requirements, irresistible incentives on green initiatives and more importantly, the customer concern on sustainability (Newell, 2009; Thompson, 2007; Yudelson, 2009). Therefore, sustainable development within shopping centres is mixed at present, with some developers leading and the rest either lagging or not even starting to implement (Yudelson, 2009). However, research has revealed that sustainable features adopted in shopping centres can be a value-add to the property (Bently, Glick, & Strong, 2015; Sinha, 2011). These measures involve optimising energy use, protecting and conserving water, optimising building space and material use, enhancing indoor environmental quality and optimising operational and maintenance practices (WGBC, 2019b). Developers, however, need more research to clarify that investments in sustainability are not a waste, but have multiple paybacks.

The next section discusses the significance of shopping centres in Australia as a building asset thus identifying the implications for the environment.

2.7 Shopping centres in Australia and associated environmental impacts

Shopping centres are a significant type of retail property in Australia in terms of urban formation, community service provided, the contribution to the investment in the property market and the employment opportunities generated. Shopping centre industry statistics in Australia demonstrate, in 2019 around 10% of the total workforce of the country is employed in the retail industry of which approximately 65% are involved in shopping centres (SCCA, 2019). Thus, shopping centres are an important aspect of cities in Australia.

2.7.1 Shopping centres in Australia

Australia records “Chermside Drive-In” shopping centre in Brisbane as its first modern shopping centre, which is now referred as “Westfield Chermside”. It was opened in May 1957 housing 25 retailers, a department store, and parking space for 650 cars (PCA, 2017). The shopping centre followed the American style of suburban shopping centres, which a local reporter referred to as ‘*an island of retailing in a lake of parking*’. After this first development, shopping centres began to spread in the metropolitan suburbs of Sydney and Melbourne as a result of the post-war immigration, local population growth, lower-priced cars, suburban living preferences and convenient public transport. The metropolitan cities grew through expansion of the suburbs with developers and retailers following where land and a pool of customers were available (SCCA, 2017).

With the development of these new suburbs and the growth in transportation options retail moved away from local strip shopping to new shopping centres housing major retailers and smaller tenants. Customers were able to experience the *'under one roof'* shopping experience, which the developers tried to deliver in a comfortable, convenient, accessible and safe place. Shopping centres became not only places to shop, but also community spaces where people could meet and enjoy as groups and families. These centres were popular and thus experienced rapid growth, with an average of 24 new centre developments in Australia every year since 1957 (PCA, 2017), with new forms of enhanced functional performances developed also as is indicated in Table 2.6.

Table 2.6: Classification of shopping centres in Australia

Type of centre	Definition
Regional shopping centres	A centre under single management and based on at least one department store, of minimum 10,000 m^2 gross lettable area and the total GLA exceeding 25,000 m^2 OR three full-line discount department stores (DDS) or equivalent each of minimum 5,000m^2 GLA and the total GLA exceeding 50,000m^2
Subregional shopping centres	A centre with one or two major discount department stores, one or more supermarkets and around 40 speciality stores
Neighbourhood centre	A centre including one or two supermarkets with speciality stores
Central business district (CBD) centres	Retail centres located in the CBDs of Australian capital cities
Other	Other shopping centres except the mentioned

Source: Property Council of Australia (2017)

According to the statistics, 1,630 shopping centres are available in Australia, with a gross lettable area exceeding 1,000 m^2, including regional, subregional, neighbourhood and Central business district centres (PCA, 2019).

Australian shopping centres have 106 m^2 of GLA per 100 persons, which is the third-highest value by global standards (SCCA, 2019). Figure 2.2 indicates the distribution of shopping centres in Australia in 2019, based on the number of centres and floor space available.

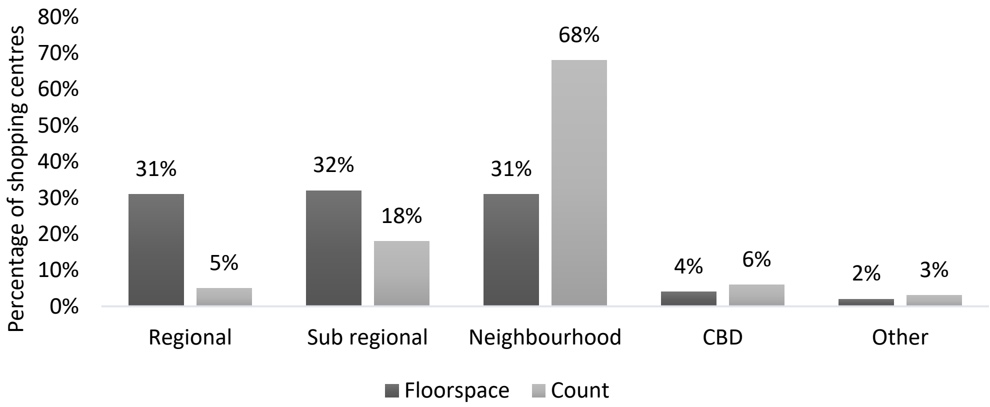

Figure 2.2: Shopping centre count and floor spaces percentage by type in 2019 in Australia

Source: Property Council of Australia (2019)

According to the statistics, neighbourhood centres are the most common type of shopping centres in Australia (PCA, 2019). Neighbourhood centres are convenient shopping places for everyday shopping such as the essentials in supermarkets and other food and non-food specialty stores. However, even though neighbourhood centres rank first based their sheer numbers, when floor space is considered subregional shopping centres are currently the most significant centre type in Australia. Furthermore, neighbourhood centres can be considered as a smaller version of subregional centres with less retailers and typically following a similar centre layout (JLL, 2019).

Therefore, subregional shopping centres are responsible for the highest resource use than any other type of shopping centre based on their floor space (PCA, 2019).

The value of retail property investments is another standard measure, which signifies the importance of different types of shopping centres from an investment perspective. According to 2018 data, total shopping centre investment transactions reached AU$ 8.1 billion from which subregional shopping centres were responsible for the highest portion of AU$ 2 billion, representing a 25% share (JLL, 2019). By comparison neighbourhood centres made 23% of the total investment transactions, ranking them as second, followed by regional centres. Thus, shopping centres hold a significant share in the Australian economy as well as in urban development, with subregional being the most important aspect.

The shopping centre industry is an innovative and economically challenging business with an ever-changing cycle of renovations and redevelopments due to their vulnerability to economic, functional or social obsolescence. Australia has reinvented the forms of shopping centres from the initial American based structures to local formats which are more connected to its culture and people. Due to growing populations and innovative forms of developments, Australian shopping centres, as a building asset, have a substantial effect on the environment as discussed further in the next section.

2.7.2 Adverse environmental effects of Australian shopping centres

Shopping centres are very significant resource users over their life cycle stages (Braslavsky, Wall, & Reedman, 2015). To maintain a comfortable environment within the centres, shopping centres use excessive amounts of energy for heating, cooling and air conditioning (Juaidi et al., 2016). Moreover, shopping centres are kept illuminated during the operational hours, creating a sophisticated and attractive environment (Woods, Skeie, & Haase, 2017). In Australia, the retail sector energy use exemplified 28% of the total commercial sector energy use in 2019 (Climateworks Australia, 2016, 2019) (refer to Figure 2.3).

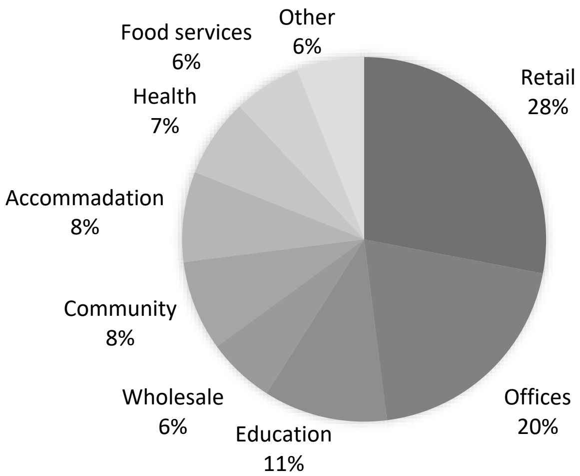

Figure 2.3: Commercial sector annual energy use by building type in 2019

Source: Department of Agriculture Water and the Environment (2019)

Australia actually has a mild temperature climate when compared with some other developed countries, yet their lower energy prices have led to inefficient energy use in shopping centres for heating and cooling purposes, increasing the environmental impacts (Climateworks Australia, 2016). According to the average energy use of shopping centres by end-use heating, cooling, ventilation, lighting and refrigeration are the most energy-intensive operations.

However, these percentages differ for different types of retail outlets in shopping centres. Food retail shops and non-food retail shops energy use percentages differ depending on the core functional requirement of the shop. The operational energy (energy used for maintaining the comfort conditions in the building (Ramesh et al., 2010)) use in shopping centres is critical in environmental considerations. Identifying the significance during use phase, several studies have investigated possible measures to mitigate the effects of retail centres (Braslavsky et al., 2015; Haase, Skeie, & Woods, 2015; Juaidi et al., 2016; Woods et al., 2017).

Nonetheless, it is not only the operational energy which causes an adverse environmental impact, but also the embodied energy of the shopping centres over its life cycle. Embodied energy is the energy used for raw building material extraction, transporting, building material manufacturing and transporting, installation, use and final demolition of building materials (Stephan, 2013). In shopping centres, as a result of shorter refurbishment cycle and continuous tenant turnover, building materials and assemblies are used repetitively over the building's lifespan (Braslavsky et al., 2015).

Therefore, to reduce the adverse environmental impacts of excessive energy use, both operational and embodied energy in shopping centres need to be taken into consideration. Operational energy reduction techniques include installation of energy-efficient appliances and fixtures, utilising renewable energy sources for electricity generation and natural means of lighting and ventilation (AlWaer et al., 2008) which are currently practised in many shopping centres as sustainable measures. However, the higher life cycle embodied energy (LCEE) of shopping centres has not received much attention, when compared to other building assets in Australia (refer to Section 3.5.3) (Carter & Allen, 2012; Fieldson & Rai, 2009; Haase et al., 2015). Thus, a proper investigation and in-depth analysis is required to assess the LCEE and embodied greenhouse gas emissions (LCEGHGE) of Australian shopping centres to identify appropriate means to mitigate adverse environmental implications.

2.8 SUMMARY

This chapter discussed the history of shopping centres development identifying the different forms available in the present. The changes in the shopping centre dynamics from being only trading places to community spaces demonstrates the evolution of shopping centres to fulfil the customers' requirements. The life cycle stages of shopping centres are described, identifying the accelerated development and maturity stage as the most critical to resource consumption, where the shopping centres require more maintenance and refurbishments. Moreover, the impact of tenant turnover on the continual renovation and refurbishment cycle of shops in the shopping centres is discussed, which again causes increased resource use. General concern for sustainability and the identification of this excessive use of energy and resources in shopping centres has created a shift towards mitigating the adverse environmental impacts of these buildings. The current trends of within sustainable shopping centres in Australia is mainly focused on operational energy reduction. However, the LCEE in shopping centres can have a similarly adverse effect due to the short refurbishment frequencies.

The latter part of the chapter discussed the significance of shopping centres in Australia, as a built asset. With many shopping centres planned to be developed, more attention needs to be given to shopping centres in Australia. Attaining greater sustainability in terms of resource use to reduce the adverse environmental impacts needs to be addressed.

However, to achieve greater sustainability in shopping centre design, it is essential to understand the sources of embodied energy in a building. Furthermore, it is also necessary to identify the implications of embodied energy reduction on the financial aspects of a shopping centre construction project. The next chapter analyses existing literature on embodied energy, possible means of embodied energy reduction and costs to identify current knowledge on the embodied energy in the built environment. Furthermore, it investigates the applicability of existing embodied energy reduction approaches to shopping centres.

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3 BUILDING MATERIALS, EMBODIED ENERGY AND COST

3.1 INTRODUCTION

The built environment is vital for the development of any nation in terms of improving the economy and quality of life. It is a measurement of economic stability of a country generating employment and increasing gross domestic production (Ng et al., 2017). Regardless, the built environment is identified as an environmental liability due to its excessive use of natural resources and generation of pollutants (Andersson, 2019; Röck et al., 2020; Teh et al., 2019). It is considered as one of the most significant users of natural resources and energy, a major generator of waste, and globally the second-highest emitter of the industrial sectors, of greenhouse gases (GHG) (Bribián et al., 2011; Krausmann et al., 2017; Ng et al., 2017; Teh et al., 2019).

This chapter will deliver the terminologies of building materials, embodied energy and material cost, which are adopted and used within the thesis. The importance of building materials as a contributor to embodied energy and the cost of a building is described. Using existing literature, the relationships between materials selection, embodied energy and material cost will be provided. Finally, a review of current material selection methods for different building assets is presented and analysed, identifying the lack of knowledge for shopping centres as a building asset.

3.2 MATERIAL USE IN THE BUILT ENVIRONMENT

The built environment is accountable for 36% of the final energy use and 39% GHG emissions globally (IEA, 2019). Building materials represent 11% of related energy and emissions from their manufacturing processes. Energy intensities have exhibited a downward trend since 2000, because of the increasing use of energy efficiency measures and renewable energy sources used in buildings (IEA, 2019; Marszal et al., 2011; White, 2016; Zakaria, 2008). However, the positive impact caused due to these measures has been dampened by the increasing energy intensities of building material manufacturing processes (IEA, 2019). Therefore, in order to assist the construction industry in achieving the global climate goals defined in the Paris Agreement (Rhodes, 2016), it is vital that the policy enablers take actions to reduce the total energy related to the manufacturing of building materials.

Building materials can be identified as any material used for construction purposes (Cornejo & Haro, 2009). Except for natural stones and unprocessed timber, all building materials are considered as fabricated products, procured using chemical and technological processes (Dvorkin, Nwaubani, & Dvorkin, 2010). The most common types of building materials used globally include concrete, steel, timber, glass, bricks and stones (Allen & Iano, 2019). Depending on the availability and the prices of building materials, their use vary from one location to another. For instance, bamboo is more commonly used in Southeast Asia but not in the Middle East. However, concrete, timber and bricks are used widely across the world. The amount of building materials used varies from type to type. For instance, concrete is the most used artificial material by volume (Kleijer, Lasvaux, Citherlet, & Viviani, 2017; Naik, 2008). A significant amount of building materials are used around the globe annually, and the value is gradually increasing (Krausmann et al., 2017).

The International Energy Agency (IEA) global status report (2019) states that the average global growth of built floor area is 2.5% per annum, while the energy intensity for building operation drop is 1.5%. While this appears to represent a sustainability movement it must be recognised that the increase in floor area requires a significant amount of building materials annually. This rising demand for building materials ultimately results in increased energy intensities and greater use of natural resources in the manufacturing of building materials. The demand for raw materials for construction purposes has increased by 40% since 1980s (Krausmann et al., 2017) and much research has been conducted highlighting the adverse environmental impacts of manufacturing of building materials (Bansal et al., 2014; Bhochhibhoya et al., 2017; Bribián et al., 2011; Horvath, 2004; Inyim et al., 2016; Krausmann et al., 2009). Many other researchers have investigated possible methods of quantifying and reducing these impacts (Bribián et al., 2011; Crawford, 2011; De Klijn-Chevalerias & Javed, 2017; Ding, 2008; Government of South Australia, 2017; Melià et al., 2014; Napolano et al., 2016; Öztaş, 2015; Papadopoulos & Giama, 2007; Thormark, 2006). Despite this vast amount of research, the building material manufacturing industry has not yet achieved its expected goals (Soares et al., 2017). Hence, more research attention should concentrate on the use of building materials and their associated environmental effects in order to achieve the expected growth in sustainability within the construction industry.

To discover ways to reduce the adverse effects of building materials, it is vital to understand their life cycle. Therefore, the next section provides details on the life cycle stages of building materials, and in particular, the adverse environmental effects associated with each phase.

3.3 THE LIFE CYCLE OF BUILDING MATERIALS

The life cycle of building materials can be described in five different stages from product stage to beyond building life stage as illustrated in Figure 3.1. These are defined in:

- EN 15978: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method', and
- EN 15804: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products', developed by British Standards Institution (2011, 2012).

EN 15978 and EN 15804 are horizontal standards which use a modular approach.

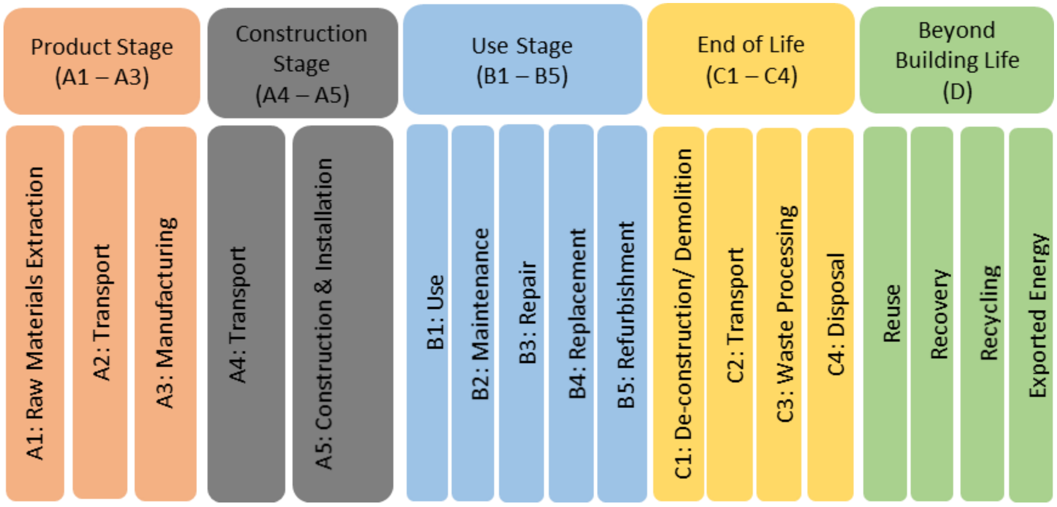

Figure 3.1: Life cycle stages from British Standards EN 15978:2011 and EN 15804:2012

Source: Adapted from (British Standards Institution, 2011)

These standards are utilised for the assessment of the environmental effects of construction work and defining environmental declarations for building products. The two standards outline the system boundaries for life cycle assessment of buildings and building products, identifying environmental aspects at the single module levels of A1-A5, B1-B5, C1-C4 and D (Achenbach, Wenker, & Rüter, 2018). Each of these stages has a different impact on the environment (Moncaster & Symons, 2013) and this classification enhances the life cycle assessment of buildings and building products.

3.4 Environmental impacts of building materials

The physical environment and the construction industry are interrelated predominantly due to the excessive use of natural resources in the construction industry (De Klijn-Chevalerias & Javed, 2017). The product stage of Figure 3.1, which represents the manufacturing of building materials and products, uses large quantities of natural resources and energy. The energy used to produce building materials are embodied in those products. It has been estimated that the energy used for manufacturing building materials and products off-site, can account for over 75% of the total energy embodied in a typical building (Ding, 2014). The built environment has witnessed a significant increase in resource use, which relates to the population growth and improved developments around the world (Krausmann et al., 2017). Therefore, the examination of the environmental impacts associated with building materials production for construction purposes has become important (Ng et al., 2017).

3.4.1 Product stage

The product stage of building materials involves the sub-stages of raw material extraction, transportation and manufacturing, as shown in Figure 3.1. The activity of raw material extraction through harvesting and mining results in resource depletion as well as damages to the biodiversity of the natural environment (Bribián et al., 2011). Extraction of renewable resources is therefore preferred over non-renewable resources, and special attention needs to be given to endangered species during this process (Berge, Butters, & Henley, 2009; Edwards, 2014). The waste generated through mining and harvesting natural resources can also cause air, water and land pollution, if not treated properly (Manhart et al., 2019). The energy expended by machinery and plant is extremely high during raw material extraction and material manufacturing activities (Berge et al., 2009; Esin, 2007). A recent study identified the most critical building materials in terms of the adversity of their environmental effects at the product stage (Ng et al., 2017). Steel (reinforcement), aluminium, copper, ceramic tiles and concrete, were identified as the top five materials with the greatest adverse impact to the environment. These findings mirror those of studies by Gursel, Masanet, Horvath, and Stadel (2014), Vieira, Calmon, and Coelho (2016), Melià et al. (2014), Guggemos and Horvath (2005), Norgate, Jahanshahi, and Rankin (2007), Norgate and Haque (2010), Ye, Hong, Ma, Qi, and Yang (2018), Leroy, Ferro, Monteiro, and Fernandes (2001), Kim and Chae (2016), De García, Gil, and Rico (2015) and Mehta (2001). The findings of these studies reveal that the product stage is critical in terms of energy use, waste and GHG emissions generation. Hence, from a sustainability perspective, immediate actions are essential to reduce the use of scarce natural resources and encourage the application of renewable raw materials and energy during the product stage of the building materials.

3.4.2 Construction stage

The construction stage involves the transportation of manufactured building materials to the construction site and installation to form the building (Allen & Iano, 2019). Impacts associated with transportation of building materials are considered insignificant when life cycle implications are taken into account at the building level (Bribián et al., 2011). The use of high-end machinery for the installation of building materials on-site requires a significant amount of energy. In addition, the construction stage causes other adverse environmental impacts due to the excessive emission of GHG and improper waste management (Ortiz, Pasqualino, Díez, & Castells, 2010). Previous research has found that the construction stage typically accounts for 8% - 20% of the life cycle environmental impacts of a building (Huberman & Pearlmutter, 2008; Koroneos & Kottas, 2007; Ortiz, Castells, & Sonnemann, 2009). Therefore, the construction stage is also considered critical in terms of life cycle assessment of the building materials. Furthermore, recent research has focused on the construction stage of a building, since the materials and assemblies installed in the building has a direct impact on the environmental implications caused during the use stage.

3.4.3 Use stage

The use stage of buildings can also have a substantial impact on the environment, in terms of the material use and construction waste generation, resulting from continuous maintenance, repairs and refurbishments (Crawford, 2011). The service life of building materials and assemblies perform a vital role during the use stage. Material service life can be considered as the amount of time the material can be expected to be serviceable (Rauf & Crawford, 2013). The service life of a building material is generally determined on the physical, functional, technical, economic, legal and the desirability life of that material (International Organization for Standardization, 2017). Building materials and assemblies with higher service lives are considered more environmentally sustainable due to the fewer number of replacements required when installed in a building form (Rauf, 2015).

Maintenance of building materials and assemblies requires resources for periodic repairs and replacements, which increases the energy embodied in the building. The service life values of building materials and assemblies are, therefore directly related to the adverse environmental impacts that occur during the use phase of the buildings (Fu, Pan, Ma, & Li, 2013). However, this can differ for various building types due to their functional requirements. In residential buildings, building materials are typically replaced once the materials reach the end of their expected service lives (Rauf, 2015; Stephan, 2013). However, in retail buildings, specifically in shopping centres, building materials can be replaced prior to completing the expected service life values because of economic, functional or social obsolescence (Holtzhausen, 2007; Sarja, 2005). Therefore, the energy embodied in the buildings due to material replacements during the use phase can vary significantly, for different building types.

3.4.4 End of life stage

At this stage, materials and assemblies in a building are typically disposed, reused or recycled (Ng & Chau, 2015). Frequent replacements of materials over the building life makes this the end of life stage more crucial. Research suggests that the construction industry is still a key generator of landfill waste from construction and demolition waste (Di Maria, Eyckmans, & Van Acker, 2018; Menegaki & Damigos, 2018; Murray, 2019), but also that it can improve its performance (Oyedele et al., 2013; Shen & Tam, 2002). As a result, Australia has reduced the percentage of construction and demolition waste that goes into landfill by almost 60% during the past decade (Murray, 2019).

Once a building material reaches the end of its first life due to economic, social or functional obsolescence, several end of life options exist (Ajayi et al., 2017; Akinade et al., 2017; Birkeland, 2004). However, all options need to be considered in order to select the most appropriate approach for the building material's optimal use (Ajayi et al., 2017; Akinade et al., 2017; Department of Sustainability environment water population and communities, 2012; Raut, Ralegaonkar, & Mandavgane, 2011).

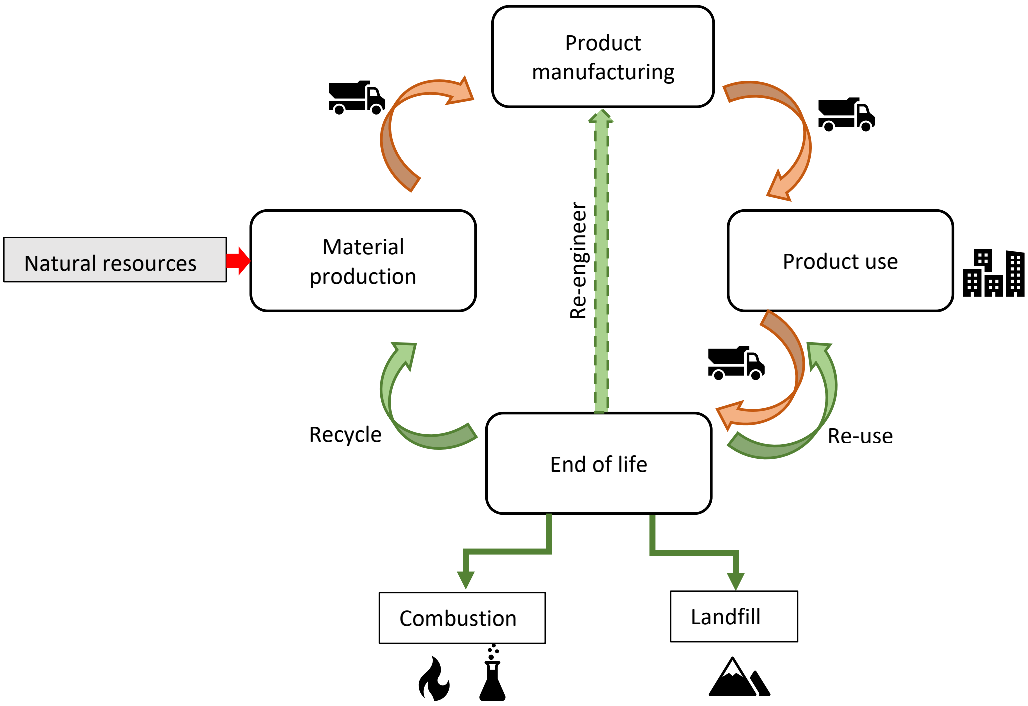

Figure 3.2: Possible end of life options for building materials

Source: Adapted from Ashby (2012)

As shown in Figure 3.2, several options exist for the end of first life for building materials. Previously, the most common situation was delivering building material waste to landfill (Ajayi et al., 2017). Nevertheless, with the increasing use of resources globally, waste generation has increased causing overload of most of the landfill sites, and thus creating significant difficulties in the management of future waste in many economies (Tam & Lu, 2016). Furthermore, considering the damage caused to the environment due to landfill sites, legal frameworks have been developed to reduce the amounts of waste delivered to landfill sites through the implementation of taxes and other policies (Bassi & Watkins, 2012; Calvo, Varela-Candamio, & Novo-Corti, 2014; Di Maria et al., 2018). As a result, other options shown in Figure 3.2 have become popular as approaches for managing construction and demolition waste.

Combustion of building materials to recover the energy embodied is an alternative option to landfill. Combustion is defined as '*the thermal breakdown of waste under excess air or oxygen to produce heat, ash and flue gas' (Environment Protection Authority, 2013, p. 5)*. Among several "waste to energy" approaches practised globally combustion can be considered a dominant method. For example, most of the timber waste generated from construction projects (formwork, scaffolding, rejects, off-cuts, etc.) are used as combustible fuel in power generating plants (Falk & McKeever, 2004). Through combustion, useful energy can be recovered, yet the process is quite sophisticated, requiring expensive equipment and controlled conditions (Zhao, Leeftink, & Rotter, 2010). If the process is not managed correctly, it can cause further damage to the environment. However, combustion can recover only a portion of energy embodied in the material while losing the material itself. Given that potentially infinite amount of energy can be produced with renewal sources but a limited quantity of raw materials are available on the planet, combustion may not be the most appropriate waste management approach for all types of construction and demolition waste (Del Río Merino, Izquierdo Gracia, & Weis Azevedo, 2010).

Recycling is considered as one of the best available methods of value-generating through waste (Colling, Oliveira, Reis, da Cruz, & Hunt, 2016; Di Maria et al., 2018; Tam, 2009; Tam & Lu, 2016). It is the process of reforming the waste materials into resources for the supply chain (Department of Sustainability environment water population and communities, 2012). Even though the recycling process requires a substantial amount of energy, this is considered less significant when compared to the energy embodied in new materials. Thus, recycling is observed as an energy-efficient and a cost-effective waste management method (Begum, Siwar, Pereira, & Jaafar, 2006; Duran, Lenihan, & O'Regan, 2006; Tam, 2008; Tam & Tam, 2006). Many developed economies follow recycling as the primary construction waste management approach with some, such as Germany and the Netherlands, achieving exceptional recycling rates of over 80% (Menegaki & Damigos, 2018).

Reengineering and refurbishing are also considered as options for managing building materials waste. The efficiency of this method depends on the type of material and the energy and cost required for the process (Richardson, 2013). However, reuse is regarded as the best option in which building materials are used in their existing condition for the similar purpose or a different purpose (Beth, 2013; Lintz, Jacintho, Pimentel, & Gachet-Barbosa, 2012; Richardson, 2013). Therefore, when considering the end of life options available, it is possible to moderate the adverse effects during this stage (Tam & Lu, 2016).

The identification of the adverse environmental impacts associated with the life cycle stages of building materials has created a movement to take actions to reduce the excessive use of energy and resources. The use of energy for building material's production and maintenance is crucial in the life cycle perspective. Therefore, investigation of all possible means for reducing the life cycle energy use of building materials is considered imperative for achieving the environmental sustainability goals of the construction industry, outlined in the Paris Agreement (Rhodes, 2016).

3.5 BUILDING MATERIALS AND EMBODIED ENERGY

Energy used by building materials over their lives is typically known as the embodied energy (Dixit, Culp, & Fernandez-Solis, 2015). Embodied energy is often used as an indicator of the environmental impacts of building materials. By definition, *'embodied energy comprises the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building'* as cited by (Dixit, Fernández-Solís, Lavy, & Culp, 2010, p.1239) based on the comprehensive definitions provided by other researchers (Crawford & Treloar, 2005; Dixit, 2017a; Pomponi & Moncaster, 2016; Ramesh et al., 2010; Reddy & Jagadish, 2003; Stephan, 2013; Treloar, Fay, Ilozor, & Love, 2001a). It is a comparative value of the energy embodied in building materials which can be used in evaluating possible material alternatives.

Embodied energy is calculated using different life cycle approaches within different boundaries (Biswas, 2014; Dixit, 2017a; Fouche & Crawford, 2015; Treloar, 1998; Treloar & Crawford, 2010). These assessments can have the scope of cradle-to-gate, cradle-to-grave (end of life), or cradle-to-cradle (including beyond building life) (Crawford & Treloar, 2003; Moncaster & Symons, 2013; Treloar, 1997, 1998). The embodied energy value of a building material is expressed usually in Joules per unit weight of the material (e.g. MJ/kg, MJ/t, etc.), whereas in a building, it is demonstrated as Joules per gross floor area (MJ/m^2) (Crawford, 2011; Dixit et al., 2015). Since embodied energy values are considered sensitive to the system boundaries, the outcomes of the life cycle studies are more suitably used for comparative purposes rather than as absolute values (Stephan, 2013). Embodied energy analysis depends on several aspects such as system boundaries, location, period of analysis, the methodology of assessment and the assumptions made. The accuracy and validity of the outcome are therefore affected by these factors.

Life cycle inventories (LCI) are compiled as part of the life cycle analysis of building materials (Crawford, Bontinck, Stephan, Wiedmann, & Yu, 2018). LCI involve the inputs and outputs which are associated with the product being studied. They are employed in quantifying embodied energy coefficients (EEC) of different building materials (Treloar, 1997). The three most common approaches used for compiling LCI are process analysis, input-output analysis and hybrid analysis (Crawford et al., 2018; Dixit et al., 2015; Treloar, 1997, 1998; Treloar & Crawford, 2010). Each approach inherits its own positive and negative features. Hence, the selection of the most appropriate approach is subject to the availability of production processes data and economic data.

3.5.1 Life cycle inventory methods

Life cycle inventory analysis is the basis of quantifying the inputs and outputs of a product or a process (Crawford et al., 2018). The embodied energy of building materials can, therefore, be analysed by compiling an LCI, focusing on the energy flows. The main three approaches used to compile an LCI are explained in detail below.

3.5.1.1 Process analysis

In this method, a process flow diagram is produced to quantify the inputs and outputs of a product or a process and the associated environmental impacts. All visible processes related to a product are examined, identifying the direct and indirect energy inputs and the effect to the environment (Baird, Alcorn, & Haslam, 1997; Crawford, 2011). Energy analysis is conducted upstream, starting from the final product and going back along the main process, quantifying all possible related energy inputs (Treloar, McCoubrie, Love, & Iyer-Raniga, 1999). Process analysis can generate the most reliable results when conducted correctly, feeding all the product-specific data along the supply chain (Bullard, Penner, & Pilati, 1978; Ding, 2008; Suh et al., 2004).

However, due to the unavailability of data associated with the upstream supply chain and the complexity of the production process, the results derived through this method can be incomplete and inconsistent (Lenzen & Dey, 2000). Another major drawback in the process analysis method is the exclusion of energy associated with plant and equipment for building material production (Pullen, 2000). This incompleteness of the process analysis method affects various products differently. Many studies have been carried out to estimate the level of incompleteness in process analysis (Lenzen & Dey, 2000; Miller & Blair, 2009; Suh et al., 2004). According to Treloar, Love, and Faniran (2001), the magnitude of incompleteness is estimated as 52%, with Crawford (2008) later identifying it as 59%, but could vary up to 87%. The embodied energy values derived through process analysis are generally lower than the other methods due to this larger magnitude of system incompleteness.

3.5.1.2 Input-output analysis

The input-output method was developed by Leontief (1936) and involves industry-based monetary flows for identifying energy use and environmental effects of a product. The energy flows within sectors are quantified using the industry input-output transaction data (Baird et al., 1997). The sectorial resource flow can be demonstrated as shown in Figure 3.3. Upstream assessment of the energy flows of the main process is conducted up to the most feasible stage.

The direct energy inputs of each stage are quantified based on the input-output data of the related industry. This method assumes the industries are inter-related, and each industry consumes fixed amounts of outputs of other industries, to produce a single output. Input-output based analysis captures the monetary flow of every sector in an economy (Baird et al., 1997). The system boundary of this method is generally considered complete when compared to process analysis. The reason being that since all the transactions at a country level are recorded in national input-output tables, system boundaries are precise (Hendrickson, Horvath, Joshi, & Lave, 1998; Suh et al., 2004).

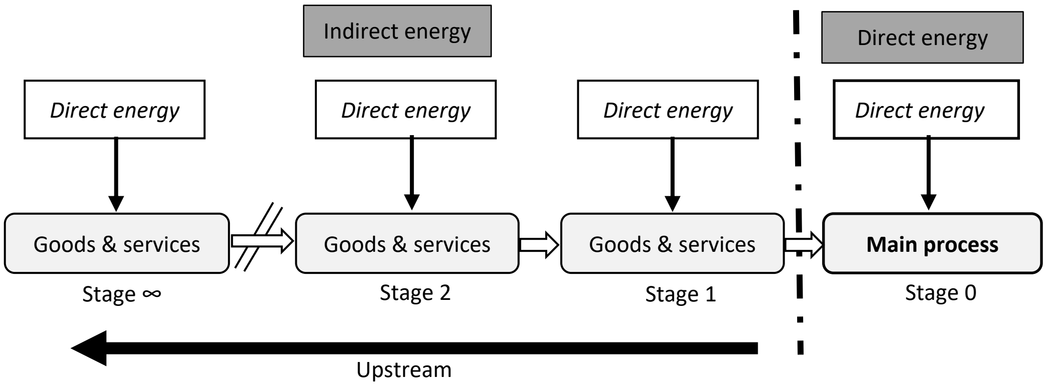

Figure 3.3: Input-output based life cycle inventory analysis for embodied energy assessment

Source: Treloar, Fay, Ilozor, and Love (2001b, p. 51)

However, input-output analysis does have some limitations with its use. The aggregation of total direct and indirect requirements across all sectors become complicated along the upstream stages, making manual quantification unmanageable (Suh et al., 2004). Additionally, the input-output data produced in economic units are transferred to physical quantities based on price assumptions, which can result in errors (Treloar, 1998). Furthermore, the data used for calculations in this method are generally older than process-based data. Therefore, the input-output method also has its advantages and disadvantages, limiting its application.

3.5.1.3 Hybrid analysis

As both process analysis and input-output analysis approaches inherit system boundaries, errors and limitations in life cycle inventory analysis, researchers have attempted to establish a more comprehensive approach, incorporating the strengths of both approaches. These are called hybrid approaches. Crawford (2008); Hendrickson et al. (1998); Lu, Le, and Song (2017); Miller and Blair (2009); Strømman, Peters, and Hertwich (2009); Suh et al. (2004) and Treloar (1997) have all developed hybrid life cycle inventory methods which can be employed to quantify embodied energy of building materials. The proportionate use of the process analysis and input-output analysis, differenciates hybrid methods into four (Crawford et al., 2018). The problems inherent in each contributing approach are also apparent to a certain extent in the hybrid methods. The amount varies depending on the degree to which the primary methods were used (Crawford et al., 2018; Treloar, Love, et al., 2001).

In their study of hybrid life cycle inventory methods Crawford et al. (2018) identified the four variations of the hybrid approach as; tiered, path exchange, matrix augmentation and integrated. Table 3.1 explains the hybrid methods identifying their similarities, differences, limitations and errors. These methods are believed to generate more accurate and comprehensive representations of the embodied energy of building materials.

Table 3.1: Comparison of hybrid life cycle inventory analysis methods

Hybrid approach	Concept	Developer/s	Strengths	Weaknesses	References
Tiered	Based on a process analysis framework yet use both input-output and process data.	Bullard et al. (1978)	Integration of both input-output and process data allow for boundary expansion for analysis.	The user defines the boundaries for the use of input-output and process data, so, it could vary significantly. The risk of double counting if boundaries for process analysis and input-output analysis are not clearly established.	(Bullard et al., 1978; Changbo, Lixiao, Shuying, & Mingyue, 2012; Crawford et al., 2018; Suh et al., 2004)
Path exchange	"*Involves the mathematical disaggregation of an input-output matrix, thus enabling the identification and modification of mutually exclusive pathways - the sum of which represents the entire matrix*" (Crawford et al., 2018, p. 1277)	Proposed by Treloar (1997) based on theories developed in the 1980s by Miller and Blair (2009). Formalised by Lenzen and Crawford (2009)	Data specific to a discrete path can be modified without affecting the whole input-output matrix.	Complexity in application. Requires time to carry out the process.	(Crawford & Stephan, 2013; Lenzen & Crawford, 2009; Rauf & Crawford, 2015; Treloar & Crawford, 2010)
Matrix augmentation (often referred to as input-output based hybrid method)	Modify the existing input-output matrix with the addition of a new theoretical sector or division into subsectors.	Joshi (1999)	Resolve the aggregation error in conventional input-output based analysis. Input-output and process data are described in a consistent framework.	As the analysis is based on the main input-output matrix, the modifications affect every layer of the supply chain under study.	(Baboulet, 2009; Crawford et al., 2018; Joshi, 1999; Suh et al., 2004)
Integrated	"*Integrates process and input-output data within a single matrix framework, using a set of vectors referred to as upstream and downstream cut-off matrix to link the two matrices*" (Crawford et al., 2018, p. 1277).	Suh and Huppes (2005)	Double counting is avoided. Compile input-output and process data into a common framework.	Complexity in application. Requires a large amount of data and time to carry out the process.	(Acquaye et al., 2011; Baboulet, 2009; Suh & Huppes, 2005)

Source: Developed from materials in Crawford et al. (2018)

3.5.2 Embodied energy coefficients of building materials

Hybrid EEC of building materials derived integrating process and input-output data following the path exchange hybrid method (Crawford, 2011; Treloar & Crawford, 2010) are identified as the more comprehensive when compared to other approaches (Crawford et al., 2018). Energy requirements of the building materials' manufacturing process are quantified considering all energy inputs along the upstream of the main process. The process of calculating EEC involves several stages. First, the energy required to produce a building material is determined using the best available process data. These can be obtained directly from building material manufacturers through energy audits or from the existing databases, which aggregate data from several manufacturers (i.e. Ecoinvent (Frischknecht et al., 2007), ICE (Hammond & Jones, 2008)). However, this data should be treated with caution as they have limitations in the boundaries set forth, acquisition of data, geographical factors and the age of data. Then, with the use of a disaggregated input-output model, the processes are identified, from which process data are acquired. The difference between the direct energy requirements of the processes and the total energy requirement of an individual sector is quantified and replaced with process data. This procedure addresses the limitation of the incompleteness of other approaches, maximising the reliability and completeness of the system and results. Calculation of the EEC using path exchange hybrid method of building materials used by Treloar and Crawford (2010) is shown in Equation 3.1.

Equation 3.1: Calculation of hybrid embodied energy coefficients of building materials using path exchange hybrid life cycle inventory analysis method

$$EC_m = PER_m + \left[TER_n - \sum(DER_i)\right] \times P_m$$

Where;

EC_m= *Hybrid embodied energy coefficient of material m, in GJ/unit*

PER_m= *Process energy requirement for a unit of building material m, in GJ*

TER_n= *Total energy requirement of the input-output sector n, in GJ/1,000 currency units*

DER_i= *Direct energy requirement of the input-output pathways representing the building material production process for which process data is available, in GJ/currency unit*

P_m= *Total price of the building material m, in currency units*

Only a few researchers have developed EEC of building materials based on hybrid approaches (Alcorn, 2003; Hammond & Jones, 2008; Treloar & Crawford, 2010). Many of these assessments are done from cradle-to-gate, limiting the scope of inputs and outputs (Hammond & Jones, 2008). However, the hybrid EEC developed by Treloar and Crawford (2010) using the energy-based input-output model developed by Lenzen and Lundie (2002), and Australian building material inventory process data accumulated by Grant (2002) are considered more comprehensive and related to Australian context (Dixit, 2017c; Stephan & Athanassiadis, 2017) (attached in Appendix 1). Table 3.2 demonstrates the EEC of some essential building materials used in Australia.

Table 3.2: Input-output based hybrid embodied energy coefficients of a few highly used building materials in Australia

Building material	Unit	Embodied energy coefficient (GJ/unit)
Aluminium - Virgin	t	252.600
Concrete - 40MPa	m^2	6.750
Cement	t	16.960
Fibreglass	m^3	432.100
Timber - Hardwood	m^3	21.330
Nylon - Carpet	m^2	0.683
Stainless steel	t	445.200

Source: Extracted from Treloar and Crawford (2010)

The coefficients developed by Treloar and Crawford (2010) are more comprehensive and specific to Australia. Many studies have used these EEC to assess embodied energy implications of the Australian building industry (Aye, Ngo, Crawford, Gammampila, & Mendis, 2012; Stephan, 2013; Zuo, Read, Pullen, & Shi, 2012). However, at the end of 2019, a new embodied energy dataset was released by Crawford, Stephan, and Prideaux (2019) using a similar LCI method, which can be applied in future research.

3.5.3 Life cycle embodied energy of buildings

Life cycle embodied energy (LCEE) of a building is a combination of initial and recurrent embodied energy and demolition energy (Dixit, 2013; Ramesh et al., 2010; Stephan, 2013). LCEE of a building can be determined based on the EEC of the building materials and assemblies used for the construction, with initial, recurrent and demolition energy values derived using EEC and the quantities of building materials (Crawford & Treloar, 2005; Dixit, 2019; Rauf, 2015). The LCEE calculation is explained in detail in Section 4.7.3.

The significance of embodied energy in the built environment is rapidly increasing as a result of the applications implemented to reduce operational energy use in the buildings (Bansal et al., 2014; Roh, Tae, Suk, & Ford, 2017; Stephan & Athanassiadis, 2017). The energy efficiency measures incorporated in the building structure can sometimes result in increased embodied energy, hence the need for them to be appropriately assessed. A study by Stephan, Crawford, and De Myttenaere (2013) investigated three case study dwellings to quantify the energy saving of a passive house in Belgium. A comparison of the life cycle energy (LCE) usage of a passive house and a standard house, with the same building footprint, revealed that they result in nearly the same energy use over 100 years. The difference was only 0.6%. The reason was that even though the increased insulation levels caused an operational energy reduction in the passive house, the embodied energy of the house increased due to specific materials and assemblies adopted to reduce operational energy use. Figure 3.4 provides a demonstration of the life cycle energy demands of the two cases.

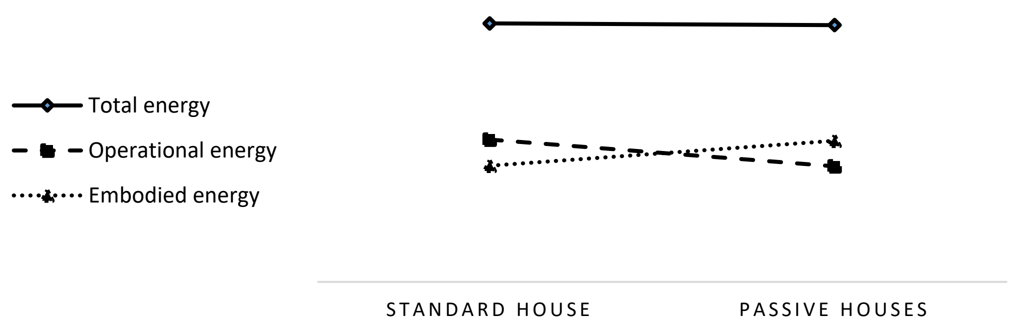

Figure 3.4: Trade-off between embodied energy and operational energy in conventional and passive houses

Source : Adapted from Stephan et al. (2013)

It is therefore apparent that both operational energy reduction and embodied energy need to be viewed together as they are closely linked (Stephan et al., 2013). Crawford, Bartak, Stephan, and Jensen (2016) revealed that if operational energy efficiency is driven to an extreme, it may not return the expected life cycle energy savings. If operational energy efficiency measures incorporated in the building structure are not appropriately managed, after a specific point, the embodied energy may take an upsurge, outweighing the operational energy savings. Therefore, it is crucial to understand the optimal point we can reach with operational energy-saving measures integrated into the building structure.

Consequently, the attention of built environment researchers and industry professionals has also focused on improving the embodied energy efficiency. A better understanding of the embodied energy of buildings over the life cycle is essential in managing the trade-off between the operational and embodied energy in the built environment.

Embodied energy in buildings can be considered as one of three types namely; initial embodied energy (IEE), recurrent embodied energy (REE) and demolition energy. Each type is described below to provide a detailed understanding of how LCEE is quantified.

3.5.3.1 Initial embodied energy

The IEE is identified as the energy embodied in building materials used at the construction stage of a building (Dixit et al., 2015). The choice of building materials is therefore the most influential factor of a building's IEE (Bansal et al., 2014). The energy embodied in the construction process, transportation of building materials, use of machinery and plant and other non-building material inputs are all involved in the IEE (Crawford, 2011; Dixit, 2017c; Treloar & Crawford, 2010). The quantification of IEE is described in Section 4.7.3.1.

The IEE of a building material, or an assembly, can vary broadly as it often depends on several variables. Life cycle inventory approach used to quantify EEC has the most effect, followed by geographical aspects and design configurations and others. In simple terms, IEE of a material or an assembly is calculated by multiplying the quantity of material, or assembly, used in the building (including any wastage), with the EEC of that material or assembly (Crawford, 2011; Dixit, 2013).

Studies on the life cycle energy of buildings often demonstrate that IEE is typically greater than the recurrent embodied energy of a building (Chang, Ries, & Wang, 2010; Crawford & Stephan, 2013; Crawford & Treloar, 2005; Thormark, 2002; Treloar et al., 1999; Van Ooteghem & Xu, 2012). The share of IEE from the LCEE found in studies varies between 20% - 70% for different types of buildings. Therefore, IEE is considered as an essential indicator to evaluate the implications of different building materials and assemblies.

Studies by Stephan and Athanassiadis (2017, 2018) on material flow and embodied environmental requirements of the urban building stock in Melbourne, Australia, revealed that the LCEE of an assembly often varies depending on the materials used. For example, when timber is used as structural members in a building, they are not replaced, but timber doors might be replaced over the building life cycle. Therefore, the consideration of IEE alone does not provide a complete representation of LCEE of a building. The material replacements that take place over the use phase must be accounted for as well.

3.5.3.2 Recurrent embodied energy

Recurrent embodied energy (REE) is the energy embodied in building materials and assemblies which are used for replacements, and the energy for maintenance of those building materials over the use phase of a building (Crawford, 2011; Dixit, 2017a). It is typically affected by the service life of the building, service lives of building materials and assemblies and EEC of building materials and assemblies. Building materials and assemblies are often replaced when they reach the end of their expected service lives (Rauf & Crawford, 2015). Most of the building materials used in the skin, space plan and services layers of a building (based on the shearing layers of change proposed by Brand (1995), refer Section 1.4) are exposed to change during the use phase.

However, in some situations, materials are replaced due to economic, social and functional obsolescence (Holtzhausen, 2007). In these cases, building materials are replaced prior to the end of their projected service lives. Poor design is considered a key reason for these early replacements, where incompatible building materials are combined to create a building assembly (Ye et al., 2018). The use of a single material with a shorter service life value in an assembly with a considerably longer service life value can result in the replacement of the whole assembly. For instance, using an insulation material with a lower service life value in a structural wall could require replacement of the whole assembly. However, in retail buildings material replacement is often a matter of aesthetics and branding. Therefore, service life is a dominant aspect in the selection of building materials for a building. A material with a longer service life can result in lower LCEE even if its EEC is high. Similarly, a material with a shorter service life and a lower coefficient can ultimately result in a higher LCEE.

In most of the building assets, material replacement decisions are made by the owner, or in the cases of commercial properties, the authority also relies on the property management and tenants. In the case of shopping centres, the owner and management are typically responsible for continuous maintenance, renovations and refurbishments, which are required to preserve attractiveness and retain foot traffic (AlWaer et al., 2008). Additionally, building material replacements also occurs in shopping centres due to tenant turnover. According to the Tenant Lease Act 2003, the minimum tenant lease period in shopping centres in Victoria is five years, except in situations stated in the Act (The Parliament of Victoria, 2003). Therefore, shopping centre tenants might be replaced every five years in Australia and each time the shop fit-outs might need to be reconfigured, to satisfy the requirements of the new tenant. This tenant turnover can ultimately cause significant resource waste as well as increased REE of the shopping centre in comparison to other buildings assets.

A study by Fridley, Zheng, and Zhou (2008) found that the IEE of a shopping centre in China was 10 GJ/m^2 floor area, which was the highest value of all the commercial buildings investigated. However, there are hardly any studies which have estimated the REE in shopping centres. Therefore, reliance on hypothetical situations have been used to demonstrate the significance of REE in shopping centres. A hypothetical situation by Weththasinghe (2017), provided a clear picture of the importance of REE.

For instance, Weththasinghe (2017) used an hypothetical scenario of a subregional shopping centre in Victoria, Australia. It was assumed to have a gross lettable area of 15,000 m^2, with two *anchor shops* and 60 *specialty shops*. According to the property planning and development guidelines for shopping centres in Australia, 40% of the GLA has been allocated to the *specialty shops*.

Area of specialty stores	15,000 m^2 × 40% = 6,000 m^2
Number of specialty stores	60
Average area of one store	6,000 m^2 / 60 = 100 m^2
Assume a wall height	5 m

The minimum tenant lease period for small tenants in shopping centres is five years in Australia. Considering a hypothetical situation where all specialty tenants leave the centre at the end of each five years and new tenants move in, or the current tenants remain but refurbish their shops, then all specialty shop fit-outs need to be recreated (in most cases interior finishes of floor, wall and ceiling are replaced). The life span of the shopping centre is assumed to be 50 years and the EEC by Treloar and Crawford (2010) are used. Hypothetical internal finishing materials used and replaced are as follows.

Element	Item	Material	Unit	Embodied energy coefficient (GJ/unit)
Floor	Carpet	Nylon	m^2	0.683
Walls	Paint	Water-based paint	m^2	0.096
Ceiling	Paint	Water-based paint	m^2	0.096

Number of replacements occur over 50 years	(50/5) - 1= 9
Material quantities replaced each time	
Floor	6,000 m^2
Wall (layout of a shop is 10 m long and 4 m wide)	(10 × 4) m × 5 m × 60= 12,000 m^2
Ceiling	6,000 m^2
Total quantity of materials replaced over 50 years	
Floor carpet	6,000 m^2 × 9= 54,000 m^2
Wall finish	12,000 m^2 × 9 = 108,000 m^2
Ceiling finish	6,000 m^2 × 9 = 54,000 m^2
Total REE of interiors	
Floor finish	54,000 m^2 × 0.683 GJ/ m^2 = 36,882 GJ
Wall finish	108,000 m^2 × 0.096 GJ/ m^2 = 10,368 GJ
Ceiling finish	54,000 m^2 × 0.096 GJ/ m^2 = 5,184 GJ

These values demonstrate the importance of REE in shopping centres which is often unseen compared to the more visible IEE and operational energy use. Therefore, REE is vital in LCEE assessment of shopping centres as it might account for a larger share of the LCEE. The process of quantifying REE is explained in detail in Section 4.7.3.2.

3.5.3.3 Demolition energy

Demolition or the end of life of a building is the stage where the building is deconstructed, and the remaining of the residual building materials are sent to landfill, re-use, or recycling plants. Demolition energy is the energy required for the activities associated with this stage. Most of the building life cycle studies have found that demolition energy is significantly low and thus, the impact is considered negligible as claimed by Crowther (1999); Dixit, Fernández-Solís, Lavy, and Culp (2012); Gaspar and Santos (2015); Winistorfer, Chen, Lippke, and Stevens (2007).

Even though demolition energy of the building is considered negligible, the waste generated at the demolition stage can cause significant environmental impacts, if managed inappropriately (Blengini, 2009; Department of Sustainability environment water population and communities, 2012). Demolition waste management in the built environment is therefore essential in reducing the environmental impacts of buildings, not only at the demolition of the building, but also the end of life of building materials used in buildings. The end of life scenarios of building materials, as explained in Section 3.4.4 are used to moderate the adverse environmental effects associated with those materials.

Recycling can result in an embodied energy saving which can be viewed in one of two ways. One argues that the potential energy-saving due to recycling needs to be deducted from the IEE (Ng & Chau, 2015; Thormark, 2000, 2006). Therefore, the selection of building materials with higher recycling potential could result in higher energy savings at the end of first life. The second postulates that the energy savings need to be attributed to the second life of the building material (Treloar, 2000). Accordingly, the first perspective promotes the use of building materials with higher recycling potential, whereas the second may be considered more realistic as it is problematic to make predictions for the entire life of a material. This study incorporates the first perspective as it can be used as a basis for building material selection resulting in lower LCEE.

The next section presents the factors affecting sustainable material selection and the significance of carbon tax as a mechanism to cause behavioural changes in the material selection of buildings in Australia to achieve sustainability goals soon.

3.6 SUSTAINABLE MATERIAL SELECTION

Building materials are identified as a critical input in any construction project. The selection of materials is considered to involve a multi-criteria decision making process, which is time and data intensive (Castro-Lacouture et al., 2009). Material selection decisions have a substantial impact on the key project performance criteria of time, cost and quality (Chan, Scott, & Chan, 2004). Furthermore, the choice of materials during the design and construction stages affects the energy demand during the use phase of the building. The selection of materials in a building project therefore becomes challenging, considering their impact and establishing a trade-off between the dependant attributes (Rahman, Perera, Odeyinka, & Bi, 2008). Selection of the most appropriate material from a range of alternatives available is also a demanding decision, which needs to consider a variety of factors and make priorities depending on different situations (Trusty, 2003). Therefore, the decision needs to be based on constant assessment and reassessment of materials and products available in order to make the most appropriate choices during the project design stage (Chan & Tong, 2007).

The built environment researchers and industry professionals are currently interested in the zero-carbon concept, and this development has increased the use of more environmentally sensitive building materials. These concerns have created an interest amongst construction stakeholders in considering environmental impacts when selecting materials, amid other priorities. By not only identifying the importance of factors affecting sustainable building material selection as well as the complexity in prioritising key attributes, but researchers are also conducting studies to investigate this issue of decision making.

Ogunkah and Yang (2013) investigated the factors affecting building material selection. Durability, availability, workability, cost, and aesthetics were identified as the critical factors among various other aspects. These findings align with previous studies by Ashby (2000); Chan and Tong (2007); Rahman et al. (2008); Wastiels and Wouters (2009) and Zhou, Yin, and Hu (2009). Additionally, more recent work by Akadiri et al. (2013); Čuláková et al. (2013) and Govindan et al. (2016) have also revealed similar findings. Amongst these factors, several barriers and drivers of sustainable material selection can be observed.

Several studies into the drivers of sustainable material selection in construction projects have identified these as financial incentives, government regulations on building planning and design, client demand, taxes and levies and client awareness (Häkkinen & Belloni, 2011; Lam, Chan, Poon, Chau, & Chun, 2010; Pitt, Tucker, Riley, & Longden, 2009). Additionally, moral convictions on resource conservation, emissions and waste reductions (Ahn, Pearce, Wang, & Wang, 2013; Giesekam, Barrett, & Taylor, 2016; Oyekanmi & Abisuga, 2014), benchmarking and creating business opportunities have also been recognised as positive influencers (Florez & Castro-Lacouture, 2013).

Despite these drivers, sustainable material selection still faces a series of barriers. A study conducted by Griffin et al. (2010) found that cost increment, lack of reliable information for comparison of available solutions and scarcity of materials as the primary barriers. Giesekam et al. (2016) study of the barriers to adaptation of low carbon materials in construction sector revealed similar findings to Griffin et al. (2010), with high cost and lack of data and benchmark information again identified. In addition to that, the level of influence and responsibility allocated among project participants in decision making and industry culture was highlighted.

In another study, Akadiri (2015) outlined 13 barriers, gathered through a literature study as well as empirical data. Those barriers were then prioritised using the relative importance index (RII) with the perception of the extra cost being incurred ranking as number one. Several other studies have collaborated these findings (Ahn et al., 2013; Gosselin, Blanchet, Lehoux, & Cimon, 2017; Häkkinen & Belloni, 2011; Opoku, Ayarkwa, & Agyekum, 2019; Patel & Chugan, 2017; Safinia, Al-Hinai, Yahia, & Abushammala, 2017; Wilson & Tagaza, 2006).

As cost has been consistently identified as a primary barrier for sustainable material selection in the construction industry. The following section describes the significance of cost as a project parameter, and possible ways to address cost militating against sustainable material selection.

3.6.1 Cost as a barrier for sustainable material selection

Cost is not only a significant factor in building material selection but also, has been identified as a major factor militating against sustainable material selection. Cost is a key performance indicator in any construction project success along with the other two predominant criteria, namely time and quality (Chan & Chan, 2004; Chan et al., 2004; Ogunlana & Toor, 2010). Therefore, the cost of a building project is a primary concern for most stakeholders involved in a project. However, it is project clients or owners who are more attentive to cost details from the initial stage, attempting to reduce the cost as much as possible. The role of the quantity surveyor (QS) in a construction project aims to achieve cost targets, while maintaining the quality of the project (Ashworth & Perera, 2015). The QS is therefore responsible for the cost management and monitoring in a construction project and thus has the authority to suggest cost-effective alternatives concerning any aspect in the project (Ashworth, Hogg, & Higgs, 2013; Hardie, Miller, Manley, & McFallan, 2005; Seeley, 1984).

Building material selection is predominantly a responsibility of the architects, designers and engineers, but the QS can influence the selection decision in relation to the costs to be incurred (Hardie et al., 2005; Kissi, Sadick, & Agyemang, 2018; Matipa, Kelliher, & Keane, 2008). Understanding the life cycle cost of building materials and assemblies can assist in building material selection decision in a project. Cost being a priority concern in building material selection makes the involvement of the QS vital. Studies have found that the capital cost (CC) of materials of a building project can represent up to 30% of the initial total project cost (Aye et al., 2012; Inyim et al., 2016; Ross et al., 2007). Moreover, the cost-in-use (CIU) of building materials due to maintenance, repairs, renovations and refurbishments also account for a substantial amount (Ali, Azmi, & Baaki, 2018; Power, 2010; Vilches, Garcia-Martinez, & Sanchez-Montañes, 2017). Hence, life cycle material costs (LCMC) of a building need to be evaluated when selecting building materials at the initial stage.

LCMC of a building involves three contributions, namely CC, CIU, and demolition costs. CC are the initial costs of the building materials, transportation and installation costs (AIQS, 2000). CC of materials form a part of the initial project cost and are non-recurrent costs (Aziz, 2013). Typically, the material selection decisions are made evaluating the CC of available options. Quantification of the CC of an assembly is carried out by multiplying the unit price of the assembly with the quantity of assembly used in the building. The algorithms used for quantification are presented in detail in Section 4.7.4.

CIU are the operating and maintenance costs, which are associated with building assembly repairs and replacements (AIQS, 2000). These are recurrent costs over the life cycle of the building. The costs of building materials and assemblies used for the repairs and replacements are accounted as CIU. As with REE, the CIU of building materials is highly affected by the refurbishment and replacement frequencies along with the service life of the building and materials (Dixit, 2017b). When quantifying the CIU, future material costs of the building are discounted to the present value, using a discount rate to demonstrate all possible future costs as an indicator of the present values.

Demolition and disposal costs are the costs related to building deconstruction or dematerialisation and disposal of the demolition waste (Calvo et al., 2014; Di Maria et al., 2018). As with demolition energy, costs associated with this phase are considered less significant when compared to CC and CIU (Dantata, Touran, & Wang, 2005; Pun, Liu, & Langston, 2006). Therefore, this study disregards the costs of demolition and disposal.

Even though cost is identified as a barrier to sustainable material selection, enforcement of taxes and levies is recognised as a driver for sustainable material selection (Pomponi & Moncaster, 2016; Quesada-Pineda, Smith, & Berger, 2018; Wong, Ng, & Shahidi, 2013). Among different approaches of taxes, carbon pricing is proven to be an effective mechanism around the globe to push built environment towards sustainability.

3.6.2 Carbon tax as an initiative to sustainable material selection

GHG emissions are considered one of the most crucial environmental implications of the built environment (Brown, Olsson, & Malmqvist, 2014; Röck et al., 2020). In addition to the GHG emissions from building operations, embodied GHG emissions generated from materials used in construction and refurbishments of a building are also significant (Noller, 2005; Stephan & Athanassiadis, 2017; Teh et al., 2019). Governments have adopted different approaches to mitigate the operational and embodied GHG emissions associated with building construction and use to achieve sustainability goals (Akan, Dhavale, & Sarkis, 2017; Braslavsky et al., 2015; Kim & Chae, 2016; Kleijer et al., 2017). Carbon pricing is one such promising approach currently used across the globe.

Carbon pricing is an emerging tool to reduce the adverse environmental implications of the construction industry (Andersson, 2019; Metcalf, 2018; Shi, Ren, Cai, & Gao, 2019). The carbon pricing mechanisms are evolving with 46 national and 28 subnational jurisdictions putting prices on carbon as of 2019 (Carbon Pricing Leadership Coalition & International Finance Corporation, 2019).

Six types of carbon pricing mechanisms have been identified, namely,

- Internal carbon pricing
- Emissions reduction credit schemes

- Emissions trading systems
- Hybrid schemes
- Carbon taxes, and
- Command and control mechanisms.

The carbon tax mechanism is widely used within construction industries around the globe in order to encourage lower embodied energy building material selection (Andersson, 2019; Carbon Pricing Leadership Coalition & International Finance Corporation, 2019; Laes et al., 2018; Murray & Rivers, 2015; Shi et al., 2019).

The carbon tax mechanism is a price-based approach, where GHG emissions are given a fixed price (Sathre & Gustavsson, 2007). Application of carbon tax to the construction process and building materials can result in immediate impacts, due to increased costs (Avi-Yonah & Uhlmann, 2009). A behavioural change by the developers and contractors can be expected due to increasing construction costs, creating a shift towards lower embodied energy materials as substitutes (Comstock & Boedecker, 2011; Mann, 2007; Wong, Ng, et al., 2013). Therefore, the carbon tax mechanism has been identified as a good way to encourage developers to increase the use of lower embodied energy building materials and assemblies (Comstock & Boedecker, 2011; Sathre & Gustavsson, 2007). The cost of embodied GHG emissions of a building over the life cycle can therefore be used as a good indicator of the environmental sustainability of a building (Röck et al., 2020; Stephan & Athanassiadis, 2017; Teh et al., 2019).

The quantification of total carbon tax of the materials used in a building requires the quantity of the embodied GHG associated with the project. Several approaches can be adopted to estimate the total embodied GHG emissions related to building materials. One is to use a direct transformation of embodied energy values to embodied GHGE values by applying a conversion factor (Dias & Pooliyadda, 2004). For Australia, the conversion factor for life cycle embodied GHG emission can be considered as 58.78 kg CO_2e/GJ (Langston, Chan, & Yung, 2018). The second approach is to use carbon emission coefficients of building materials. Carbon emission coefficients are presented in kgCO_2e/kg of building materials (Dias & Pooliyadda, 2004; Hammond & Jones, 2008). While this approach is more reliable and accurate since the emissions are accounted for each material and assembly separately based on the quantities of materials used (RICS, 2004), it is more resource and data intensive (Stephan & Athanassiadis, 2017). Carbon coefficients need to be developed for each building material. Therefore, where the LCEE values are available for a building, it is appropriate to use the conversion factor method to obtain a comparative value of the embodied GHG emissions (Aye et al., 2012; Changbo et al., 2012; Lu et al., 2017).

In Australia, the carbon tax mechanism was implemented for two years, from 2012 to 2014 (Burke, 2016). During the time of enforcement, emissions from the construction industry showed significant reductions (Department of Agriculture

Water and the Environment, 2019). However, since the retraction of the carbon tax policy, emissions increased to a level higher than that experienced before the policy. This indicates that regulative change can be quite powerful. However, Australia, as a signatory in the Paris Agreement, needs to push forward the sustainability agenda at an increased pace in order to achieve the goals it has set (Shi et al., 2019). Therefore, the reintroduction of the carbon tax may occur, but this decision needs to be evaluated to assess the implications before implementation (Wong, Holdsworth, Crameri, & Lindsay, 2019; Wong, Lindsay, Crameri, & Holdsworth, 2015; Wong, Owczarek, Murison, Kefalianos, & Spinozzi, 2014). Shopping centres in Australia as a significant building asset, play a vital role in emissions reductions (Braslavsky et al., 2015). Hence, it is important to also assess the implications of a carbon tax enforcement on LCMC for shopping centre development in Australia as it may simulate changes.

This section recognized the significance of cost as a factor affecting material selection decision making. The following section analyses how building material selection affects the embodied energy and material cost of a building project and identifies relationships between these three variables.

3.7 IMPACTS OF MATERIAL SELECTION ON EMBODIED ENERGY AND MATERIAL COST OF BUILDINGS

The previous sections discussed how materials and embodied energy are interrelated and the implications of cost on material selection decision making. By identifying embodied energy and cost as two key variables to assess both the environmental and financial performances of a building, this section offers a thorough analysis of the impact of material selection on embodied energy and building material cost. It reviews the types of building assets which have previously been examined, to identify the comprehensiveness of existing knowledge on shopping centres.

An analysis of current literature identified that the majority of LCEE assessment studies are conducted for residential buildings across different geographies. A study by Dixit (2017c) analysed the existing literature on LCEE assessment of residential buildings. The study covered 96 case studies across America, Europe, Oceania and Asia to investigate embodied energy parameters. Accordingly, it was established that for the dominant materials namely; bricks, wood, concrete and steel, the average LCEE per year, based on expected lives, were 0.144 GJ/m^2, 0.116 GJ/m^2, 0.153 GJ/m^2 and 0.310 GJ/m^2 respectively. The study interpreted the results of different studies in a common platform identifying their discrepancies in terms of embodied energy assessment and the system boundaries. The normalised results suggest that the use of wood (or timber) in residential construction tends to have lower LCEE value as well as lower variations, when compared to other materials.

It was observed that the existing knowledge on LCEE assessments are concentrated on residential and then commercial building assets. A study by Dixit, Culp, Lavy, and Fernández-Solís (2014) compared the case studies with commercial buildings of different construction. The results revealed that brick, concrete, steel and wood account for average LCEE of 0.179 GJ/m^2, 0.217 GJ/m^2, 0.203 GJ/m^2 and 0.092 GJ/m^2 respectively. Accordingly, yet again wood-based construction was proven to have the least impact in terms of embodied energy over the life cycle.

Recycling potential of building materials, which is an indicator of possible embodied energy savings of a building at the end of its life cycle, has also been intensely studied in residential and commercial buildings (Dodoo, Gustavsson, & Sathre, 2014; Thormark, 2006). A study conducted by Thormark (2002) on an energy-efficient apartment building in Sweden found that recycling potential was 35% to 40% of the energy demand of the building, which is recoverable energy. Furthermore, Colling et al. (2016) studied the recycling potential of building materials in Brazil and found that the most substantial energy savings are achievable through plastic and aluminium recycling. Carlisle and Friedlander (2016) investigated the importance of recycling on different types of window frame assemblies and found that recycling potential is significant for materials like metals, plastic and wood products. Blengini (2009) conducted a life cycle assessment of a residential building in Italy, which was demolished in 2004, paying more attention towards the end of life and recycling scenarios. Results demonstrated that the recycling potential was 29% of the life cycle energy of the building. Whilst Thormark (2001) suggested that the '*design for dismantling'* concept needs to be applied more in the industry, Blengini (2009) provided empirical evidence to support this assertion.

Although many studies have assessed embodied energy, most of them have focused on residential and commercial sector office buildings. A significantly lower number of studies have assessed the embodied energy relating to retail building assets and these are noted in Table 3.3.

Table 3.3: Existing studies on embodied energy assessment of retail building assets

Reference	**Building type**	**Embodied energy**	
		Initial	**Recurrent**
Fridley et al. (2008)	Shopping centre	Y	
Fieldson and Rai (2009)	Retail fit-out	Y	
Van Ooteghem and Xu (2012)	Retail	Y	Y

Only three studies, one in Canada, one in the United Kingdom, and another one in China could be found which considered embodied energy in the retail area. This demonstrates the knowledge gap in LCEE assessment of shopping centres for material selection decision making, which from a sustainability perspective needs to be addressed urgently.

Fridley et al. (2008) found that the IEE of a shopping centre in China was 10 GJ/m^2 floor area, which was the highest value of all the commercial buildings investigated. The study by Fieldson and Rai (2009) investigated the GHG emissions of a department store fit-out in the United Kingdom. The results suggested that the use of timber-based products and materials that are more in natural form can result in substantial amounts of embodied GHG emissions over the life cycle. However, Van Ooteghem and Xu (2012) found that the development of a retail building structure in Canada using pre-engineered steel building structure, led to significant embodied energy savings. The difference in roof systems were cited as the main reason for the variance, where the typical scenario of a 4-ply built-up asphalt roof system was used but in the pre-engineered steel building scenario a commercial standing seam steel roof was used. Observations from those two studies indicate that the retail building structures become more embodied energy efficient with the use of pre-engineered steel systems and the 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, including all shops and common areas.

Research has identified cost as a major factor affecting both the selection of materials as well as a barrier for sustainable material selection (Akadiri, 2015; Williams & Dair, 2007). Therefore, it is crucial to evaluate the impacts of sustainable lower embodied energy material selection on LCMC of buildings as well. A study by Tam et al. (2017) on the impact of timber applications on LCMC of residential buildings proposed the most suitable timber applications for different weather conditions with minimum costs. Aye et al. (2000); Cabeza, Rincón, Vilariño, Pérez, and Castell (2014); Carter and Keeler (2008); Gluch and Baumann (2004); Ing Liang, Perera, and Eames (2010); Kneifel (2010); Rahman et al. (2008) have also conducted studies on the impact of different building materials and assemblies selection on LCMC of buildings from the perspectives of materials and the buildings. These studies have compared different building materials and assemblies to identify the most effective scenarios leading to environmental implication reductions as well.

The current studies on the cost implications of sustainable material selection are also majorly dedicated to residential and other commercial property assets creating a knowledge gap for retail shopping centres. Creating a trade-off between material cost and embodied energy saving in relation to sustainable material selection is essential to achieve more realistic and consistent results. Therefore, the knowledge of the relationship between embodied energy and material cost of buildings is crucial to implement sustainable material selection approaches in the built environment properly.

3.7.1 Relationship between embodied energy and material cost of buildings

Several researchers have investigated the relationship between embodied energy and cost of buildings. Lavine and Butler (1982), as cited by Langston and Langston

(2012) argue that the embodied energy is a good reflector of environmental pricing, which can be assisted in environmental policy making.

Langston and Langston (2008) analysed 30 case studies (residential and commercial) in Melbourne to improve the understanding of the relationship between the IEE and CC. The analysis was carried out at various levels of project as elemental groups, elements and work items, and the relationship between two variables is computed. The results obtained through linear regression analysis identified that IEE and CC at the project level shows a strong linear relationship but, the correlation by elements is weak, and the results are scattered. Therefore, Langston and Langston (2008) suggest that the optimisation of embodied energy and cost are not mutually exclusive goals.

A similar study carried out by Jiao, Lloyd, and Wakes (2012) investigated the correlation between embodied energy and cost of commercial buildings. It also considered the embodied energy and cost of labour component, improving the comprehensiveness of the study, yet limited only to initial inputs. Findings of the study revealed that the embodied energy and cost of buildings have a strong positive relationship supporting the findings by Langston and Langston (2008). However, this can be explained with the quantity of building materials used for the construction, which affects both IEE and CC.

Bansal et al. (2014) studied the impact of building materials on embodied energy and cost of residential houses in India. The findings identified that there is no linear relationship between embodied energy and cost per functional unit (per unit floor area) of the case study buildings. This result is contrary to the findings by Langston and Langston (2008) and Jiao et al. (2012). However, the findings of the study by Bansal et al. (2014) suffers from several limitations, such as the assessment of a limited number of building materials categorised by weight proportions about overall construction and lack of reliability of embodied energy data as only a proportion of embodied energy is considered.

A research carried out by Copiello (2016) investigated the relationship between embodied energy and the cost of building materials. The study incorporated two sets of data; energy inventory of building materials published by Hammond and Jones (2008) and building material prices obtained from bills of quantities (BOQ)[5]. Three models were used to examine the relationship as a linear function, logarithmic transformation of the independent variable, and logarithmic transformations of both independent and dependent variables. Independent variable is the unit price of building materials in Euros/kg, and the dependent variable is the EEC in MJ/kg. The study was carried out for different groups of building materials and the results demonstrated a strong relationship between unit prices and EEC but energy to cost ratio varies in value for different types of

[5] The document "which models the structure (or pattern) of the Contractor's costs for his/her obligations for the work which he/she has to do for the Client, its purpose being to enable the financial control of the work to be satisfactorily done" (Singh & Banjoko, 1990, p. 32)

building materials. The relationship is found positive for groups of semi-finished or finished building materials except for raw building materials. Limitations of the study are the limited sample size in groups, degree of uncertainty of obtained energy inventory, and building material prices data which could have hindered the results.

Stephan and Stephan (2016) investigated the life cycle energy and cost of 22 different energy reduction measures in the means of embodied energy, operational energy and user-transport requirement. A case study of an apartment building in Lebanon was evaluated considering a life span of 50 years. Embodied energy analysis is based on the input-output hybrid analysis technique, and LCMC was calculated using the net present value approach. Results demonstrated that the use of conventional building materials might not deliver a significant reduction in LCEE and radical changes to the selection of building materials are required to reach up to a noticeable embodied energy reduction which are typically higher in cost. A study by Dixit (2017b) further identified a strong positive correlation between embodied energy and the cost of building materials.

A profound understanding of the relationship between embodied energy and the cost of building materials and their implications over a building life cycle is essential to make necessary changes in the dynamics of the built environment. The current movement in eco-friendly and zero-energy building construction can be amplified if the material selection decision focuses on the embodied energy alongside other factors. The common perception of '*sustainability costs more*' is proven irrational based on the current research findings, identifying a strong positive correlation between embodied energy and building material costs. However, many studies have accounted for only the IEE and CC in determining the relationship. The implications of material selection on LCEE and LCMC are analysed only in a limited number of researches focusing on a limited number of building assets. Therefore, the existing research demonstrates a paucity of knowledge on the assessment LCEE and LCMC of shopping centres as a building asset, for material selection.

3.8 SUMMARY

This chapter provided an introduction and definitions of building materials, embodied energy and cost. Importance of building materials as a natural resource was explained, identifying the necessity to conserve. Life cycle stages of building materials were described thoroughly, providing the details of associated environmental impacts. Concept of embodied energy was defined. Possible approaches for life cycle inventory analysis were compared, and their potential to assess the embodied energy of building materials was delivered. Input-output based hybrid analysis was found as the most reliable method and the EEC compiled using this method by Treloar and Crawford (2010) are used in this research. LCEE in buildings was defined and the contributors (IEE, REE and demolition energy) were explained in detail. Significance of the LCEE over operational energy in energy-efficient buildings was demonstrated. LCMC of building materials was defined. Previous studies on LCEE of buildings were reviewed identifying the significance of embodied energy in both conventional and non-conventional (passive houses, zero-energy buildings) buildings. The current literature on the impact of building material selection on LCEE and LCMC of different buildings were reviewed, recognising a paucity of research in retail building assets. Finally, the relationship between LCEE and LCMC of building materials was discussed. Literature analysis revealed a knowledge gap on investigation of the impact of building material selection on embodied energy and cost of buildings in life cycle perspective. Lack of focus on REE and CIU of building materials in establishing the correlation between embodied energy and cost was also identified.

3.9 RESEARCH GAPS

A thorough analysis of the existing literature and industry reports on shopping centres in Chapter 2 ascertain the growth of the built asset in Australia (JLL, 2019; PCA, 2019). Continuous building material replacements in shopping centres due to shorter refurbishment frequencies (Fieldson & Rai, 2009; Holtzhausen, 2007; Sarja, 2005) and periodic tenant turnover (The Parliament of Victoria, 2003) can potentially result in a substantial amount of REE during the use phase. Consequently, LCEE in shopping centres is recognised significant.

Analysis of current studies on embodied energy assessment of different building assets shows a major weighing towards residential and commercial office buildings (Dixit, 2017c). Only a few cases have assessed the embodied environmental impacts of retail buildings (Fieldson & Rai, 2009; Fridley et al., 2008; Van Ooteghem & Xu, 2012). Even in most remaining studies, only initial impacts of embodied energy and cost are assessed, neglecting the contributions during building use phase. Accordingly, current literature indicated a paucity of knowledge on LCEE assessment of Australian shopping centres identifying their significance as a building asset for emissions reductions.

Furthermore, the importance of building materials was established in Chapter 3, identifying the relationship between materials, embodied energy and cost (Dixit, 2017b). Majority of prevailing research indicated a strong positive relationship between embodied energy and cost of materials at building level, which seems to deteriorate at individual material or assembly level (Bansal et al., 2014; Copiello, 2016; Jiao et al., 2012; Langston & Langston, 2012). Consequently, the selection of environmentally responsive materials is recognised as the key to embodied energy reduction of a building asset, while cost of materials is identified as a barrier for the selection (Akadiri, 2015; Gosselin et al., 2017; Patel & Chugan, 2017; Quesada-Pineda et al., 2018).

Therefore, this research aims to address these research gaps, by conducting LCEE and LCMC assessment of Australian shopping centres for material selection decision making. Research method incorporated to achieve the aim is presented in detail in the following chapter. The findings of the research could assist decision-makers such as architects, designers, quantity surveyors and developer in the built environment in assessments for material selection. They could further assist environmental policy makers including the government and other authorities in assessments of future construction projects and developing effective regulations and policies as carbon tax to reduce emissions generation. The research aim is achieved by answering the following questions, as explained in the subsequent chapters.

"How can building material and assembly selection reduce life cycle embodied energy and material cost of shopping centres in Australia?"

1. *What building materials and assemblies reduce life cycle embodied energy the most, and at what financial cost?*
2. *What are the optimal combinations of building materials and assemblies that reduce both life cycle embodied energy and material cost of shopping centres?*
3. *What mechanism can be used to encourage behavioural changes in material selection decision-makers' in shopping centres to achieve embodied energy reductions in Australia?*
4. *What is the impact of refurbishments frequencies towards the selection of building materials and assemblies to reduce life cycle embodied energy and material cost of different types of shops in shopping centres?*

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4 RESEARCH METHOD

4.1 INTRODUCTION

Chapters 2 and 3 provided the rationale for the study alongside a critical analysis of the existing knowledge on relevant research areas. It established the importance of life cycle embodied energy (LCEE) and material cost (LCMC) of shopping centres as well as the necessity to identify building materials and assemblies with improved environmental and financial performances. The review of the prevailing academic and commercial tools for selecting environmentally sensitive building solutions demonstrated a gap for shopping centres, addressing their unique refurbishment frequencies. This gap demonstrated the need for development of a mathematical model to assess LCEE and LCMC and to identify building solutions for the shopping centres, that result in reduced embodied environmental effects at a reduced cost. Moreover, the significance of a carbon tax enforcement as a mechanism to induce behavioural changes among developers in material selection to adopt environmentally sensitive solutions in the construction industry was also recognised.

The principal objective of this chapter is to describe the research method used to seek answers for the questions raised within the research, stated in Section 3.9. Two main research methods were incorporated to address these questions, namely a case study method and mathematical modelling. Mathematical modelling represents a significant part of this research. This section describes the process of modelling, its scope, aim, and different stages. Furthermore, it outlines the selection of the most appropriate techniques to quantify embodied energy and material costs at different life cycle stages of a shopping centre. Data requirements for the model development process are also identified, indicating their sources along with the creation of the required databases. Case studies were used to acquire the necessary data, and this chapter discusses them along with justifications for their selection. The uncertainties of the research findings and approaches used to address any issues are also detailed.

4.2 RESEARCH STRUCTURE

The study followed the design steps presented in Figure 4.1 to address the research questions. As mentioned, the study incorporates mathematical modelling as the primary research method to quantify LCEE and LCMC of different building materials and assembly combinations for case study buildings.

The subsequent sections in this chapter discuss these steps in detail, starting with research methodology.

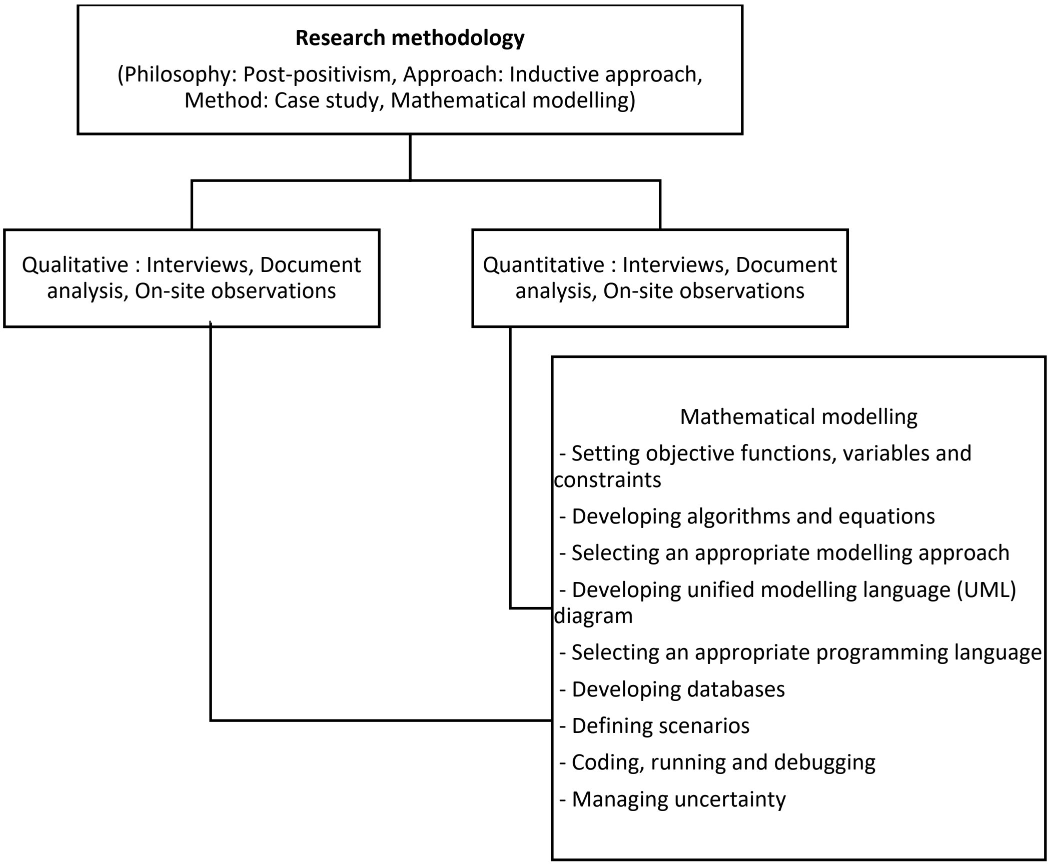


Figure 4.1: Structure of the research design used in the study

4.3 RESEARCH METHODOLOGY

This section provides the rationale for the selection of post-positivism research philosophy, inductive research approach, and mixed research method. As the methodological strategies utilised in the execution of a research study has a significant influence on reliability and significance of research findings (Creswell & Clark, 2007), selection of the most appropriate methods and techniques are critical. This selection depends solely on the nature of research questions and background of the study (Yin, 2014). The research questions in this study attempt to address the significance of material selection for shopping centres for achieving better environmental performances at optimal financial costs in Australia. The justification for selection of the research design is provided below.

Post-positivism recognises that all observations made of any phenomena are fallible, and all the theories are reversible (Groff, 2004). Therefore, post-positivism focuses on consistency in research on natural phenomena and attempts to achieve reality, even when it is impossible at times (Scotland, 2012). As post-positivism considers all observations and theories can be fallible, the importance of repetitive observations, differences and deviations from the real facts are significant (Ryan, 2006). In post-positivism, theories are constructed based on the observations made, and thus perceptions could differ depending on each point of view (Clark, 1998). Thus, objectivity is considered a characteristic that exists in an individual researcher rather than a common attribute in post-positivism. This research investigates the relationship between LCEE and LCMC of building materials in order to derive different outcomes and hence, the research can be considered to have a post-positivism approach.

The research uses an inductive research approach (Saunders, Lewis, & Thornhill, 2019) based on the research problems, aims, and objectives set forth at the beginning of the study. These research questions were used to search for patterns and to develop explanations for the identified patterns (Creswell & Creswell, 2017). Furthermore, the study uses a mixed research method with case studies to derive answers for research questions. This research method assists in defining the research process and is presented in the following sub-sections.

The case study method incorporates both qualitative and quantitative data collection in the research, hence a mixed-method approach is proposed (Yin, 2014). Qualitative data was collected through semi-structured interviews, document analysis and on-site observations. The interviews were carried out with professionals involved in shopping centre developments, management bodies and shopping centre managers themselves. Qualitative data of types of building materials and assemblies were directly fed as input to the model. Quantitative data was also collected through interview findings, document analysis, and observations. Both qualitative and quantitative data were input as quantitative data in mathematical modelling to obtain answers to the research questions. The next few headings explain these research steps further.

4.4 RESEARCH METHODS

The subsequent sections explain the research methods identified above in detail. The use of a mixed-method case studies was considered the most appropriate research method to collect data on different materials and assemblies that can be used to construct shopping centres in Australia and the refurbishment frequencies of different types of shops in shopping centres.

4.4.1 Case study research method

This research used case study method to answer the “how” research question stated in Section 3.9.

The case study research method provides the ability to study and analyse the building as a single integrated unit (Gagnon, 2010). This method is used when a holistic, in-depth analysis of a particular matter is required (Harrison, Birks, Franklin, & Mills, 2017). Yin (2009, p. 23) describes the case study research method as an “empirical inquiry that investigates a contemporary phenomenon within its real-life context.” The method is mostly applied in scenarios where the boundaries of the phenomenon and the reality are not well established and defined (Gagnon, 2010). This study examined 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 case study method in this study can be rationalised.

The case study research method has become popular among researchers over the past decade (Yin, 2014) and has several advantages. Typically, a case study data examination is within the scenario where the actions take place, and thus, the researcher gets the opportunity to observe the phenomenon within its context (Yin, 2009). The case study research method provides the ability to incorporate both qualitative and quantitative analyses of the data, which can balance the positive and negative attributes of both (Harrison et al., 2017).

Despite these advantages, the case study research method has drawbacks observed by researchers. Case studies typically rely on a limited number of cases and thus, only a small basis is created for generalising the findings. However, it has been argued that through a better selection of case studies using the most representative cases, the issues of generalisation can be reduced to a satisfactory level (Evans, Gruba, & Zobel, 2014). Despite these disadvantages, the case study research method continues to be used in research studies. Systematic approaches are adopted in the case study research in order to obtain valid (the relationship between the findings and the reality) and reliable (consistency in observations) evidence.

4.4.1.1 Selection of cases

The study used three cases for data collection and for the application of the object-oriented model. Multiple case design was selected based on the understanding of literal replications (similar results) of potential outcomes or theoretical replications (contrasting results) that can be predicted explicitly (Yin, 2014) of shopping centres in relation to the research question. In this study case studies were used for setting the business as usual (BAU) scenario of the Australian shopping centres in terms of material selection and to assess their LCEE and LCMC. They were further used for comparison purposes to investigate relationships between gross lettable area (GLA) and embodied energy, and between GLA and material cost. Subregional shopping centres were selected as they represent the largest share of shopping centre floor space in Australia.

According to the Property Council of Australia (2019), 5,246,278 m^2 of subregional shopping floor spaces are currently available in Australia representing 21% of the total shopping centre floor space followed by neighbourhood centres accounting for 19% of the total. The GLA of subregional shopping centres in New South Wales (NSW), Victoria (VIC) and Queensland (QLD) represent almost 75% of the total floor space in Australia. Population distribution statistics of Australia in 2019 published by the Australian Bureau of Statistics (2019) demonstrate that more than 75% of the population is in the same three states (Figure 4.2).

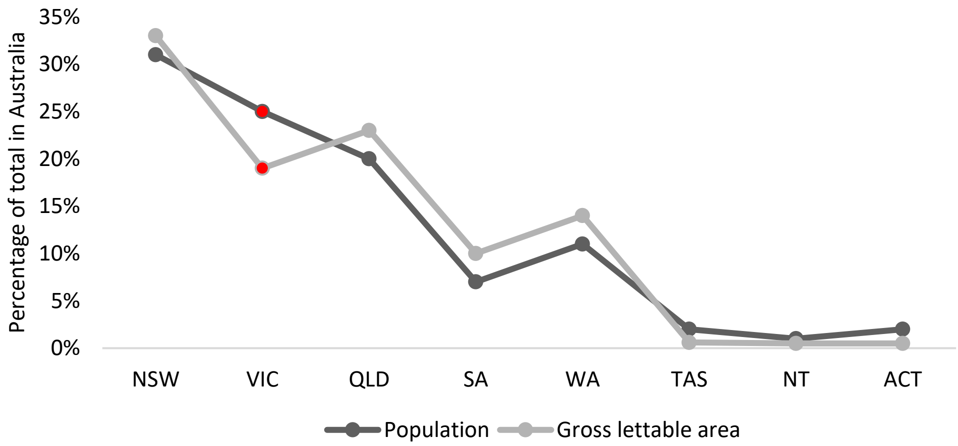


Figure 4.2: Subregional shopping centre gross lettable area retail vs population

Source: Australian Bureau of Statistics (2019)

The distribution of shopping centres is almost substantial to the demography of the states. The average population growth rate of VIC is stated at 1.81% since 2011, which is the highest in Australia, followed by QLD 1.55% and NSW 1.28% (Australian demographic statistics, 2018). According to Figure 4.2, as of 2019, subregional shopping centre GLA of both NSW and QLD are proportionate to their populations, whereas in VIC a significant gap is visible (marked in red). Hence more subregional shopping centre floor spaces are planned to be constructed to meet the population growth requirements and the demand (SCCA, 2018). Therefore, the study focused on VIC as the primary data collection demographic area, which is also where the researcher was based.

The selected case studies were single-storey shopping centres which have followed the typical construction methods in Australia. Statistics showed that the majority of subregional shopping centres (almost 80%) in Australia and in VIC as a state, are single-storey centres (PCA, 2019). The selection of case studies was, therefore limited to single-storey centres. However, the selection was subjected to modifications depending on the availability and accessibility of data, availability of interviewees and scarcity of resources. In such situations, the boundaries of the shopping centre population were widened to facilitate a broader collection of case studies.

Three case study subregional shopping centres were selected based on GLA, representing the smallest, average and the largest of the total. The average shopping centre was used to apply the BAU scenario of the Australian subregional shopping centres and assess relative embodied energy and material cost. The two case studies selected representing the average of the bottom 25% and top 25% of shopping centres by GLA were used to compare how embodied energy and material cost varies with different GLA. Cases were generalised based on the parameters of the number of speciality stores and anchor tenants, GLA, and several others, as described in Chapter 5. Furthermore, the composition of speciality shops in the centres needed to follow the Shopping Centre Council of

Australia's typical tenant mix. Therefore, the case study selection followed the benchmark values presented in Table 4.1.

Table 4.1: Benchmarks for case study selection for the study

Criteria	Case 1 (Average)	Case 2 (Small)	Case 3 (Large)
No of anchor tenants	3	2	4
Anchor tenants-Gross lettable area retail (m^2)	11,660	6,844	13,818
No of specialty stores	49	36	64
Specialty- Gross lettable area retail (m^2)	6,381	4,305	8,536
Total centre- Gross lettable area retail (m^2)	17,490	13,538	22,042
Total centre- Gross lettable area (m^2)	18,426	14,530	24,717
Speciality proportion	34.44%	25.80%	44.07%
Anchor proportion	63.00%	52.00%	73.00%
Cinemas	No	No	No
Centre type	Enclosed	Enclosed	Enclosed
Ventilation	Fully airconditioned	Fully airconditioned	Fully airconditioned
Enclosed car bays	No	No	No

The benchmarks for case study selection were defined based on the median (second quartile), first quartile and third quartile values of the parameters. They were quantified based on the values of all single-storey subregional shopping centres in Victoria published in the directory of shopping centres (PCA, 2017). The shopping centre with parameter values closer to median was selected as the average centre (Case 1). Most suited shopping centres with parameter values closest to the average of first quartile values and third quartile values were selected as the small centre (Case 2) and the large centre (Case 3), respectively.

Accordingly, the study selected the following three shopping centres as the case studies (refer to Table 4.2). Chapter 5 presents detailed descriptions of the cases. The selected cases were also used to obtain qualitative and quantitative data required for the mathematical model.

Table 4.2: Case study profile of the study

Case study identification	Shopping centre name	Gross lettable area
Case 1	Average shopping centre	21,000 m^2
Case 2	Small shopping centre	11,774 m^2
Case 3	Large shopping centre	30,735 m^2

4.5 DATA COLLECTION

Different data collection strategies are available for collecting qualitative and quantitative data. This research followed a mixed-method approach collecting qualitative data through semi-structured interviews, project document analysis and on-site observations, whereas quantitative data collection followed document analysis, on-site observations and desk studies.

4.5.1 Qualitative data

Qualitative data collected in this research include types of building materials, and assemblies used for shopping centre construction. Semi-structured interviews were carried out with professionals involved in Australian shopping centre construction, management and on-site centre managers to obtain qualitative data. On-site observations and project document analysis were also conducted. These data were used to provide an understanding of the building materials used in shopping centres over its life cycle. Semi-structured interview guidelines used are attached in Appendix 2. Table 4.3 presents a sample of qualitative data collected on different types of building assemblies used for shopping centre construction (for detailed lists of qualitative data, please refer to Appendix 3: *Materials* database and Appendix 4: *Assemblies* database).

Table 4.3: Qualitative data: A sample of building assembly solutions

Assembly type	Assembly name
Roof structure	Roof structure with Steel beams 530UB92, Purlins C30024, bracings and steel truss and Colourbond sheets
Roof structure	Roof structure with Glue Laminated Timber beams 535 mm x 85 mm Beam 21 and Colourbond sheets
Structural wall	150 mm thick precast panel SL92 central with 1N16 trimmer bar central each edge
Structural wall	Insulated precast sandwich wall panels 220 mm thick (70 mm exterior, 50 mm insulation, 100 mm interior)
Structural wall	Cross-laminated timber 205 mm thick (5-layer panel, self-weight 1.2 kPa)

4.5.2 Quantitative data

Quantitative data was at the core of the mathematical model development. Quantities of building materials and assemblies in the case study buildings, embodied energy coefficients (EEC), unit prices and wastage coefficients of building materials, typical refurbishment frequencies of shopping centres, periods of tenant leases, quantities of materials in different building assemblies and period of analysis of the buildings were the quantitative data collected through interviews, document analysis, observations on-site and desk studies. These data were then used to create databases in the mathematical model development process. Table 4.4 presents a sample of quantitative data collected (EEC and unit prices of different types of building materials used for building assembly construction mentioned in Section 4.7.2.2).

Table 4.4: Quantitative data: A sample of embodied energy coefficients and unit prices of building materials

Material type	Unit	Material embodied energy coefficient (GJ/unit)	Material unit price (AU$/unit)
Dampproof course (1 mm)	m^2	0.514	2.44
Polished exposed concrete 20 MPa (100 mm)	m^3	4.440	500.00
Hollow blocks (200 mm)	m^2	0.805	47.50
Mortar (10 mm)	m^3	2.000	748.00
Fibreglass (100 mm)	m^2	0.217	571.00
Steel rebar (Virgin)	t	85.460	1,700.00
Burnt clay bricks (110 mm)	m^2	0.560	32.86

The next step in the research process, data analysis, is presented in the following section.

4.6 DATA ANALYSIS

Both qualitative and quantitative data were provided as input to the mathematical model. Even though quantitative values were directly fed, qualitative data needed to be converted to quantitative format to be used in the model. The model was tested using the case studies and the results generated were then analysed.

Therefore, the semi-structured interviews conducted in the study were not analysed since the responses were not expressions of extensive opinions of certain matters but direct data points that could be used as input in the model. The refurbishment frequency values of shops in shopping centres extracted from the existing literature (Fieldson & Rai, 2009; Yudelson, 2009) were validated for Australia using interview findings and document analysis (The Parliament of Victoria, 2003). Five semi-structured interviews were carried out with centre management and four with developers till reaching data saturation point. The findings of the interviews validated the refurbishment frequency values of different shop categories in shopping centres as typically five years for specialty tenants and 15 to 20 years for anchor tenants. These values were directly used as input in the model to assess LCEE and LCMC of shopping centres in Australia. The next section provides details on the development and use of the model to identify building materials and assemblies minimising LCEE and LCMC.

4.7 MODEL DEVELOPMENT

A model is a simplified representation of a real-world system using mathematical concepts of variables, operators, functions, equations, and inequalities. Typically, the choice of a model depends on the form and accuracy of the expected solution and availability of data. Since the model developed in the study was predominantly based on the empirical data patterns, it is an ‘empirical’ or a ‘data model’. Aims of the model were to investigate the behaviour of the building materials and assemblies in shopping centre scenarios regards to LCEE and LCMC minimisation while considering all possibilities of material and assembly combinations for shopping centre construction, evaluating those alternatives and excluding impossible solutions based on the defined constraints. Verification of the results of the model was carried out through comparison of the model generated LCEE and LCMC values with manually calculated values of random ten scenarios. The relative error limit was set at ±10%, and the real values were manual calculations of LCEE and LCMC. The next few sub-sections present the details of the model.

4.7.1 Determining optimal solutions

This study focused on proposing combinations of materials and assemblies which minimises LCEE and LCMC, as stated before. In the study, LCEE and LCMC were the two objectives to be minimised. When the objectives were minimised separately, two sets of solutions of assembly combinations could be obtained. So, it became two single objective problems (either LCEE or LCMC at a time). However, when attempted to minimise both LCEE and LCMC at once, it became a multi-objective problem.

Here the optimisation (selection of materials and assemblies) is determined based on more than one criterion (LCEE and LCMC minimisation). In a multi-objective context, the optimal solution mainly involves determining the best compromise among the set of possible solutions satisfying specific criteria. The existing literature on the built environment includes a significant number of studies in resolving multi-objective problems (see Section 3.7).

Traditionally multi-objective problems are resolved by converting the objective functions into a single combinatorial objective function using various methods. However, these methods do not allow the trade-off between different objectives. They play a vital role in the optimisation and enforce defined and fixed trade-off values to the objectives. The solution must be compatible with other objectives, and therefore, it is not accurate to select a solution based on a single objective function. Finding multi-objective optimal solutions in the study follows two stages as finding the limits of the Pareto curve and finding the optimal solutions that correspond to the Pareto frontier.

The Pareto frontier development or the Pareto optimality is a well-known method to resolve multi-objective problems. The process is named after the economist Vilfredo Pareto who found the concept of “Pareto improvements” where solutions to an objective function do not hurt another objective function (Mattson, Mullur, & Messac, 2004). The Pareto optimal solution is defined as;

‘a one for which any improvement in one objective will result in the worsening of at least one other objective. That is, a trade-off will take place’ (Pareto, 1906) as cited in Messac and Mullur (2007, p. 123).

Mathematical interpretation can be presented as follows.

> A solution f^* of a vector of length n_f is taken as a Pareto optimal, if the design objective space does not contain any other solution f^s, such that;

$$f_i^* \geq f_i^s \text{ for all } i = 1 \ldots n_f, \text{ and } f_i^s > f_i^p \text{ for at least one } i.$$

This mathematical notation is defined as a minimisation problem where smaller values of the objectives are desired more. The trade-off solutions with optimal objective values are the key to solving a multi-objective problem. The number of Pareto optimal solutions depend on the objective functions and the design space. However, typically many solutions can be obtained as Pareto optimal solutions. The solutions can be identified through design variable values and design objective values. If design objective values are used in the process, a Pareto frontier can be generated. It is defined as;

'the set of all the Pareto optimal solutions represented in the design objective (f) space (Messac & Mullur, 2007, p. 125)'.

It is a useful tool which provides a graphical environment for making effective trade-off decisions in the design space. Typically, all the solutions in the Pareto frontier are considered reasonable since they represent different levels of minimisation regards to each design objective. Therefore, a Pareto frontier for bi-objective minimisation problem can be presented as in Figure 4.3.

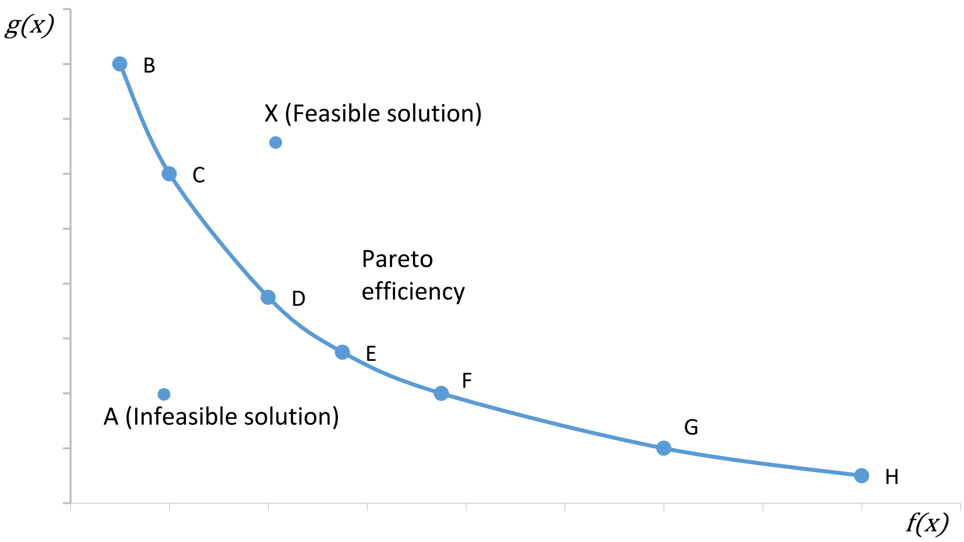


Figure 4.3: A Pareto frontier example

Source: Adapted from Deb and Gupta (2011, p. 1182)

The domination of the solutions in design space is defined as follows *(Miettinen, 2008)*.

> A solution in design space *s* is considered dominant over solution *t,* only if the following conditions are right;
>
> C1: In all objectives, the solution *s* is no worse than solution *t.*
>
> C2: Solution *s* is strictly better than solution *t* in at least one design objective.

In domination concept, any solution could not be dominated by itself and the relation is not reflexive; it is asymmetric and antisymmetric (Ali & Mahdi, 2013). However, the domination relation is transitive.

The selection of the most preferred solution from these non-dominated solutions or the Pareto solutions depends on the decision maker's preference of which design variable to be prioritised over the other and by what amount. Three different classes of methods have been identified in the existing literature to obtain the most preferred solution, considering the decision processes and the search are integrated (Kaliszewski, 2006; Miettinen, 1999) as the priori methods, the posteriori methods and interactive methods.

In the priori methods, decision-makers must pre-define his or her preferences, expectations, and options before developing the Pareto optimal solutions. This method can be presented as an aggregation of individual objective values into a single value. Posteriori method uses the Pareto optimal set generated without the decision maker's preferences and the most preferred among alternatives in the design space is selected as the best solution. The interactive method, as defined in the name itself, is interactive. Here, simultaneous processes of decision making and generating the Pareto optimal sets are carried out through all the stages of the procedure.

Several methods have been developed following posterior concept to find the most preferred Pareto optimal solution from a set. Weighted sum method (WSM) (Kim & De Weck, 2006), weighted metric method (WMM) (Ferreira, Fonseca, & Gaspar-Cunha, 2007) and weighted stress function method (WSFM) (Ferreira et al., 2007) are three such methods commonly used in research. This research used the WSM method to find the most preferred optimal solution based on the Pareto optimal set generated since it is a widely used simple approach to identify a single unique solution to resolve convex multi-objective optimisation problems, as the problem of minimising LCEE and LCMC. This method combines multiple objective values into a single objective value by multiplying each of them by a predefined weighting factor and summing up them to create an aggregated value. Different scenarios of the decision maker's preferences are evaluated to compare and analyse the optimal solutions. Even though WSM is considered subjective due to the decision maker's preferences in allocating weights, for this study the implication is limited since both objectives are prioritised equally assigning equal values (0.5 and 0.5).

However, the model attempted to reach optimal solutions through hierarchical calculations of LCEE and LCMC based on their values per unit of measurement as described in Section 4.7.7. Details on the modelling process are presented from here onwards.

4.7.2 Data requirements

The model developed in this study relies on the data required for calculation of embodied energy and material cost of different combinations of materials and assemblies. Figure 4.4 represents the dataflow of the study, indicating possible sources of data.

Quantification of embodied energy and material cost is the key function of the model and thus acquiring data on types of materials, EEC, quantities and cost figures became significant. The refurbishment frequency is also significant for calculating LCEE. Different types of data required, their sources and data collection techniques are demonstrated in Table 4.5.

Table 4.5: Data requirements and sources for calculation of the life cycle embodied energy and life cycle material cost

Data Requirement	Source
Material embodied energy coefficients	Material hybrid energy coefficients developed by Treloar and Crawford (2010)
Materials and techniques used in subregional shopping centre development	Semi-structured interviews, project documentation, on-site observations, material suppliers' details, industry publications, existing studies
Environmentally sustainable material specifications	Research studies, Australian construction material suppliers
Material quantities	Rawlinson's cost guide, existing studies, material supplier details, specifications
Material cost details	Rawlinson's cost guide, material supplier details
Refurbishment frequencies	Maintenance schedules of case study buildings, semi-structured interview with subregional shopping centre management, tenant leases, existing studies
Material service life data	Rauf (2015), existing studies
Shopping centre designs	Drawings and specifications, on-site observations
Embodied energy to embodied greenhouse gas conversion factor	Literature (Langston et al., 2018)
Carbon tax	Literature (proxy based on previous values published by (Department of Industry Science Energy and Resources, 2015))

The data requirements and sources briefed in Table 4.5 are explained in detail under next few subheadings.

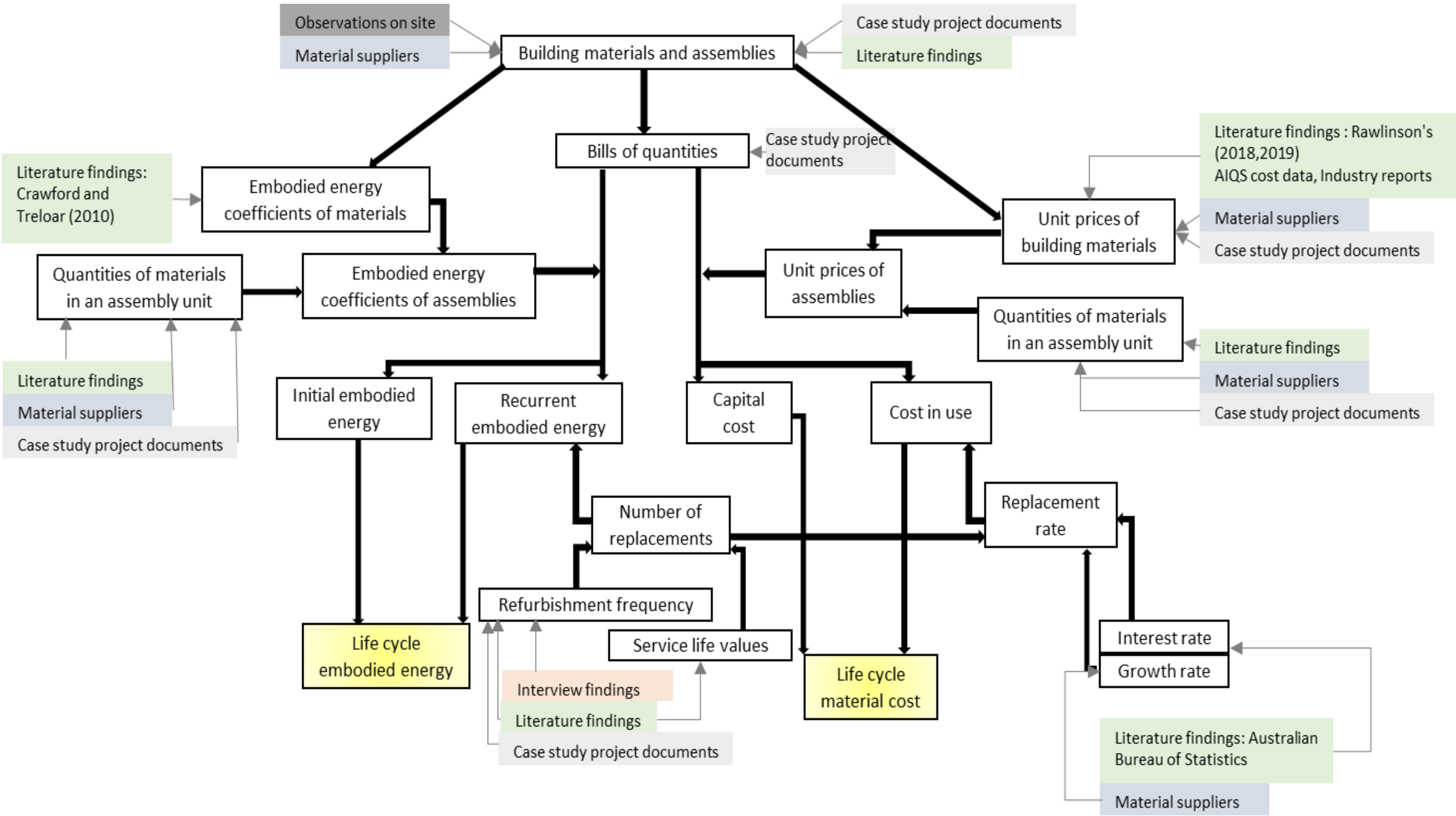


Figure 4.4: Dataflow diagram of the study

4.7.2.1 Material embodied energy coefficients

EEC can be calculated using three life cycle inventory analysis approaches as described in Section 3.5.1. The approaches include process analysis, input-output analysis, and hybrid analysis.

According to the studies of Crawford (2004, 2008); Crawford et al. (2018); Lu et al. (2017); Majeau-Bettez, Strømman, and Hertwich (2011); Muller and Schebek (2013); Suh et al. (2004), embodied energy intensities derived using input-output based hybrid analysis are identified as the most comprehensive values that can be obtained at a material level. Therefore, this study used material EEC developed by Treloar and Crawford (2010), based on an input-output based hybrid analysis, to quantify LCEE 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 database by Treloar and Crawford (2010) was considered the most suitable for this study since by the time the model was developed it was the most recent. It must be noted that a new dataset of EEC was published in November 2019 (Crawford et al., 2019), even though it is considered outside the scope of this research due to time constraints. Implications of this limitation is discussed further in Section 8.6.1. Table 4.6 represents a list of EEC compiled by Treloar and Crawford (2010). A detailed list is attached in Appendix 1.

Table 4.6: Input-output based hybrid embodied energy coefficients of a few common building materials

Material	Unit	Material energy coefficients (GJ/unit)
Aluminium (Virgin)	t	259.100
Brick	m^2	0.935
Carpet – Wool	m^2	0.575
Carpet – Nylon	m^2	1.063
Cement	t	14.540
Paint – Oil-based	m^2	0.070
Paint – Water-based	m^2	0.068
Plasterboard 13 mm	m^2	0.182
Tile – ceramic	m^2	0.236
Timber – hardwood	m^3	4.298
Timber – softwood	m^3	5.386

Source:Treloar and Crawford (2010)

The initial embodied energy (IEE) and recurrent embodied energy (REE) of materials and assemblies used in shopping centres were calculated based on these hybrid EEC to determine LCEE. Materials which did not have exact EEC were assigned with proxy figures based on a similar material (Stephan, 2013).

4.7.2.2 Types of materials and assemblies

Different types of materials and assemblies used for shopping centre development were the most critical type of data used in the mathematical model. The research outcome relies mainly on the details of materials and assemblies. These data were obtained from interview findings, on-site observations, and project documentation (bills of quantities (BOQ), material specifications and drawings) of shopping centres. These empirical data were used to establish the BAU scenario representing the current practice in Australia. They were further used to identify possible assembly combinations that were utilised in the model.

Moreover, local construction materials available in the Australian market were also observed and incorporated in the model. Local material specifications were obtained from material suppliers. Materials with improved environmental performances suggested in other research studies were also observed and entered in the database. Ultimately the purpose of all the methods was to create a detailed and complete database of different materials and assemblies available for shopping centre construction in Australia.

4.7.2.3 Material quantities and cost details

Material quantities were also based on BOQ and drawings of case study buildings. The shopping centres were considered parametric rectangular-shaped buildings to generate automated BOQ. Cost details of different types of materials and assemblies were obtained from actual project BOQ if available. When cost figures were unavailable in BOQ, the prices of materials were determined based on the market prices at the time of construction.

The quantities of materials and assemblies of the designs were delivered from automated BOQ developed in the model (Section 6.6). Material unit prices for BOQ were based on the market prices of material suppliers in 2018 and previous BOQ rates.

4.7.2.4 Refurbishment frequencies

Average refurbishment frequency of shops in shopping centres was taken as 2 to 10 years based on the literature findings. However, semi-structured interviews with shopping centre management were also used to assist in determining the refurbishment frequencies of Australian shopping centres to have a better understanding of the actual practice. Maintenance schedules from the case studies were also used to assist in determining the refurbishment frequencies of different building assemblies.

Building maintenance schedules are the documents which contain details on scheduled maintenance of building items. They provide information on the frequency of maintenance works to be carried out for different building items based on their service lives and functional requirements. The refurbishment frequencies of building elements were derived based on these documents and data collected through interviews. The retrofitting of speciality shops tends to occur frequently due to tenant replacements in shopping centres. Those tenant turnover data were collected from the records maintained by centre management on tenant profiles. Tenant replacements in shopping centres happen due to several reasons. The expiry of the tenant lease period is the common cause, which is five years for small tenants in subregional shopping centres in Victoria and 25 years for anchor tenants. However, replacements can happen even before the expiry of the lease period in various situations as if the tenant is not performing well financially in business and not capable of paying the rental rates. Therefore, special attention needed to be given to tenant replacements happening in shopping centres to identify the frequency of retrofitting the shops.

4.7.2.5 Material service life values

Service life data of building materials (as defined in Section 3.3) were also required to determine the LCEE and LCMC. When a building material reaches the end of its service life, it needs to be replaced and thus would cause REE. Therefore, service life data of the materials and assemblies used in subregional shopping centres needed to be gathered. However, in most situations, materials are replaced in shopping centres long before expiring their service lives due to economic, functional and/or social obsolescence. Nonetheless, identification of material service life values provides a better understanding of the material life cycle and a basis for selection. Material service life data were used from the study by Rauf (2015). Table 4.7 presents the service life data of a few primary building materials. Please refer Appendix 5 for an extended list.

Table 4.7: Material service life values

Material	Minimum service life	Average service life	Maximum service life
Wall			
Concrete	Lifetime	Lifetime	Lifetime
Bricks	Lifetime	Lifetime	Lifetime
Paint – Exterior	7	11	15
Interior			
Paint – Interior	5	10	15
Wall plasterboard (Gypsum)	20	35	70
Floor			
Carpet – Nylon	7	10	20
Tile ceramic	20	60	100
Timber floor	15	29	50

Source : Rauf (2015)

4.7.3 Assessment of the life cycle embodied energy

The LCEE is a combination of initial, recurrent and demolition energy of a building (Ramesh et al., 2010). However, in the modelling context, LCEE was considered as the combination of IEE and REE only, as presented in Equation 4.1. Figure 4.5 shows the flowchart to assess the LCEE of a shop in the shopping centre.

Equation 4.1: Life cycle embodied energy calculation

$$LCEE = IEE + REE$$

Where,

IEE= *Initial embodied energy, in GJ*

REE= *Recurrent embodied energy, in GJ*

For shopping centres, the equation was updated as follows.

Equation 4.2: Calculation of life cycle embodied energy of a shopping centre

$$LCEE_{sc} = \sum_{s} \sum_{a} IEE_{a,s,sc} + \sum_{s} \sum_{a} REE_{a,s,sc}$$

Where,

$LCEE_{sc}$ = *Life cycle embodied energy of the shopping centre sc, in GJ*

$IEE_{a,s,sc}$= *Initial embodied energy of assembly a, in shop s in the shopping centre sc, in GJ*

$REE_{a,s,sc}$= *Recurrent embodied energy of assembly a, in shop s in the shopping centre sc, in GJ*

4.7.3.1 Initial embodied energy calculation

The IEE of materials includes embodied energy inputs required for raw material extraction and transportation, material manufacturing, and transportation to the construction site. The IEE quantification requires quantities and EEC of materials. Material quantities were considered to include on-site wastage which represents 10% of the wastage created by the construction industry as a whole (Bekr, 2014; Berge et al., 2009; John & Itodo, 2013). Disregarding the wastage amount of materials can therefore result in incorrect embodied energy figures. The material wastage factors used in the study are attached in Appendix 6.

The material quantities derived after applying the wastage factors were then used to calculate IEE. For this study, the IEE was considered at individual shop levels of the shopping centres as conducting calculations for the whole building at once was complicated and could affect the reliability of the results (Figure 4.6).

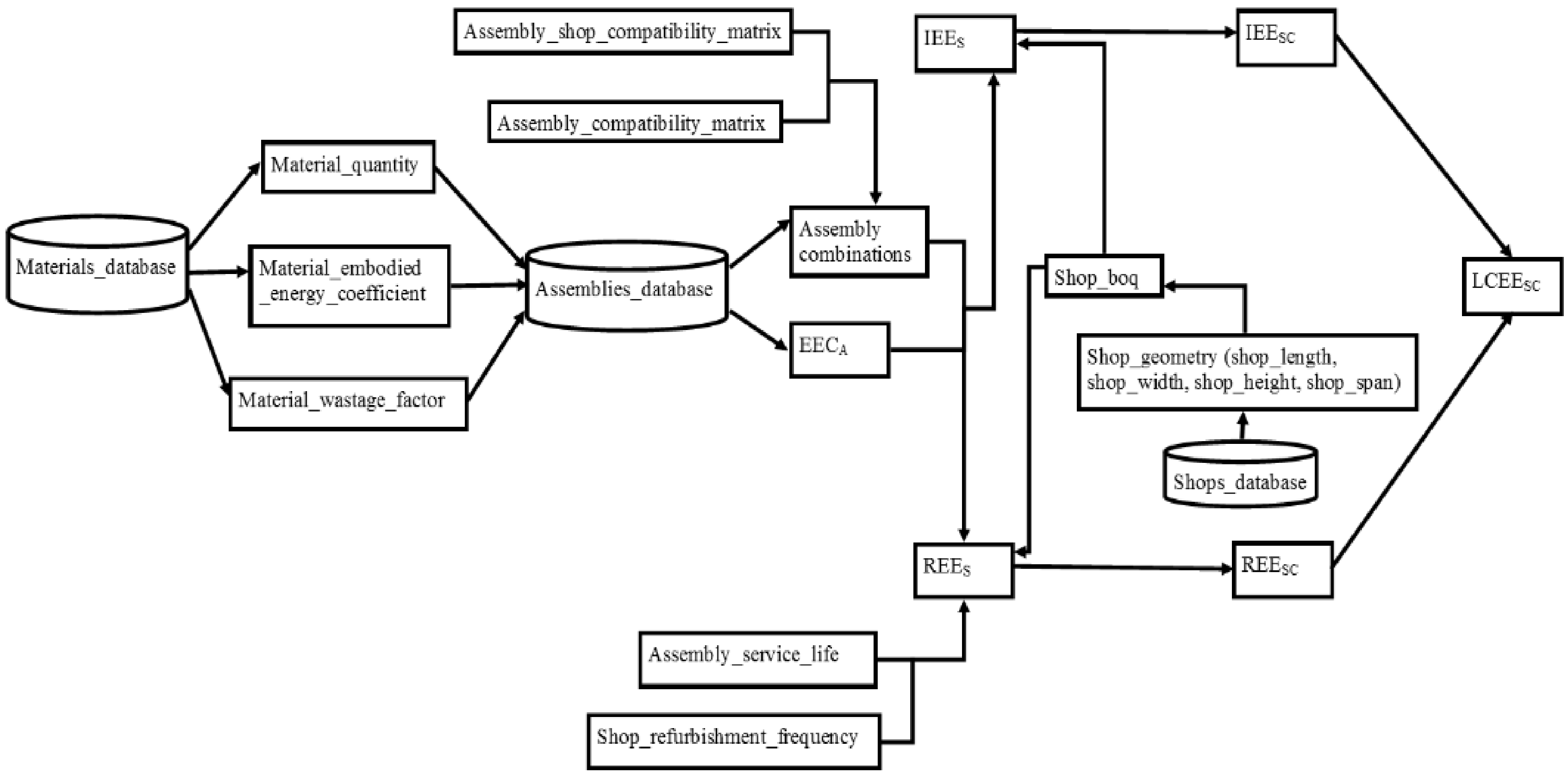


Figure 4.5: Life cycle embodied energy assessment flow chart

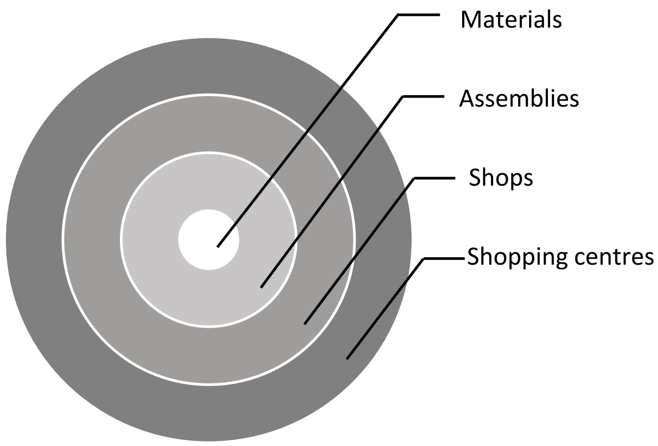


Figure 4.6: Levels of shopping centre breakdown

The IEE of all shops was summed to quantify IEE of the entire shopping centre. IEE of a shop was quantified by summing IEE of all assemblies in the shop. This similar process of calculation was used for REE quantification. Following equations denote IEE calculation at different levels.

Equation 4.3: Calculation of initial embodied energy of a shopping centre

$$IEE_{sc} = \sum_{s=1}^{S} IEE_{s,sc}$$

Where,

IEE_{sc}= *Initial embodied energy of the shopping centre sc, in GJ*

$IEE_{s,sc}$= *Initial embodied energy of shop s in the shopping centre sc, in GJ*

Equation 4.4: Calculation of initial embodied energy of a shop in a shopping centre

$$IEE_{s,sc} = \sum_{a=1}^{A} IEE_{a,s}$$

Where,

$IEE_{a,s}$= *Initial embodied energy of assembly a, in shop s, in GJ*

The IEE of assembly a, in a shop is calculated using the following equation.

Equation 4.5: Calculation of initial embodied energy of an assembly in a shop

$$IEE_{a,s} = \left(EEC_a \times Q_{a,s} \times WF_a\right)$$

Where,

EEC_a= *Embodied energy coefficient of assembly a, in shop s, in GJ/unit*

$Q_{a,s}$= *Quantity of assembly a, in shop s in units*

WF_a= *Wastage factor of assembly a*

Even though the IEE of the shopping centre can be calculated using the above equations, one boundary is remaining. The non-material energy inputs of the building at the construction stage, which are not easily quantifiable, are disregarded. These involve the inputs associated with the financial, communication, marketing and other service sectors, which are considered as further sideway inputs (Crawford, 2011). The total input-output based hybrid EEC of the assemblies are calculated using Equation 4.6.

Equation 4.6: Calculation of embodied energy coefficient of an assembly

$$EEC_a = \sum_{m=1}^{M} (EEC_m \times Q_{m,a}) + \left[TERBS - \sum_{m=1}^{M} (TER_m)\right] \times C_{m,a}$$

Where,

EEC_m= *Embodied energy coefficient of material m, in assembly a, in GJ/unit*

$Q_{m,a}$= *Quantity of material m in unit quantity of assembly a, in units*

$TERBS$= *Total energy requirement of the related building sector in GJ/currency unit*

TER_m= *Total energy requirement of the material related input-output pathways in GJ/currency unit*

$C_{m,a}$= *Cost of material m, in assembly a, in currency unit*

4.7.3.2 Recurrent embodied energy calculation

The REE is the energy involved in material maintenance, replacements, renovations, and refurbishments. Therefore, REE is highly dependent upon the refurbishment frequency of materials in the building. The service life of materials and service life of the building are considered as the factors affecting REE of a building. However, unlike in other buildings, shopping centres' refurbishment frequency is not only dependent upon the service life of materials. In shopping centres materials are replaced way before expiring their service lives due to social, functional and economic obsolescence (Holtzhausen, 2007; Sarja, 2005). REE of shopping centres was calculated using the following equation (Equation 4.7) (Stephan & Crawford, 2016) with the addition of non-material energy inputs.

Equation 4.7: Calculation of recurrent embodied energy of a shop

$$REE_s = \sum_{a=1}^{A} \left[RR_a \times [(EEC_a \times Q_{a,s} \times WF_a) + (TERBS - TER_a - NATER_a) \times C_{a,s}]\right]$$

Where,

REE_s= *Recurrent embodied energy of shop s in GJ*

RR_a= *Replacement rate of assembly a in shop s*

EEC_a= *Embodied energy coefficient of assembly a, in GJ/unit*

$Q_{a,s}$= *Quantity of assembly a in shop s, in units*

WF_a= *Wastage factor of assembly a*

$TERBS$= *Total energy requirement of the related building sector in GJ/currency unit*

TER_a= *Total energy requirement of the assembly a, related input-output pathways in GJ/ currency unit*

$NATER_a$= *Total energy requirement of all input-output pathways not associated with the installation or production process of assembly a being replaced in GJ/ currency unit*

$C_{a,s}$= *Cost of assembly a in shop s in currency unit*

Following equation 4.8 was used to quantify the replacement rate.

Equation 4.8: Calculation of replacement rate of an assembly in a shop

$$RR_a = \left\{\left\lceil \frac{POA_{a,s}}{SL_{a,s}} - 1 \right\rceil \Leftrightarrow \left\lceil \frac{POA_{a,s}}{SL_{a,s}} - 1 \right\rceil \leq RF_s \right\} \left\{ RF_s \Leftrightarrow \left\lceil \frac{POA_{a,s}}{SL_{a,s}} - 1 \right\rceil \geq RF_s \right\}$$

Where,

RR_a= *Replacement rate of an assembly a, in shop s*

$POA_{a,s}$= *Period of analysis of assembly a, in shop s in years*

$SL_{a,s}$ *Service life of assembly a, in shop s in years*

RF_s= *Refurbishment frequency of shop s in years*

However, the replacement rate can also be represented as the refurbishment frequency of the shops in the shopping centre. To determine which value to be considered for RR that vary depending on the type of assembly selected, the following process is used as demonstrated in Figure 4.7.

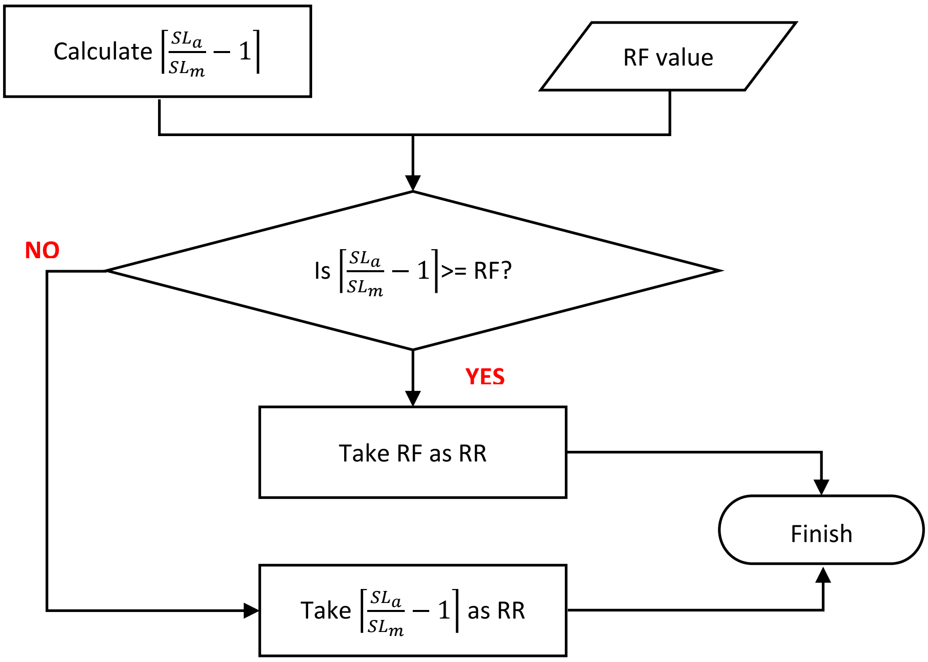


Figure 4.7: Determination of replacement rate value of a shop

4.7.4 Assessment of life cycle material cost of shopping centres

Estimation of LCMC of a building consists of the information of capital cost (CC), 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 (CIU) to account for the time value of money. Equation 4.9 presents the calculation of LCMC.

Equation 4.9: Calculation of life cycle material cost of a shopping centre

$$LCMC_{sc} = \sum_{s=1}^{S}\sum_{a=1}^{A} CC_{a,s,sc} + \sum_{s=1}^{S}\sum_{a=1}^{A} CIU_{a,s,sc}$$

Where,

$LCMC_{sc}$= *Life cycle material cost of shopping centre sc, in currency units*

$CC_{a,s,sc}$ = *Capital cost of assembly a, in shop s, in shopping centre sc, in currency units*

$CIU_{a,s,sc}$= *Cost in use of assembly a, in shop s, in shopping centre sc, in currency units*

4.7.4.1 Capital cost calculation

Capital material costs are the costs of materials consumed at the construction stage. CC of a shop was calculated using the following equation.

Equation 4.10: Calculation of capital cost of a shop in a shopping centre

$$CC_{s,sc} = \sum_{a=1}^{A} CC_{a,s}$$

Where,

$CC_{s,sc}$= *Capital cost of shop s, in shopping centre sc, in currency units*

$CC_{a,s}$= *Capital cost of assembly a, in shop s in currency units*

CC calculation of assembly a, in a shop s was calculated using the following.

Equation 4.11: Calculation of capital cost of an assembly in a shop

$$CC_{a,s} = (UP_a \times Q_{a,s} \times WF_a)$$

Where,

UP_a= *Unit price of assembly a, in currency units/unit*

$Q_{a,s}$= *Quantity of assembly a, in shop s in units*

WF_a= *Wastage factor of assembly a*

Unit price of assembly a was calculated using the Equation 4.12.

Equation 4.12: calculation of unit price of an assembly

$$UP_a = \sum_{m=1}^{M} Q_{m,a} \times UP_m$$

Where,

$Q_{m,a}$= *Quantity of material m, in assembly a, in units/unit*

UP_m= *Unit price of material m, in currency units/ unit*

4.7.4.2 Cost-in-use calculation

Recurrent material costs or CIU are related to building use phase. Hence CIU are expected future costs to incur throughout building life cycle. These future costs were therefore converted to present value for calculation purposes using present value (PV) approach. PV is an economic evolution analysis method which demonstrates the benefits or expenses by discounting the investments to present value (Vepa, 2013). This method is proven to be very useful when determining long-term profitability. The future cash flows over the time horizon were adjusted using a discount rate using the present value formula stated in Equation 4.13.

The discount rate for calculation was derived depending on time value of money and financial risks associated. In previous studies discount rate has been derived based on different aspects such as inflation, cost of capital, time value of money, and investment opportunities (Gluch & Baumann, 2004; Wong, Perera, & Eames, 2010). Therefore, discount rate for the study was determined based on the real interest rate of the Reserve Bank of Australia in 2019. Real interest rate was used to remove the effects of inflation as the equation accounts for real price escalation. PV 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. Therefore, CIU of the building were calculated using the following equation.

Equation 4.13: Calculation of cost-in-use of an assembly in a shop

$$CIU_{a,s} = UP_a \times Q_{a,s} \times WF_a \times \sum_{i=1}^{I} \left[\frac{(1+g)^{(i-1)}}{(1+r)^i} \right]$$

Where,

$CIU_{a,s}$=	*Costs in use of assembly a, in shop s in currency units*
UP_a=	*Unit price of assembly a, in currency units/unit*
$Q_{a,s}$=	*Quantity of assembly a, in shop s in units*
WF_a=	*Wastage factor of assembly a*
g=	*Real price escalation rate at 1.9%*
r=	*Real interest rate at 3.304%*
i=	*Replacement years (i.e. 5,10,15…,45, if replacement rate is 5)*

4.7.5 Assessment of life cycle embodied greenhouse gas emission of shopping centres

Other than the primary objectives of LCEE and LCMC quantifications, the model calculates life cycle embodied greenhouse gas emissions (LCEGHGE) of shops and the shopping centres to identify the emissions related to shopping centre construction in Australia. These LCEGHGE values were further used to determine the implications of a carbon tax scheme on behavioural changes of stakeholders involved in shopping centre construction projects and material selection decision making.

LCEGHGE was calculated based on an embodied energy to EGHGE conversion factor of 58.78 $kgCO_2e/GJ$ (Langston et al., 2018) and the LCEE values of shops and shopping centres. The algorithm used direct LCEE values for the quantification process, as presented in Equation 4.14.

Equation 4.14: Calculation of life cycle embodied greenhouse gas emission of a shopping centre

$$LCECE_{sc} = \sum_{s=1}^{S} (LCEE_{s,sc} \times f_{eghge})$$

Where,

$LCECE_{sc}$= *Life cycle embodied greenhouse gas emission of shopping centre sc, in tonne* CO_2e

$LCEE_{s,sc}$= *Life cycle embodied energy of shop s, in shopping centre sc, in GJ*

f_{eghge}= *Embodied energy to embodied greenhouse gas emission conversion factor at 58.78 tonne* CO_2e/GJ

4.7.6 Assessment of life cycle material cost with carbon tax of shopping centres

The implications of a carbon tax on the LCMC were quantified in the model using Equation 4.15. These values were used to analyse the dynamics in material combinations with minimum LCEE in LCMC with and without carbon tax scenarios.

For quantification purposes, the carbon tax in 2019 was taken as AU$ 32.36 per tonne CO_2e. This value was derived based on the past carbon tax trends of Australia (Department of Agriculture Water and the Environment, 2014). It was modified for 2020 to derive more reliable results. Since carbon tax is a fluctuating value, the future values were determined using a real price escalation rate (based on inflation rate of goods and services) and discounted to present value using Equation 4.15 as follows. The calculations assumed that the real price escalation rate for the carbon tax equals the inflation rate.

Equation 4.15: Calculation of life cycle material cost with carbon tax of a shopping centre

$$LCMCAT_{sc} = \sum_{s=1}^{S} LCMC_{s,sc} + \left\{ LCECE_{s,sc} \times \left[CT_{current} \times \left[\frac{\left[1 - \left[\frac{(1+g)}{(1+r)}\right]^{poa}\right]}{(r-g)} \right] \right] \right\}$$

Where,

$LCMCAT_{sc}$= *Life cycle material cost with carbon tax of shopping centre sc, in AU$*

$LCMC_{s,sc}$= *Life cycle material cost of shop s, in shopping centre sc, in AU$*

$LCECE_{s,sc}$= *Life cycle embodied greenhouse gas emission of shop s, in shopping centre sc, in tonne*CO_2*e*

$CT_{current}$= *Current carbon tax, at 32.36 AU$/tonne*$CO_2$*e*

g= *Real price escalation rate at 1.9%*

r= *Interest rate at 3.304%*

poa= *Period of analysis of shopping centre sc, in years*

4.7.7 Determining optimal solutions

The following flowchart (Figure 4.8) presents the process of developing optimal solutions.

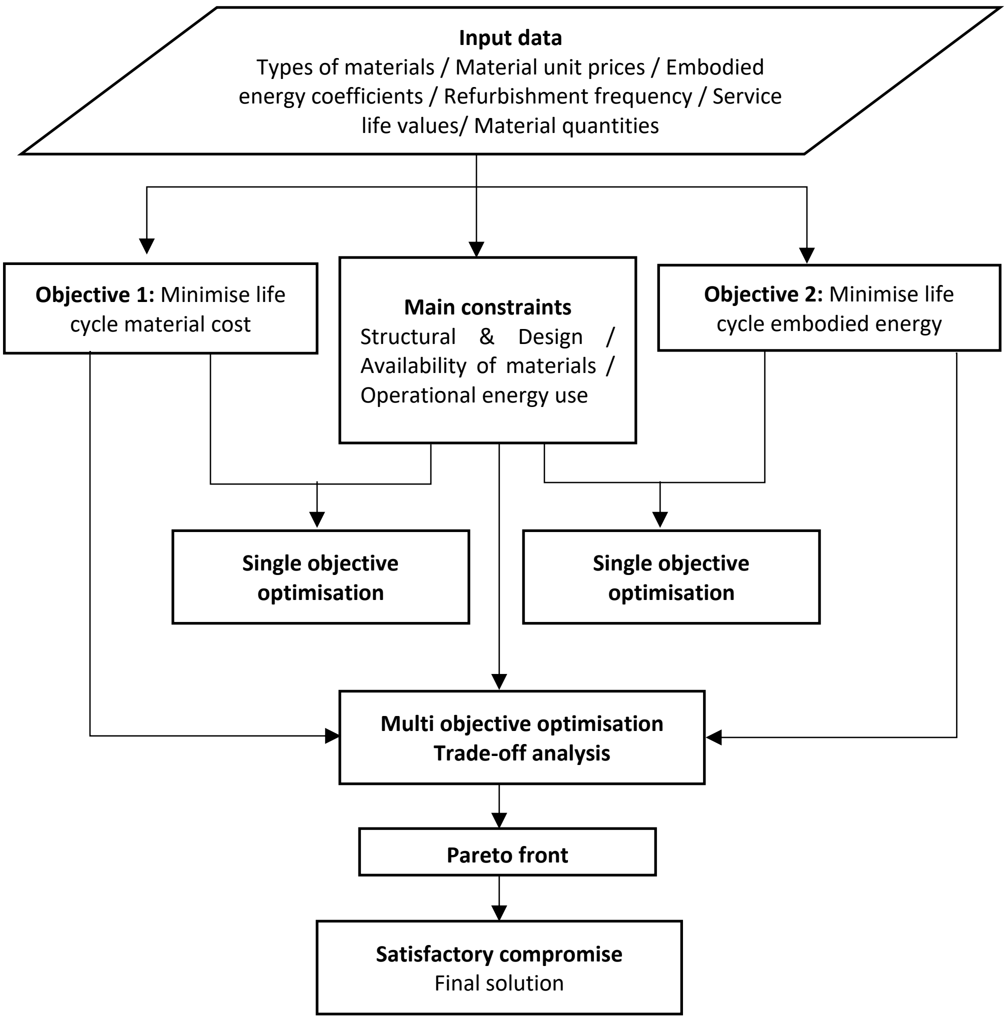


Figure 4.8: Optimal solutions flow chart

Input data: Types of assemblies, Material cost data, Embodied energy coefficients, Material service life data, Building service life data, Refurbishment frequency, Material wastage factor, Material quantities

4.7.7.1 Selection of objective functions

An optimisation model usually comprises three major components, namely the objective function, decision variables, and constraints (Cominetti, Facchinei, & Lasserre, 2012; Messac & Mullur, 2007; Nowatzki, 2014). The objective function is the goal of the problem, which needs to be optimised, and can also be identified as the fitness function (Sarker & Newton, 2008). The objective function can be expressed in numerical or non-numerical form. If the model is to achieve only a single objective, the measures of effectiveness can be expressed in a single value (Miettinen, 2008). However, if the case is a multiple objective problem, a matrix of values is required in determining the best solution. Therefore, this study incorporates multiple objectives with a matrix of values for resolving the research problem.

Decision variables are the unknowns of the model usually denoted by x, y, z or $x_1,x_2..x_n$. Constraints are the limitations to the model which consist of two components of a function and a constant correlated by an equal or unequal sign.

The objectives of the study were established depending on the research problems. The study focused on identifying combinations of materials and assemblies that optimise LCEE and LCMC of shopping centres in Australia. The objective functions, decision variables, and constraints of the study are presented as followings.

Objectives	: Minimising LCEE of shopping centres and minimising LCMC of shopping centres.
Decision variables	: Selection of materials and assemblies.
Exogeneous variables	: Refurbishment frequencies of shops.
	: Tenant lease periods.
Constraints	: Structural engineering and design constraints.
	: Assemblies compatibility constraints.
	: Availability of materials and technology changes.
	: Expected annual operational energy use.

The objectives were optimised in 3 phases:

Optimisation 1	: Minimising LCEE of shopping centres as a single objective minimisation.
Optimisation 2	: Minimising LCMC of shopping centres as a single objective minimisation.
Optimisation 3	: Minimising LCEE and LCMC of shopping centres as a multi-objective Pareto front based optimisation.

The objective functions, variables and constraints of the model were represented in mathematical notation as follows.

Optimal assembly combination of shop s,

$$A_s^* = \arg min_{A_s} \; e(A_s), c(A_s)$$

Where A_s is a candidate assembly combination of shop s. Embodied energy $e(A_s)$ and cost $c(A_s)$ are functions of A_s

Given, L is the list of assemblies;

$L = \{BM, CF, CL, DR, EW, FF, FD, IW, LT, RF, SL, WF, WD\}$ and

L_s is the approved list of assemblies compatible with the shop type of shop s.

$L_s = \{A_{e_1}, A_{e_2}, A_{e_3}, A_{e_4}, A_{e_5}, \dots \dots \dots \dots ., A_{e_m}\}$,

A_s can be defined as a collection of different assemblies (A_e):

$$A_s = \cup_{A_e \in L_s} A_e$$

$$\forall_{\substack{e,e` \in L \\ e \neq e`}} f(A_e, A_{e`}) = 1$$

$f(A_e, A_{e`}) = 1$ denotes the structural engineering constraint.

Each assembly $A_e$is a collection of different assemblies' quantities.

$$A_e = \cup_{B \in M} B$$

B is a given quantity from a given material from the material list.

$[M_1, M_2, M_3, M_4, \dots \dots \dots . M_m]$

$$e(A_s) = \sum_{A_e \in L_s} e(A_e)$$

$e(A_e)$ is the embodied energy of assembly A_e in the shop.

$$e(A_e) = q(A_e)\, ec(A_e)$$

$q(A_e)$ is the quantity of assembly and $ec(A_e)$ is the embodied energy coefficient of assembly A_e.

$$ec(A_e) = e_B(A_e)$$

$e_B(A_e)$ is a function of embodied energy coefficients of contributory materials of assembly A_e.

This mathematical notation provides a logical representation of the objectives mentioned above.

4.7.7.2 Selection of an appropriate programming language for model development

A programming language was required to represent the model so that the optimisation could be numerically solved. Several factors determine the selection of a suitable language. Researcher's level of expertise in the language becomes a priority in the selection process. However, as the researcher was a novice in coding, language needed to be selected considering ease of learning at a shorter period. Therefore, from the vast list of possible programming languages which could be used for optimisation MATLAB developed by MathWorks©(MathWorks, 2018) and Python^{TM} (Python Software Foundation, 2018) were shortlisted bearing all the factors in mind.

MATLAB is a widely used software for engineering applications which is not open source. It is also a commercial programming language. MATLAB has its advantages as well with a substantial number of functions, excellent products as Simulink, easier for beginners, and a broad scientific community. MATLAB refers to the whole system including the integrated development environment (IDE). However, MATLAB has several restrictions in using for this study. The libraries in the standard MATLAB do not include much generic programming functionality. For extra functionalities the provider has other toolkits to be purchased. More importantly, the algorithms in MATLAB are proprietary, so the code of most algorithms is not visible to the user. Restrictions on portability is also a problem with MATLAB. Therefore, for this study MATLAB seemed not to serve the purpose.

When compared, Python is free and opensource. It offers a vast array of libraries, classes and functions which are designed to deal with specific aspects of programming. Various free Python-based modules are utilised to generate databases, graphs and charts and develop matrices and other numerical operations. Object-oriented programming (OOP) in Python is recognised as an effective approach for resolving real-life problems. Therefore, this study used Python as the programming language.

4.7.7.3 Databases for the mathematical model

The optimisation process heavily relies on databases to analyse and compute LCEE and LCMC of different combinations of materials and assemblies of the case studies. For the study, five databases were created as *Materials*, *Assemblies*, *Shops_catalogue*, *Shops* and *Shopping_centres*.

Details on materials and assemblies were extracted from semi-structured interview findings, project documentation, and on-site observations. The study examined only three building layers of shearing layers of change proposed by Brand (1995) (Figure 4.9).

Shearing layers of change is a concept developed by Brand (1995) explaining the dynamic nature of the building structure and how it changes over time. It clearly describes that buildings are not just static objects but are dynamic. The layers are defined as follows (Brand, 1995).

- Site: The geographical setting of the building. This exists for generations.
- Structure: The foundation and load-bearing elements which are expensive to change. The life span varies from 30 to 300 years depending on other factors.
- Skin: Exterior surfaces of the building, such as structural walls. These are vulnerable to fashion and social changes. Changes occur every 20 years or so.
- Services: The major parts which make the building operate. Includes electrical, plumbing, drainage, HVAC, fire protection, communication and mechanical services. These services obsolete every seven to ten years mainly due to functional inefficiencies.
- Space plan: The interior layout of the building including walls, floors, ceilings and doors. Commercial buildings change the space plan every three years or so whereas residential would last a little longer.
- Stuff: Mainly the furniture used in the buildings and all other things which are used daily to monthly are defined stuff.

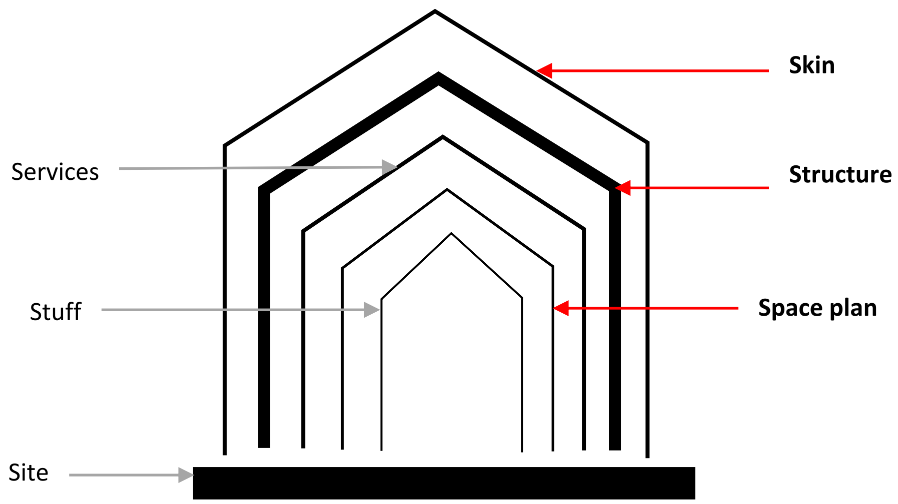


Figure 4.9: Representative figure of building layers considered in the study marked in red

Source: Brand (1995)

This study examined only structure, skin and space plan, as they are the most changing layers over time in shopping centres. Data on materials and assemblies used for the construction of those three layers were collected to develop the databases.

The database of materials played a vital role in determining LCEE and LCMC of different combinations of materials and assemblies. The database consists of 14 different fields. Some significant fields are presented in Table 4.8. For the detailed list of building materials database refer to Appendix 3.

Table 4.8: Selected fields of database

Field name	Data type	Description
material_name	string	Name of the material e.g. Concrete
material_type	string	Type of material e.g. 40 MPa
material_eec	float	Embodied energy coefficient of materials (GJ/Unit)
material_unit_price	float	Unit price of materials (AU$/unit)
material_lifespan	integer	Material service life (Years)

The database was developed using Microsoft Excel, as it is one of the most common and widely used software for creating databases in the world. Moreover, the researcher's competence and familiarity in performing tasks in Microsoft Excel for similar research-related activities came as a value addition.

The database stores details of all accessible material options for subregional shopping centre construction in Australia. Data were primarily based on industry-related case studies and specifications from material suppliers. EEC, waste factors, and service life data were extracted from existing research findings. When data became unreachable necessary actions were taken, and the fields were provided with proxy values based on materials with similar characteristics and properties.

4.7.7.4 Finding multi-objective optimal solutions

The mathematical model was run based on three objectives of minimising LCEE and minimising LCMC as two single objective optimisations and together as a multi-objective optimisation problem. Those objectives were modelled under four different scenarios.

Scenario 1: Combinations of materials and assemblies minimising LCEE at a given refurbishment frequency/ tenant replacement rate

Scenario 2: Combinations of materials and assemblies minimising LCMC at a given refurbishment frequency/ tenant replacement rate

Scenario 3: Combinations of materials and assemblies minimising life cycle material cost with carbon tax at a given refurbishment frequency/ tenant replacement rate

Scenario 4: Combinations of materials and assemblies minimising LCEE and LCMC at a given refurbishment frequencies/ tenant replacement rates

Based on these four scenarios, combinations of materials and assemblies were identified. Scenario 1 was run converting LCMC to a constraint and Scenario 2 converted LCEE to a constraint. The results deriving from different scenarios were then exported and graphed to identify the variations of the results under each scenario.

4.7.7.5 Assumptions and uncertainty

The study used input-output based hybrid EEC for quantifying the LCEE of the shopping centres. Although hybrid LCI analysis has been proposed as a method which provides a comprehensive analysis on the embodied energy of materials, it is vulnerable to erratic and systematic errors. The potential errors of the data used in the study were, therefore, considered to deliver a divination of the possible variations to occur in the results of the study. The error range of process data and input-output data were $\pm 20\%$ and $\pm 50\%$ respectively (Crawford, 2011). Therefore, an uncertainty analysis was carried out as proposed by Crawford (2011) and Stephan (2013) using the interval analysis approach. Interval analysis in simple terms is a method that delivers an interval of values with boundaries (upper and lower) for a variable instead of a single fixed value. The mathematical representation is; all possible values for $f(x)$ for all $x \in [a, b]$, where a and b are the lower and upper boundaries (Moore, 1966). This study used this method to analyse the uncertainty and variability of the results to better understand their effect on the results as discussed further in Section 8.6.7.

The material quantities required for the study were based on the detailed BOQ of the case studies as it was considered the most accurate document to estimate material quantities. In the model, the assembly quantities were generated through an automated BOQ which uses logical algorithms to quantify different assembly types in shopping centres. Nonetheless, these BOQ were also prone to errors due to omissions, discrepancies, unavailability of relevant documents, and conflicts of data in drawings, specifications and other sources of information (Davis, Love, & Baccarini, 2009). Also, variations occur during construction and the resulting additional materials were not included in the BOQ, whereas dayworks[6] were disregarded as well. Therefore, the resultant embodied energy figures derived through these BOQ can be deemed conservative.

The refurbishment frequencies and tenant replacement cycle data were the critical inputs in calculating REE. However, the data were subject to variations depending on limited literature available and the saturation of empirical data. Thus, REE values derived using these data were vulnerable to variations from the reality.

Choice of materials was a variable with limitations. Material variations available during the study were assumed to be consistent throughout the study, restricting any changes due to technological improvements. Moreover, the study depended on several assumptions based on the limitations in literature and empirical data collected. The assumptions were made considering preferable physical contexts to minimise the deviations.

4.7.7.6 Sensitivity analysis

The mathematical model used for resolving research questions used input data fed for variables of the objective functions and the constraints of the model. The optimal solutions obtained through the model were therefore based on input data provided for the variables. However, these input data were vulnerable to uncertainties, as mentioned in the previous section, as many of them were functions of uncontrollable parameters. Types of materials available, refurbishment frequencies, discount rate for LCMC, period of analysis, and any

[6] The method of valuing work on the basis of time spent by the contractor's workpeople, the materials used and the plant employed (RICS, 2012, p. 11)

other factors, which were subject to change in future and could not be predicted accurately at the time of analysis, were included as parameters. Therefore, the optimal solution determined based on the existing inputs were considered incomplete as the solution was subject to changes based on the variations in input data. However, to construct a comprehensive approach allowing for all possible contingencies, a detailed study needed to be carried out identifying how changes in input data affect the optimal solution. This approach is defined as a sensitivity analysis ((Ravindran, Phillips, & Solberg, 1987) as cited in (Wallace, 2000)).

Sensitivity analysis is defined as '*the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input*' ((Saltelli, Tarantola, Campolongo, & Ratto, 2004) as cited in (Saltelli et al., 2008, p. 1)). It is a statistical approach used in order to determine how changes of input data or independent variables influence the dependent variable under given conditions (Pamučar, Božanić, & Ranđelović, 2017; Pianosi et al., 2016). The validity of research and calculations is tested through sensitivity analysis. Sensitivity analysis can be conducted in different approaches including one-at-a-time, differential sensitivity analysis, and relative deviation method (Triantaphyllou & Sánchez, 1997; Wallace, 2000). This study incorporates relative deviation method based on the correlation between input and output values and mapping in a scatter plot. This method is considered useful for understanding the value trends and relationships and allows the opportunity to investigate the sensitivity of data parameters and monitor the level of variance in output. Therefore, it was considered more useful in determining the variations in objective functions of the model of optimal LCEE and optimal LCMC.

The study performed sensitivity analysis for several parameters based on their importance to the optimal solutions involving refurbishment frequency, types of materials, carbon tax, and any other factors deemed to be significant.

4.8 SUMMARY

Following the literature analysis in Chapters 2 and 3 regarding the significance of shopping centres as a building asset, and exploitation of building materials and assemblies in shopping centres which could potentially lead to increased embodied environmental effects, this chapter presented the research method used in the study to address research questions outlined in Section 3.9. This chapter discussed the positive and negative outcomes of using case studies as a research method along with mathematical modelling and found it as the most suitable method to assess the LCEE and LCMC of the typical construction (BAU scenario) of shopping centres and to identify assembly combinations with potentially lower effects.

Case study selection of three single-storey subregional shopping centres in Victoria was rationalised, followed by details in Chapter 5. Selection of mixed-method research strategy using semi-structured interviews, project document analysis, and on-site observations for qualitative and quantitative data collection was outlined. Data analysis techniques associated with the model development were described followed by detailed explanations in Chapter 6.

Data requirements for quantification of embodied energy and material cost of case studies were presented identifying their sources. The LCEE, LCMC and LCEGHGE calculations were described systematically, providing suitable algorithms and inputs. This chapter suggested making several assumptions and limitations in relation to the quantifications processes, which are further discussed in Section 8.6. Assessment process of the implications of a carbon tax scheme on material selection decisions of shopping centres in Australia was also discussed. Finally, the use of mathematical model to seek answers to research questions through objective functions of minimising LCEE and LCMC under several scenarios was established. Next chapter presents detailed descriptions of the three case studies used to apply the model.

5 CASE STUDIES PROFILES

5.1 INTRODUCTION

This chapter provides information on the case studies (average, small and large) selected for the study, as indicated in Section 4.4.1.1. Details on each case study shopping centre are presented, including floorplans, tenant mixes, shop layouts, gross lettable area (GLA), number of shops, and several other vital aspects. These were based on information ascertained through a series of interviews, observations and document analysis. This chapter begins with a discussion of details on the typical methods of construction of subregional shopping centres and types of building materials used in Victoria, Australia. The details of the three cases are provided, where the average case was selected for setting the base case and the small and large cases selected for comparison purposes as per Section 4.4.1.1. These cases represent the majority (more than 75%) of subregional shopping centres in Australia and are presented separately. The case study data were used as input in the mathematical model, which is outlined in the following chapter.

5.2 TYPICAL CONSTRUCTION METHODS AND BUILDING MATERIALS USED IN SUBREGIONAL SHOPPING CENTRES IN AUSTRALIA

Shopping centres in Australia are classified under Class 6 buildings which includes any ‘shop or other building for the sale of goods by retail or the supply of services direct to the public, including an eating room, café, restaurant, milk or soft-drink bar; or a dining room, bar area that is not an assembly building, shop or kiosk part of a hotel or motel; or a hairdresser’s or barber’s shop, public laundry, or undertaker’s establishment; or market or sale room, showroom, or service station’ (ABCB, 2019, p. 33). The National Construction Code specifies the deemed to satisfy provisions for structure, fire resistance, access and egress, service and equipment, and health and amenity for shopping centre construction.

Typical subregional shopping centres in Australia follow “Core and Shell” construction ‘where the developer's scope of works is the design and construction of the base building including mostly finishes and services are applied to common areas only’ (GBCA, 2020a, p. 5). Building shells are constructed to accommodate shops. The shell consists of the structural elements of the building, namely, foundation, columns, roof, and structural walls. This study collected data about the types of building materials and assemblies used in these shopping centres through nine semi-structured interviews (four with developers and five with management), document analysis of 11 projects (specifications, drawings and/or other contract documents accessed via interviewees and through online platforms[7]), and observations made on 21 single-storey subregional shopping centres (equivalent to 50%) across Victoria.

[7] EstimateOne (Ashcroft & Ritchie, 2020)

Selection of the sites for observations was primarily based on different climate conditions followed by ease of access (refer Appendix 17 for the map of locations of all on-site observations). NCC defines eight climate zones in Australia for thermal designs in buildings as outlined in Table 5.1. Climate zone map of Australia is exhibited in Figure 5.1.

Table 5.1: Climate zones in Australia

Climate zone	Description
1	High humidity summer, warm winter
2	Warm humid summer, mild winter
3	Hot dry summer, warm winter
4	Hot dry summer, cool winter
5	Warm temperate
6	Mild temperate
7	Cool temperate
8	Alpine

Source: Australian Building Codes Board (2015)

All locations across Victoria fall within three zones as identified in Table 5.2 (ABCB, 2015). Therefore, the selection of sites for observations represented all three climate zones in Victoria but the majority was from zone 6.

Table 5.2: Climate zones for thermal designs across Victoria

Climate zone	Location	Total number of locations
4	Echuca, Mildura, Shepperton, Swan Hill	4
6	Anglesea, Brainsdale, Benalla, Bendigo, Colac, Dandenong, Geelong, Horsham, Melbourne, Portland, Sale, Traralgon, Warrnambool, Wodonga	14
7	Ararat, Ballarat, Bright, Hamilton, Wangaratta	5

Source: Australian Building Codes Board (2015)

As described in Section 4.4.1.1, more than 75% of Australian subregional shopping centres by GLA are located in New South Wales, Victoria and Queensland. The largest share of subregional shopping centres across these three states are located in zone 6. The findings of this study can therefore be generalised to many subregional shopping centres in Australia.

Only four semi-structured interviews were carried out with shopping centre developers (Table 5.3) as respondents represented a portfolio of shopping centres and no further interviews were needed as data saturation was achieved.

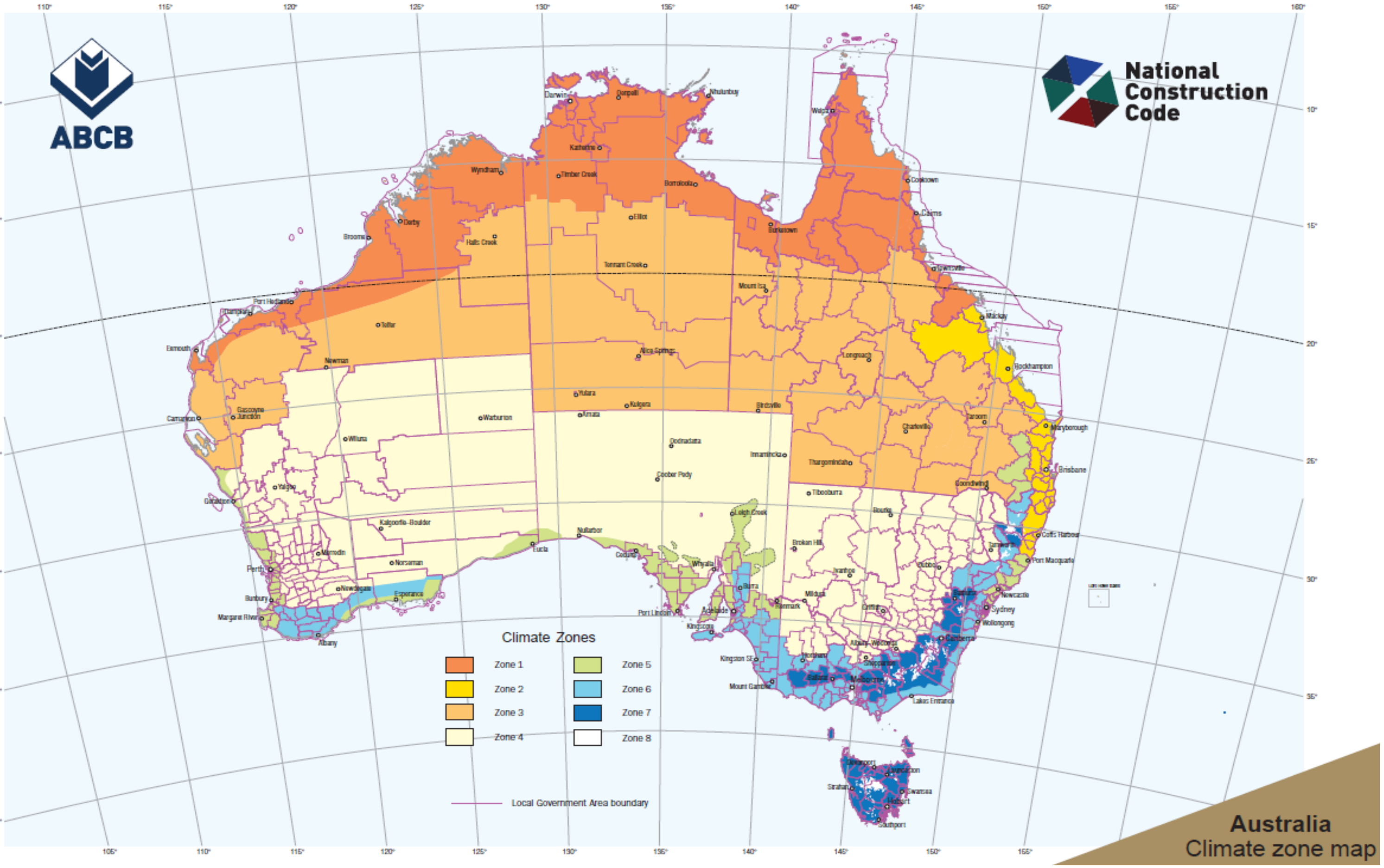


Figure 5.1: Australia climate zone map

Source: Australian Building Codes Board (2015)

Table 5.3: Profile of interviewees – Shopping centre developers

Interviewee ID	Developer	Number of subregional shopping centres developed in Australia
D01	Developer 1	16
D02	Developer 2	6
D03	Developer 3	1
D04	Developer 4	10

As anonymity of respondents was part of the ethics application the interviewees are identified as D01 to D04 while the developers are identified as Developer 1 to Developer 4. These companies are well known within the Australian property market and represent developers with a range of shopping centres within their portfolios. They can, therefore, be considered as representatives of the sector.

The Green Building Council of Australia (GBCA, 2017) identified concrete and steel as the two most used building materials in retail centre structures which was further supported by both the primary and secondary data. The majority of project documents revealed that steel and concrete dominate typical shell construction, and this was corroborated by all the interviewees in relation to their developments. More than 80% of project documents showed that they had concrete foundations using general purpose Portland cement, with vertical and horizontal steel framed structures (refer Appendix 18 for drawings and photographs). The rest of the cases used general purpose blended cement in the concrete mix. Similarly, a majority of single-storey subregional centres used steel framed structures due to their ease of construction and speedy erection. In some multi-storey projects' composite structures (steel and concrete) were used.

External load bearing walls have also been constructed using concrete where precast panels take the lead owing to their cost effectiveness and speedy construction. Roof structures of the shopping centres were typically structural steel, but in some cases concrete flat roofs, where they were also used as a car park space. More than 70% of centres used steel roof trusses.

The inter tenancy walls (walls that are common to adjoining tenants in a shopping centre (ABCB, 2019)) also form part of the shell or base building construction. These walls are the responsibility of the developer. Typically, all inter tenancy walls have performance requirements including fire resistance, acoustic and thermal insulation, security, and structural performance. In general, inter tenancy walls are not load bearing and have the flexibility to be removed to allow for future tenancy changes without affecting structural performances. Project documents and shopping centre tenancy fit-out guides established that these walls are mainly structural framed with unpainted and fire-rated plasterboard.

The shop fit-out designs including all internal walls, finishing works of floors, and all ceilings are carried out by the tenants according to their preferences. This was ascertained through interview responses of the subregional shopping centre management bodies in Victoria (Table 5.4).

Table 5.4: Profile of interviewees – Shopping centre management bodies

Interviewee ID	Management body	Number of subregional shopping centres managed in Australia
M01	Management 1	25
M02	Management 2	26
M03	Management 3	17
M04	Management 4	10
M05	Management 2	26

Again, as anonymity of respondents was part of the ethics application the interviewees are identified as M01 to M05 while the management bodies are identified as Management 1 to Management 4. Their companies are well known within Australia and would be considered as representative.

According to the five interviewees' responses, in most shopping centres, a tenancy fit-out guide is provided to the tenants when establishing the lease agreements. The tenancy fit-out guide states how tenants should carry out their fit-out constructions in accordance with the base building standards. In almost all subregional shopping centres these guides specify that tenants are responsible for internal walls, ceilings (finishes and framing), and all the finishes of walls and floors of the fit-out. However, the building material choices need to adhere to the base building standards, planning regulations and industry standards.

The building materials used in tenant fit-outs typically differ based on the type of shop, which is further explained in Chapter 6. Based on observations and project documents the most common wall finish type used among the majority of shops is paint, while floor finish type is carpet or ceramic tiles, with ceiling finish type plasterboard on a suspended metal grid. However, common areas in the centres usually have open ceilings, with a glass roof or a truss roof or in case of a concrete roof (when roof top is used as a carpark space), a plastered and painted soffit. The different types of building materials and assemblies that can be used to construct the shopping centres are presented as appendices, which were used to develop databases of materials and assemblies used in the model (refer to Appendix 3 and Appendix 4).

The interview findings with shopping centre developers (four) and management bodies (five), project document analysis (of 11 projects) and on-site observations (21 sites) were used to establish the BAU scenario of a single-storey subregional shopping centre identifying their typical construction methods, building materials and assemblies used.

A single-storey subregional shopping centre was then selected as the case study (an average centre based on median values of GLA, tenant mix and several other criteria) for applying the BAU scenario in the model (further elaborated in the following section) and to assess its effects on embodied energy and material cost. This case was further used to analyse embodied energy effects and material cost of other possible alternative material choices for shopping centres identified through prior research. Selecting a case study that represents the majority of the population of shopping centres provide the possibility to generalise the findings to both a state and national level. Interviews with developers mentioned 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 NCC. However, a majority of other building materials utilised in the shell and fit-outs were identified to be not that different from Victoria. Locations of these case studies are marked in the map below (Figure 5.2).

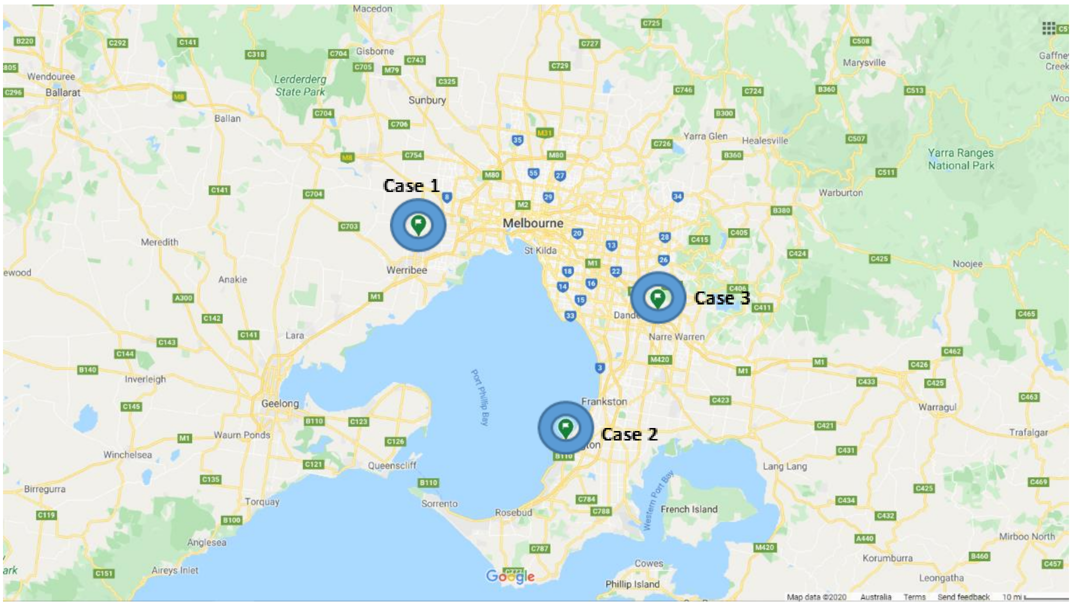


Figure 5.2: Locations map of the selected three cases

Source: (Google, 2020a)

Two more case studies were then identified for comparison purposes representing the average of the lower 25% and upper 25% of GLA distribution. These are referred to, for simplicity, as small and large centres. The embodied energy effects and material cost of the BAU scenario and alternative material choices would vary with the different GLA of the other two case study shopping centres. This comparison using case studies allow the findings to be generalised to most subregional shopping centres (representing 75% of the total), rather than limiting the results to the average case. The following sections provide further details of the three case studies.

5.3 CASE 1

Case 1 is the representative of the average subregional shopping centres in Australia as per the selection criteria. According to the analysis carried out on the directory of shopping centres in Australia (PCA, 2017) and observations made on sites of 21 single-storey subregional centres, the following is identified as the most representative centre. The selection of Case 1 was primarily based on the criteria defined in Table 5.5, which as can be seen was very similar to the benchmark values of the average case.

Table 5.5: Benchmark values vs actual values of predefined criteria of the selected Case 1

Criteria	Benchmark values: Average case	Actual values: Case 1
No of anchor tenants	3	3
Anchor tenants-Gross lettable area retail (m^2)	11,660.00	12,100.00
No of specialty stores	49	47
Specialty- Gross lettable area retail (m^2)	6,381.00	5,802.00
Total centre- Gross lettable area retail (m^2)	17,490.00	20,250.00
Total centre- Gross lettable area (m^2)	18,426.00	22,498.00
Speciality proportion	35.00%	39.00%
Anchor proportion	63.00%	60.00%
Cinemas	No	No
Centre type	Enclosed	Enclosed
Ventilation	Fully airconditioned	Fully airconditioned
Enclosed car bays	No	No

Benchmark Case 1 was determined based on the median values of the criteria shown in Table 5.5, as described in detail in Section 4.4.1.1. Median values were quantified using the data on single-storey subregional shopping centres in Victoria published in the directory of Australian shopping centres (PCA, 2017) (refer Appendix 19 for a sample of the directory). The statistical parameter 'median' is selected against 'mean' of benchmark values for selection criteria. The median is selected since it is robust against outliers, whereas the mean is sensitive to them. Therefore, the median provides a more realistic representation of the data set across a skewed distribution. The last four parameters of cinemas, centre type, ventilation and enclosed car bays are decided based on the majority data. Hence, Case 1 is defined as an enclosed fully airconditioned shopping centre with no cinemas and no enclosed car bays.

However, the actual shopping centre which had the closest values to the benchmark values was non-typical in its construction and had a non-standard layout. For this reason, the next closest case was selected, and the criteria values were found to be within ±10% of the benchmark values. Case 1 was also the closest to the benchmark values with accessible data (project documents, drawings, specifications, etc.) and followed typical and standard construction described above. Further details on Case 1 subregional shopping centre is provided in the subsequent section.

5.3.1 Case 1 building profile

Case 1 is a single-storey subregional shopping centre located approximately 27 km west of Melbourne's central business district, in Tarneit as shown in Figure 5.3.

Tarneit, a northern suburb of the City of Wyndham, is one of Australia's most significant growth corridors (Victorian Planning Authority, 2017). As it is in climate zone 6 (ABCB, 2015), Case 1 can, therefore, be generalised to a majority of the locations across Victoria. As identified in Section 5.2 it can also be generalised to more than 60% of Australian subregional shopping centres as they are located in climate zone 6.

Figure 5.3: Aerial view of Case 1 shopping centre

Source: (Google, 2020a)

Tarneit was mainly agriculture-based land but urban sprawl has changed the landscape in the area. This change has created a growth in property developments in the area for residential, commercial and retail in recent years.

This shopping centre was completed in September 2017 and opened for the public in October 2017. With a GLA of 21,000 m^2, it is anchored by two supermarkets and one discount department store and provides roofing to 49 specialty stores and several kiosks. It also includes a designated indoor play area for children with interactive components and facilities, such as cafes and infant feeding rooms for young families. The centre is accessible by both public and private transport, and it includes 935 on-grade car parking spaces (car park areas are beyond the scope of this research).

The centre provides shopping facilities to 76,600 residents in the total trade area (Ranfurlie Asset Management, 2019) along with four other shopping centres. In retail assets, the trade area is defined as 'the area in which an existing or proposed centre or retailer is most likely to draw custom' (Urbis, 2013). These trade area statistics directly affect the shopping centre tenant mix and proportionate distribution of retailers.

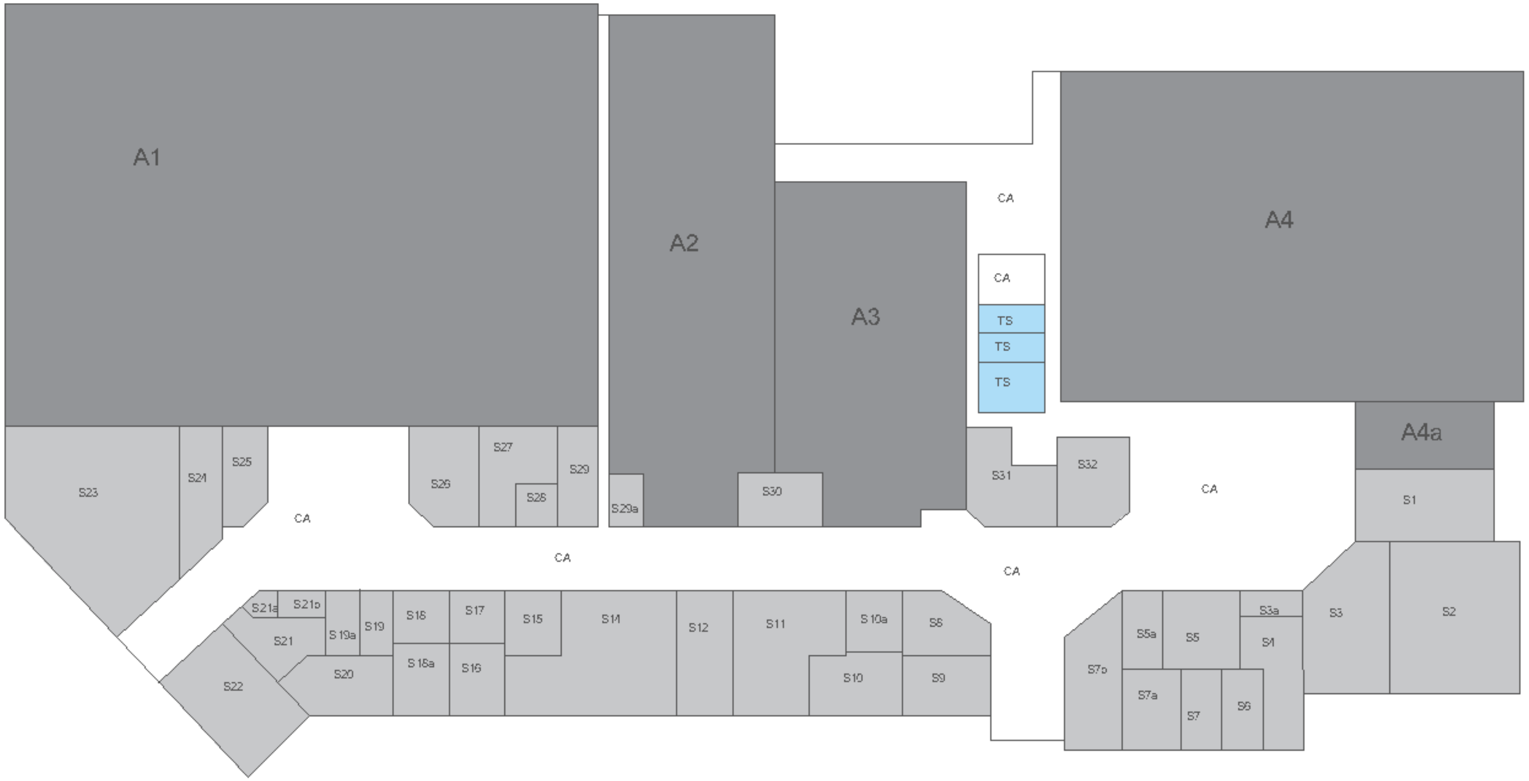
Figure 5.3 provides the floor plan details of Case 1. It closely represents the typical layout observed in the 21 subregional shopping centres visited and the documental (centre maps and plans) evidence from 35 centres (out of a total of 43). Typically, supermarkets and discount department stores are placed at the corners of a centre with specialty tenants in between. Across the large corridors or the common areas, other small tenants are located (kiosks including some services providers such as phone companies, newspaper agents and refreshment services). A centre management office is typically located near the middle part of the centre, as are the sanitary areas (toilets and changing rooms). As can be seen in Figure 5.4 this arrangement is very similar to that of Case 1.

In a typical subregional shopping centre, different clusters of shops can be identified. These clusters define the tenant mix which is used as shop types in the model (further explained in Chapter 6). To maintain the shopping centre retail revenue, a centre needs to provide all types of services required by the trade profile and the demographic profile of the expected customers (Burnaz & Topcu, 2011). Average household income also affects the decision on the tenant mix as it will determine the spending abilities and patterns of the shoppers (Garg & Steyn, 2015).

An industry research report (CBRE Research, 2018) outlines the typical retail tenant mix based on GLA in subregional shopping centres in Australia. This is presented in Table 5.6 alongside GLA proportions of Case 1.

Table 5.6: Clusters of specialty shops and gross lettable floor area proportions of Case 1 against CBRE benchmarks

Clusters	Tenant mix (CBRE)	Tenant mix (Case 1)
Anchor supermarket	32.00%	28.15%
Anchor discount department store	28.00%	31.60%
Clothing	4.00%	2.00%
Food supplies	5.50%	7.38%
Household	5.25%	11.54%
Multimedia and electronics	1.25%	0.00%
Gymnasium	1.50%	2.01%
Leisure and entertainment	2.75%	0.46%
Health and beauty	1.50%	4.80%
Café and restaurant	2.50%	4.71%
Other retail	2.50%	0.10%
Shoes	1.25%	0.52%
Services	12.00%	6.73%



Legend

- Anchor tenants
- Speciality tenants
- Toilets and sanitary areas
- Common areas

Case 1
Drawing Name: Average shopping centre
Drawing No: 001

Figure 5.4: Floor plan of Case 1

Source: Case 1 project documents (2019)

As shown, nearly 60% of the tenant mix was the anchor shops in both the CBRE and Case 1 data. Food supplies and café/restaurant shops represent almost 13% of the specialty GLA, while household is almost 12% which are different from the CBRE tenant mix. The significant difference in household was due to a comparatively large household shop which represented 7% of GLA. Services shops account for only 7% of the total GLA, which is lower than the CBRE value. Other clusters also form a part of the GLA distribution but are not as significant. The on-site observations and the analysis carried out based on shopping centre directory showed that Case 1 has a similar and typical tenant mix based on the CBRE data and GLA. However, it also illustrates the ability of one or two shop differences, which may be related to the demographics of the area to make some changes to the speciality shop mix. Overall, the tenant mix for Case 1 was considered suitable for the study.

Identification of the tenant mix and the shops in Case 1 provides the basis of the shopping centre scenarios considered in the model. Importantly, Case 1 is used to apply the BAU scenario of subregional shopping centres as identified in Section 5.2. The use of the most representative case study in terms of GLA and tenant mix provides the opportunity to generalise the findings to a broader scope. This case study is also used as a source to gather data on building materials and assemblies used for the construction (through analysis of project documents) which are also used as inputs to determine the most representative BAU scenario.

5.3.2 Construction methods and building materials and assemblies

As the centre is in climate zone 6, building materials have been selected to meet the Building Codes Australia's minimum building standards for this zone. According to the project documentation for Case 1, the building materials and assemblies presented in Table 5.7 and described below have been identified as the key structural elements in Case 1.

Although a single specification is provided in the table for a single assembly type, it must be noted that the shopping centre shell was constructed using a number of building assemblies of different sizes and different materials to meet the required design loads at different locations. For instance, the ground slab depth in Case 1 has four different scenarios based on the different design loads and locations (i.e. 120 mm in some specialty areas, 150 mm in some supermarket areas, 180 mm in storage rooms and 200 mm in some loading zones). However, a 150 mm slab was selected as it best represented the average volume for the overall centre. Selection of foundation footings is influenced by the soil conditions of the site and Case 1 used strip and pad footings of different sizes. Similarly, other structural assembly types have different scenarios based on the structural requirements. This would have been difficult to model, therefore, an average which represents a similar volume of materials has been selected. The complexity of the design makes quantification of life cycle embodied energy (LCEE) and life cycle material cost (LCMC) of shopping centres very challenging. Hence, in the model the researcher makes several assumptions to simplify the process by defining a single scenario for each assembly type in Case 1 (i.e. as mentioned in the specification in Table 5.7) which is assumed to be used throughout the building. These were based on the average volumes of building assemblies. The assumptions were made in accordance with the industry standards and regulatory requirements. The assembly choices were verified for structural suitability through an experienced commercial structural engineer and an estimator. These limitations are addressed in Section 8.6.6.

Table 5.7: Sample of building materials and assemblies used in Case 1 shopping centre structure

Assembly type	Assembly/material used	Specification
Foundation	Concrete	Generally, 150 mm thick slab-on-ground throughout UNO[8] provide SL92[9] fabric top, poured on PVC damp proof membrane lapped and tapped at joints on 50 mm bedding sand. Pad footings to be 2300 mm × 2300 mm × 500 mm with N16[10]-250 mm each way. Strip footings to be 450 mm × 400 mm with 4L11-TM[11] top and bottom, and R10-450[12] ties. Concrete grade: N32 (dense weight) To AS 3600.
Column	Steel	150 mm × 150 mm × 8 mm SHS[13] steel grade C350 to AS 1163.
Structural wall	Precast concrete	150 mm thick precast panel. SL92 central with 1N16 trimmer bar central each edge to AS 3850.3.
Roof structure	Steel	Trusses (top/bottom chord 150PFC[14]), verticals 100 mm × 100 mm × 10 mm EA[15], end verticals 150 PFC, diagonals 100 mm × 100 mm × 6 mm EA, verticals at roof beams 150 UC[16] 30, fully welded 6CFW[17] typical/ cold formed purlins and girts to AS 1397 :G450 Z350.

Source: Project documents of Case 1

The fixtures and ironmongery (i.e. nut, bolts, brackets and braces) used in structural assemblies were assumed to be similar across all scenarios and were therefore not included in the assembly specifications.

The selection of the average assembly scenario was based on the design loads and the total volume of the assembly in the entire shopping centre. The list of selected

[8] Unless noted otherwise
[9] Square mesh with 9 mm bars at 200 mm each way
[10] Nominal diameter 16 mm deformed bars
[11] Trench mesh with our bars of 11 mm diameter
[12] 6 mm diameter plain round bars with circular tie of 450 mm
[13] Square hollow section
[14] Parallel flange channel
[15] Equal angle
[16] Universal column
[17] Continuous fillet weld

assembly scenarios is presented in Appendix 7. Once the structural assembly details were finalised, attention was directed to shop fit-out details.

Although building materials and assemblies used in the shell were obtained from project documentation, shop fit-out materials were gathered through Case 1 project documentation and on-site observations. The two four-hour site visits supplemented the documentation to identify shop fit-out finishing materials and assemblies. As mentioned earlier, only the finishing assembly types; wall, floor and ceiling are considered under shop fit-out level. All finishing materials and assemblies from Case 1 are listed in Appendix 7. As with the shell, shop finishes also have several scenarios depending on the tenant requirements. In most shops, several finish types are used for a single assembly type. For instance, in a single speciality shop, two types of floor finishes (tiles and a rubber carpet) were observed. However, in the model, the finishes in each speciality shop are defined to have only one type of finish for walls, floor and ceilings so as to not overly complicate the model. The most commonly observed materials were used when more than one type was identified.

Details on finishing materials and assemblies of shops were based on the 13 clusters of shops identified in Table 5.6. Shopping centre common area and toilets and sanitary stations are considered as two separate clusters. The materials and assemblies used in those areas were also obtained using the documentation and on-site observations. The types of materials and assemblies based on the clusters of shops are listed and presented in Appendix 8.

The building materials and assemblies identified in Case 1 for shell and shop fit-out construction are used as inputs in the mathematical model to quantify LCEE and LCMC. Furthermore, the shopping centre and shops geometries are also used as inputs to *shop* objects in the model which is explained in detail in Chapter 6. The collection of details on shop sizes and areas and refurbishment frequencies is described under the next sub-heading.

5.3.3 Assembly quantities and refurbishment frequency

Quantities for various assemblies required for the calculations of LCEE and LCMC of shopping centres were obtained through the auto-generated bill of quantities (BOQ). Refer to Section 4.7.4 for details on the auto-generated BOQ. The mathematical model used the basic geometries of the shops (length, width, height and span) to generate the BOQs. All the shops were listed in a datasheet including length, width, height and span. Irregular shaped shops or areas were transformed into rectangular shapes with similar GLA. All shops and the entire shopping centre were considered to be rectangular in shape to simplify the LCEE and LCMC quantification process in the model. The full list of shops in Case 1 are presented in Appendix 9-A. A manual calculation to check the accuracy of the auto-generated BOQ was also conducted. The Australian Standard Method of Measurements of Building Works was used when measuring quantities (AIQS, 2016).

According to the literature, refurbishment frequency of retail shops in shopping centres is typically 2-10 years (Fieldson & Rai, 2009; Petermans & Kent, 2016; Yudelson, 2009). This finding was also verified by the five semi-structured interviews with shopping centre management bodies, including the one interview relating to Case 1 (refer Table 5.4 in Section 5.2). The responses revealed that for specialty tenants, the typical lease period is five years, and they may or may not renew their leases at the end of five years. If the tenants do not renew the leases, they have to return the shop to its original condition or 'make good of the shop'. That means at the end of the lease period the shop fit-outs are redone to meet the requirements of the new tenant. Even if the tenant stays and renews the lease it is often required to refurbish the shop fit-out to freshen it for the next five years.

According to the interviews, the situation with anchor tenants is quite different. The usual tenant lease period for anchor tenants is 20 to 30 years, and they do, much more often than not, renew their leases. Refurbishments of anchor tenants are not as frequent as for speciality shops which is related to the nature of the shop as well as the lease period. Therefore, these anchor tenants mostly undergo major refurbishments in every 15 to 20 years with minor maintenance in between. The typical refurbishment frequency for anchor tenants was thus considered as 20 years for modelling purposes.

The common area refurbishments, according to the interviews occur only when required or when a change in layout happens. The shopping centre owner makes this decision, not the centre management. The interviews revealed that this decision typically differs from centre to centre. However, on average most centres undertake common area refurbishments every 10 to 15 years. For modelling purposes, Table 5.8 outlines the typical refurbishment frequencies considered for different shop categories.

Refurbishment frequency of the centre structure or the shell was considered similar to the period of analysis of the shopping centre (50 years) as the structure typically does not undergo refurbishments over its life span. This was also obtained from primary and secondary data. Alternative refurbishment frequencies were developed to conduct a sensitivity analysis and evaluate its effect on embodied energy and material cost of different shops. The alternate values were obtained from the interview findings with the management bodies, where they identified the second most common refurbishment frequencies based on their experiences.

Interviews with Case 1 centre management further showed that the weighted average lease expiry (WALE) period by GLA of the shopping centre is four years. WALE is defined as 'the weighted average lease term remaining to expire across a portfolio, it can be weighted by rental income or square metres' (PCA, 2008). Typically, a WALE by GLA above 5 is considered good for the shopping centres. Four years indicates a slightly higher vacancy rates and tenant turnover (Chuen & Gregoriou, 2014; Crosby, Hughes, & Murdoch, 2006). These vacancy rates and tenant turnover ultimately result in premature replacement of building materials and assemblies in shop fit-outs causing higher embodied energy use and emissions. However, as WALE is a provisional value (which changes annually), the model used the predetermined refurbishment frequencies mentioned in Table 5.8 for the assessment of LCEE and LCMC.

Table 5.8: Refurbishment frequencies considered for quantifying life cycle embodied energy and material cost of shops

Shop	Typical refurbishment frequency	Alternative refurbishment frequency for sensitivity analysis
Centre structure	50	50
Anchor shops	20	15
Speciality shops	5	10
Common areas	10	15

The data collected from semi-structured interviews, project document analysis and on-site observations were used to determine the most representative BAU scenario of subregional shopping centre design. Case 1 shopping centre was used as a representative of average subregional shopping centres in terms of GLA and tenant mix. The case study was then used in the model to apply the BAU scenario of subregional shopping centres and to quantify its LCEE and LCMC and compare the effects of different assembly combinations to identify potential savings. The findings were later generalised as the embodied energy and material cost values of an average subregional shopping centre in Australia. Cases 2 and 3, outlined below, were used to quantify and compare how LCEE and LCMC values of shopping centres would change with different GLA in the BAU and other assembly scenarios. These two cases were representatives of the average bottom 25% and top 25% of single-storey subregional shopping centres in Australia. The building profile of Case 2 shopping centre is presented next.

5.4 CASE 2

Case 2 is representative of the bottom 25% of single-storey subregional shopping centres based on GLA. As in Case 1, the model applied the BAU scenario to Case 2 shopping centre and embodied energy and material cost values were quantified. The primary function of Case 2 was to assess and compare the differences in embodied energy and material cost values in the BAU scenario when gross lettable is decreased in comparison to Case 1.

As with Case 1, the selection of cases was primarily based on the quantitative and qualitative criteria defined in Table 5.9. The case was based on the case closest to the benchmark values, as well as accessibility and availability of data, as mentioned in Section 5.3. Benchmark values were quantified using the data on the directory of shopping centres in Australia (PCA, 2017). The first quartile values (median of the lower half of a dataset) of the entire dataset of single-storey subregional shopping centres in Victoria for the criteria quantified and selected for establishing benchmark values.

Table 5.9: Benchmark values vs actual values of predefined criteria of Case 2

Criteria	Benchmark values: Small case	Actual values: Case 2
No of anchor tenants	2	2
Anchor tenants-Gross lettable area retail (m^2)	6,844.00	8,831.00
No of specialty stores	36	32
Specialty- Gross lettable area retail (m^2)	4,305.00	2,826.00
Total centre- Gross lettable area retail (m^2)	13,539.00	11,657.00
Total centre- Gross lettable area (m^2)	14,530.00	11,776.00
Speciality proportion	25.80%	24.00%
Anchor proportion	72.00%	75.00%
Cinemas	No	No
Centre type	Enclosed	Enclosed
Ventilation	Fully airconditioned	Fully airconditioned
Enclosed car bays	No	No

The most suitable shopping centre with parameter values lower than the benchmark values was selected as the Case 2. Further details on Case 2 are presented in the following section.

5.4.1 Case 2 building profile

Case 2 is a single-storey subregional shopping centre located approximately 45 km south-east of Melbourne's central business district, in Mornington Peninsula, in climate zone 6, as depicted in Figure 5.5.

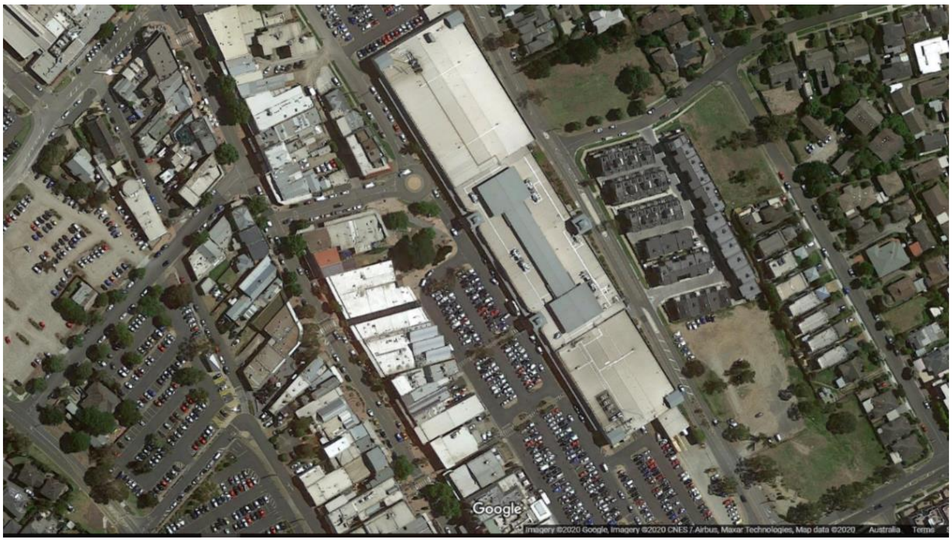


Figure 5.5: Aerial view of Case 2 shopping centre

Source: (Google, 2020c)

This shopping centre was opened to the public in August 2000. With a GLA of 11,776 m^2, it is anchored by one supermarket and one discount department store including 36 specialty stores. The centre provides roofing to 38 tenants and centre management and amenities. It has access through both private and public means and consists of 505 on-grade car parking spaces. This shopping centre, along with three other centres provide shopping facilities to 65,570 residents in the total trade area (Vicinity Centres, 2018). Vicinity Centres (2018) estimated that 42% of the residents in the trade area are homeowners.

As with Case 1, this shopping centre was also built using mainly concrete and steel in the shell construction. Building materials and assemblies used in fit-out constructions were observed and outlined in Appendix 3 and 4.

Figure 5.6 provides the floor plan of the Case 2 shopping centre which follows the typical layout of shops in a subregional shopping centre in Australia, as described in Section 5.3.1. Table 5.10 presents the typical tenant mix based on GLA of a small subregional shopping centre (CBRE Research, 2018) alongside GLA proportions of Case 2.

Table 5.10: Clusters of specialty shops and gross lettable area proportions of Case 2 against CBRE's benchmarks

Clusters	Tenant mix (CBRE)	Tenant mix (Case 2)
Anchor supermarket	37.00%	28.00%
Anchor discount department store	25.00%	47.00%
Clothing	4.00%	6.62%
Food supplies	6.00%	3.57%
Household	2.25%	2.37%
Multimedia and electronics	1.25%	1.81%
Gymnasium	2.00%	2.01%
Leisure and entertainment	2.75%	0.46%
Health and beauty	2.50%	1.56%
Café and restaurant	4.50%	4.71%
Other retail	3.50%	1.23%
Shoes	1.25%	2.42%
Services	8.00%	5.68%

As shown, more than 60% of the tenant mix was the anchor shops in the CBRE data but in Case 2 data was 75%. The supermarket GLA was identified to be more than of the discount department stores in CBRE but is reversed in Case 2. This difference may be related to the changes in demographics of the shopping centre. Services and food supply shops had lower values in Case 2 than in the CBRE data, whereas clothing shops showed a higher value. Household, café/restaurant, and gymnasium shops follow almost similar values of CBRE data. The on-site observations and the analysis of tenant mix indicated that other than differences in a few shops, Case 2 has a similar and typical tenant mix based on the CBRE data and GLA. Overall, the tenant mix for Case 2 was considered suitable for the study.

Legend
- Anchor tenants
- Speciality tenants
- Toilets and sanitary areas
- Common areas

Case 2
Drawing Name: Small shopping centre
Drawing No: 002

Figure 5.6: Floor plan of Case 2

Source: Case 2 project documents (2019)

Figure 5.6 provides the floor plan of the Case 2 shopping centre which follows the typical layout of shops in a subregional shopping centre in Australia, as described in Section 5.3.1. Table 5.10 presents the typical tenant mix based on GLA of a small subregional shopping centre (CBRE Research, 2018) alongside GLA proportions of Case 2.

Table 5.11: Clusters of specialty shops and gross lettable area proportions of Case 2 against CBRE's benchmarks

Clusters	Tenant mix (CBRE)	Tenant mix (Case 2)
Anchor supermarket	37.00%	28.00%
Anchor discount department store	25.00%	47.00%
Clothing	4.00%	6.62%
Food supplies	6.00%	3.57%
Household	2.25%	2.37%
Multimedia and electronics	1.25%	1.81%
Gymnasium	2.00%	2.01%
Leisure and entertainment	2.75%	0.46%
Health and beauty	2.50%	1.56%
Café and restaurant	4.50%	4.71%
Other retail	3.50%	1.23%
Shoes	1.25%	2.42%
Services	8.00%	5.68%

As shown, more than 60% of the tenant mix was the anchor shops in the CBRE data but in Case 2 data was 75%. The supermarket GLA was identified to be more than of the discount department stores in CBRE but is reversed in Case 2. This difference may be related to the changes in demographics of the shopping centre. Services and food supply shops had lower values in Case 2 than in the CBRE data, whereas clothing shops showed a higher value. Household, café/restaurant, and gymnasium shops follow almost similar values of CBRE data. The on-site observations and the analysis of tenant mix indicated that other than differences in a few shops, Case 2 has a similar and typical tenant mix based on the CBRE data and GLA. Overall, the tenant mix for Case 2 was considered suitable for the study.

Semi-structured interviews, on-site observations (two four-hour visits) and project document analysis as mentioned in Section 5.3.1 were carried out for Case 2 as well to gather data on building materials and assemblies used for construction and refurbishment frequencies. Those data inputs were used to establish the BAU scenario of subregional shopping centres which was applied in Case 1 and Case 2 shopping centres. Results of Case 2 were then compared with the embodied energy and material cost values of Case 1 to identify their relationships with shopping centre GLA.

Interviews with Case 2 centre management and Vicinity Centres (2018) retail property portfolio showed that the weighted average lease expiry (WALE) by GLA of the shopping centre is three years. However, the model used the predetermined refurbishment frequencies mentioned in Section 5.3.3 for the assessment of LCEE and LCMC for similar reasons mentioned before.

A similar process as mentioned in Section 5.3.3 was used to determine the geometries (length, width, height and span) of all shops of the Case 2 and the full list of shops is attached as Appendix 9-B. These geometric values were used to generate automated BOQs of the shops, which were later used to assess LCEE and LCMC of the Case 2 shopping centre. Details of Case 3 are presented next followed by a summary of the chapter.

5.5 CASE 3

Case 3 is the representative of the average of the top 25% of single-storey subregional shopping centres based on GLA. The function of this case was similar to that of Case 2, including assessment of embodied energy and material cost of the BAU scenario and to compare the results to identify any relationships between GLA and embodied energy and material cost of shopping centres. In Case 3, GLA is increased in comparison to the average shopping centre (Case 1).

As with Case 1, the selection of cases was primarily based on the quantitative and qualitative criteria defined in Table 5.11. The case was based on the benchmark values as well as accessibility and availability of data, as mentioned in Section 5.3.

Table 5.12: Benchmark values vs actual values of predefined criteria of Case 3

Criteria	Benchmark values: Large case	Actual values: Case 3
No of anchor tenants	4	5
Anchor tenants-Gross lettable area retail (m^2)	13,818.00	15,164.00
No of specialty stores	64	72
Specialty- Gross lettable area retail (m^2)	8,536.00	7,974.00
Total centre- Gross lettable area retail (m^2)	22,042.00	23,138.00
Total centre- Gross lettable area (m^2)	24,717.00	30,058.00
Speciality proportion	34.53%	26.55%
Anchor proportion	55.91%	50.45%
Cinemas	No	No
Centre type	Enclosed	Enclosed
Ventilation	Fully airconditioned	Fully airconditioned
Enclosed car bays	No	No

Benchmark values were quantified using a similar method as described in Sections 5.3 and 5.4. The third quartile values (median of the upper half of a dataset) was used for establishing benchmark values. The most suitable shopping centre with parameter values higher than the benchmark values was selected as the Case 3. The following section presents the details of Case 3.

5.5.1 Case 3 building profile

Case 3 is also a single-storey subregional shopping centre located in 32 km south-east of Melbourne central business district, in Endeavour Hills, and is shown in Figure 5.7 (Australian Bureau of Statistics, 2019). As with Case 1 and 2, it is also in climate zone 6 (ABCB, 2015); therefore, the case can be generalised to most of the locations across Victoria (as mentioned in Table 5.2).

Figure 5.7: Aerial view of Case 3 shopping centre

Source: (Google, 2020b)

This shopping centre was opened to the public in 1979. The current owner acquired the centre in 2007 and has undertaken several renovations and refurbishments to increase customer foot traffic. The centre is anchored by five major tenants: three supermarkets and two discount department stores, accounting for a GLA retail of 23,138 m^2. Total GLA of the centre is 30,058 m^2 housing more than 90 specialty retailers. It can be accessed by both public and private means of transport and has 2,200 on-site car spaces.

According to the Property Council of Australia (2019), retail tenants in the centre benefit from the steady foot traffic of more than 4.8 million customers annually. The weighted average lease expiry period (WALE) of the centre is estimated as 6.3 years (Markis, 2018), which is a comparatively good, indicating a lower vacancy rate and tenant turnover.

As with Cases 1 and 2, Case 3 shopping centre shell construction mainly involved concrete and steel. Building materials and assemblies used in fit-out constructions were observed and outlined in Appendix 3 and 4.

Figure 5.8: Floor plan of Case 3

Source: Case 3 project documents (2019)

Figure 5.8 provides the floor plan of Case 3. The typical tenant mix based on GLA of a large subregional shopping centre (CBRE Research, 2018) alongside GLA proportions of Case 3 are presented in Table 5.12.

Table 5.13: Clusters of specialty shops and gross lettable area proportions of Case 3 against CBRE's benchmarks

Clusters	Tenant mix (CBRE)	Tenant mix (Case 3)
Anchor supermarket	26.00%	32.52%
Anchor discount department store	33.00%	18.66%
Clothing	9.00%	10.50%
Food supplies	5.50%	6.71%
Household	7.25%	8.55%
Multimedia and electronics	1.25%	0.95%
Gymnasium	1.50%	0.00%
Leisure and entertainment	2.75%	2.35%
Health and beauty	1.50%	5.50%
Café and restaurant	2.50%	4.80%
Other retail	2.50%	0.96%
Shoes	2.25%	1.00%
Services	5.00%	7.50%

The tenant mix of Case 3 does differ from CBRE data regards to anchor tenancies. Supermarket and discount department store GLA represent almost 60% of CBRE tenant mix but in Case 3 shopping centre they account for around 52%. Even though CBRE suggests more GLA to discount department stores, in Case 3 supermarkets are more dominant in GLA distribution. Additionally, Case 3 lacked a gymnasium and had comparatively lower GLA for shoes, other retail and multimedia and electronics shops. Conversely, clothing, household, food supplies and health and beauty shops in Case 3 had larger GLA than CBRE data. Albeit these differences, Case 3 was identified as the most representative in terms of the tenant mix and GLA of the large subregional shopping centres in Victoria and was considered suitable for the study.

As with Cases 1 and 2, building materials and assemblies selection was carried out to establish the BAU scenario and to identify alternative assembly combinations. Shop sizes and refurbishment data were obtained in a similar manner as mentioned in Section 5.3.1. The full list of shops of Case 3 is presented in Appendix 9-C. The findings of the cases are then used as inputs to the model development and application as described in Chapter 6.

5.6 SUMMARY

This chapter presented detailed descriptions of the three selected case study shopping centres in the study. These were developed using academic and industry literature, primary research data collected for the study through nine semi-structured interviews, 21 on-site observations and project documentation. The BAU scenario of subregional shopping centre construction in Victoria in terms of building materials and assembly choices was established. Three case studies of subregional shopping centres were selected representing the average (Case 1), small (Case 2) and large (Case 3) centres in terms of GLA and tenant mix. The case studies were used to apply the established BAU scenario and alternative scenarios and to quantify embodied energy and material cost using the model and compare their effects with GLA and identify relationships. The findings of interviews confirmed the findings of the literature regarding refurbishment frequencies.

The next chapter discusses the databases and classes required to perform the mathematical process to quantify LCEE and LCMC of shopping centres, using Python as the programming language. The data inputs to the model were developed based on the findings of primary and secondary research data mentioned in this chapter. Chapter 6 provides the process of mathematical model development using object-oriented programming in Python.

6 OBJECT-ORIENTED MODEL DEVELOPMENT

6.1 INTRODUCTION

Research data obtained from case studies mentioned in Chapter 5 are processed to obtain information to resolve the research questions stated in Section 3.9. This chapter describes the development process of the mathematical model using case study data as input. Therefore, this chapter aims to provide information on the process of mathematical model development from the initial design stage to the final data validation stage. As the initial step, the identification of mathematical model requirements is discussed with the reliability of object-oriented programming (OOP) to fulfil the requirements. This section also presents the development of the class diagram at object-oriented design stage, developing databases, and finally defining classes for computing core for OOP. The quantification strategies used to generate automated bills of quantities (BOQ) in the model are also detailed as part of the computing core development. Details on the quantification of life cycle embodied energy (LCEE), and material cost (LCMC) of case study shopping centres are discussed. Furthermore, the process of obtaining combinations of building materials and assemblies which achieve the objective functions established in Chapter 4 are also provided. This chapter concludes with an introduction to the next chapter, where results are presented.

6.2 MATHEMATICAL MODEL REQUIREMENTS

The process of developing the mathematical model starts with the critical step of identifying model requirements. As observed in Chapter 4, LCEE and LCMC calculations of shopping centres are complex tasks due to their size and 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. The mathematical model, therefore, requires automation of shopping centre designs and systems, and rigorous processes of conduct LCEE and LCMC quantification. The core of any mathematical model development is the process of setting requirements, and it defines the whole model itself (Sarker & Newton, 2008). This step can be described as the process of developing answers to the 'What?' question in the development process where the developer has to define what the model has to perform, and in which form the model should be designed to receive the expected results. Therefore, the mathematical model needed to accomplish following requirements and specifications in order to achieve the objectives established in Chapter 1. The identified requirements and the strategies used to accomplish the requirements are described under the next sub-heading.

6.2.1 Accomplishing model requirements

The key requirements of the model are described below. As the model might be extended to a software tool in the future, the current model should be able to adapt to future requirements as well.

A key requirement of the model was to conduct scenario analysis, where embodied energy and material cost of different assembly combinations are assessed and compared, with reduced run time. The model architecture required resilience and flexibility. The model development approach was, therefore, selected critically considering the identified requirements. Accordingly, OOP was selected as the modelling approach for developing the mathematical model. Among several other programming paradigms in Python that can be adapted as imperative, functional, procedural, and object-oriented (Lott, 2014; Phillips, 2015; Python Software Foundation, 2018), the last was identified as the most suitable concerning the requirements stated above. Imperative coding changes programme state to achieve a goal. It works fine on simple applications, yet too slow for complex applications. Functional coding treats every statement in the programme as a mathematical equation. This coding style bears the main advantage of lending itself well to parallel processing since it does not have a state to consider. However, in Python, the implementation of functional coding is not the standard and has the potential to create state and side effects leading to errors. The final alternative coding style is the procedural paradigm where statements are structured into procedures. This style is a subtype of imperative coding and follows the stateful structure and therefore suffers from the same limitations of execution options. Therefore, the main reason for the selection of OOP is that it provides solutions to all the above-stated requirements from the paradigms mentioned above.

6.2.1.1 Object-oriented programming as a modelling method

The model uses OOP as the programming paradigm. It is organised around "objects" and data (Lott, 2014; Phillips, 2015). An object comprises a set of data with related behaviours. Objects pertaining different attributes and methods are categorised under different classes. A "class" is a blueprint of an object, which describes its attributes, methods and variables. Different types of objects may have different class modules (Steels, 1994).

The study defined four parent class modules as *Materials, Assemblies, Shop, and ShoppingCentre*. Classes have relationships based on the objects created in each class and how they are linked to each other. These relationships can be in different forms as one to one, one to many, many to one, and many to many. The relationships between different classes in OOP are represented through a class diagram or a unified modelling language (UML) diagram. A UML diagram provides information on the state of a class presenting its attributes and methods with input and output data types. More importantly, it indicates relationships between classes. The UML diagram for the study is presented in Figure 6.1.

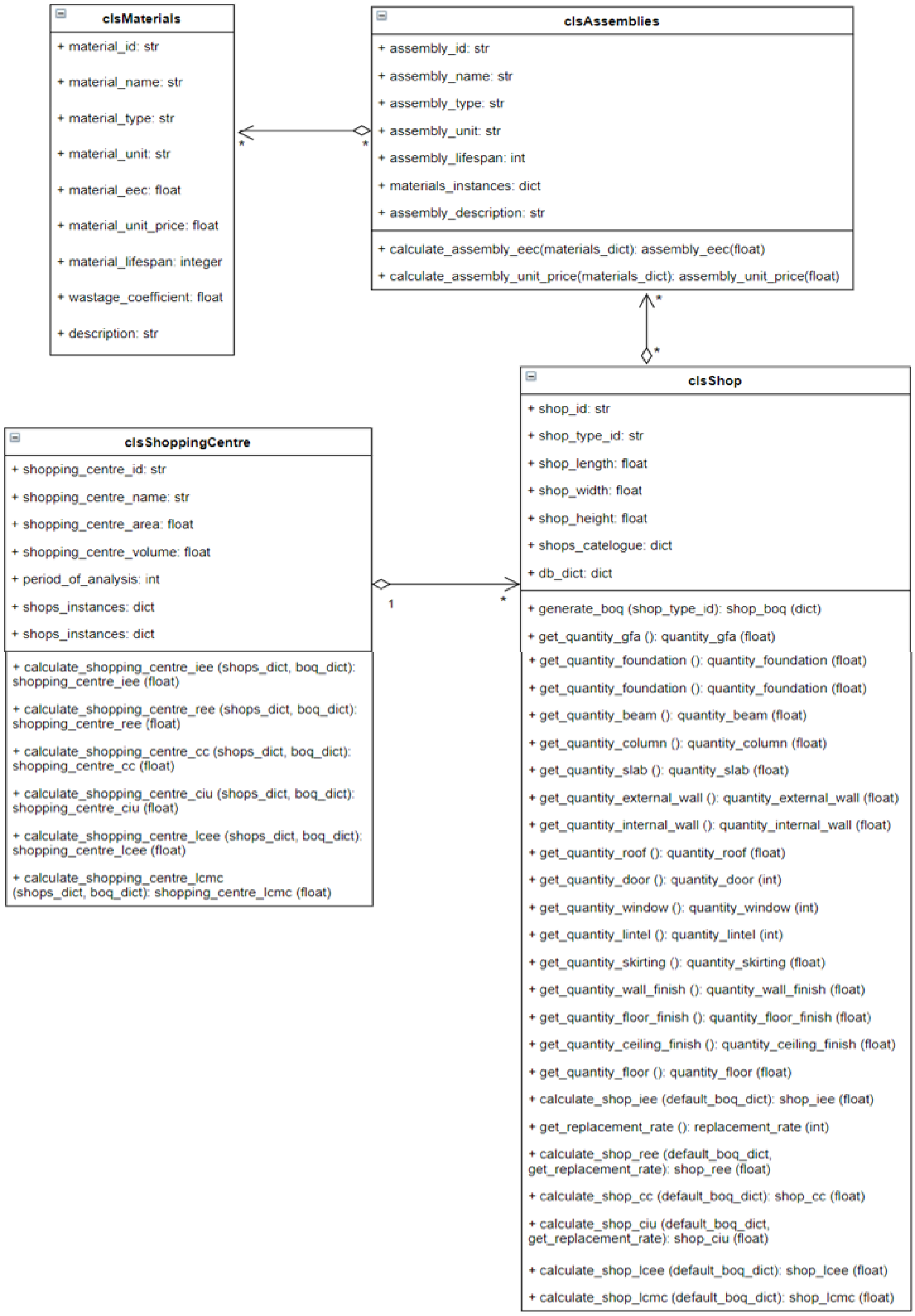


Figure 6.1: Unified modelling language diagram for the study

Classes create instances or objects based on the data input to itself. Each class instance can have attributes attached to maintain its state. Class instances can also have methods (defined by its class) to modify its state (Phillips, 2015). For instance, the *Shop* class has attributes such as length, width and height to create a shop object. Each shop object defined with a different set of attribute values become an independent object. The methods defined in the class are accessible by any object in the class itself. The methods are created to modify the state of the objects in a class.

For instance, the *Shop* class has methods created to calculate the quantities of the shop by building element. The building elements are the components of a building, as described in Section 4.7.3. Therefore, to calculate the quantity of floor area, the *Shop* class has a method defined as; '*get_quantity_floor*'. This method includes the attributes defined in *Shop* class to perform a simple multiplication using shop length and width, which returns the quantity of floor area. Since the methods created under a class are accessible by all its objects, once the code is executed, *Shop* class can calculate floor areas of all shop objects independently and store the results in each object.

OOP offers a flexible architecture, which allows the attributes of classes to be modified without having to change the algorithms. This nature provides the opportunity to assess different instances of a class based on their attributes. For instance, adding a new attribute as 'location' (defines the location of the shop in the shopping centre) to *Shop* class does not necessarily affect any method or any calculation in the class, it just provides new information to the object. New methods can be added to a class without affecting other methods in it. Revisions are possible with minimal effect on the model due to the modular structure (Lott, 2014). Therefore, OOP was selected as the programming paradigm in this study to develop the model architecture.

6.2.1.2 Using comma-separated values file format to export data

The results or the outputs of the model are exported in comma-separated values file format as it is extensively used in spreadsheet software and is highly versatile. Further, it requires less memory compared to other available file types and can be used directly in spreadsheet software.

6.2.1.3 Python and python related modules

The selection of a suitable programming language was the next critical aspect of the model development process. This study used Python^{TM} 3.7 as it is free and opensource (Python Software Foundation, 2018). The selection of the language is justified in detail in Section 4.7.7.2. It offers an extensive array of libraries, and classes and in-built functions which are designed to address specific aspects of programming (Lott, 2014). Various free Python-based modules are available to generate databases, develop data frames (i.e. Pandas), perform numerical operations (i.e. NumPy), and generate graphs and charts (i.e. Matplotlib). The graphs and charts are developed using Matplotlib to analyse the results at assembly, shop and shopping centre levels.

Most importantly, the model required multi-objective minimisation at the shop level and the shopping centre level. The study used the Pareto frontier as the method to search local optima of the results canvas. OOP in Python has been demonstrated to be efficient for real-world applications (Phillips, 2015), and therefore, Python and its related modules were used in model development.

6.3 MODEL ARCHITECTURE

The model consists of two main segments, a computing core and databases. Both components are equally crucial for the precision of the model and reliability of the outcome. Even though at this research the model is limited to the computing core and the databases only, it has the potential to be developed as a software in the future including a graphical user interface (GUI).

6.3.1 Computing core

The computing core is referred to as the 'model architecture' which contains all the classes with defined attributes and methods. Classes contain methods to perform all related quantifications of the LCEE and LCMC at different levels of the shopping centre for various assembly combinations. The data inputs required for quantifications are mostly extracted from the databases. However, sometimes data are extracted from the values of attributes of different objects created in other classes. For instance, to calculate the initial embodied energy (IEE) of a shop object in the *Shop* class, the model uses the quantities of building elements calculated in the *Shop* class itself and the embodied energy coefficient (EEC) of the assembly used to construct the element calculated and stored in the mentioned assembly object in the *Assembly* class (refer to Section 4.7 for calculation process).

6.3.2 Databases

The databases contain the data sets of materials, assemblies, shops and shopping centres which provide attribute values to the classes. Therefore, the model significantly relies on the databases to execute commands and generate required results. A summary of all the databases used in the model is presented below in Table 6.1.

Different material combinations generate different assemblies which are defined in the *Assemblies* database. Assemblies in the database are categorised based on their element type (i.e. *foundation, wall_finish*, *etc*.) Shops are constructed using a different assembly for each building element. Finally, a shopping centre is created by combining different shops. Each shopping centre has a different combination of shops based on type and geometry.

Table 6.1: Databases developed for the model

Database Name	Description
Materials	Provides details on all materials and their properties as defined in class attributes. i.e. material unit price
Assemblies	Contains details of assemblies with properties that can be generated using the materials in Materials database. i.e. assembly lifespan
Shops_catalogue	Lists all different types of shops with their default assemblies used for construction. i.e. refurbishment frequency
Shops	Provide geometry details of all shops. i.e. length
Shopping_centre	Contains details on all shopping centres. i.e. service life

The *Materials* database is at the lowest level of the hierarchy, as presented in Figure 6.2.

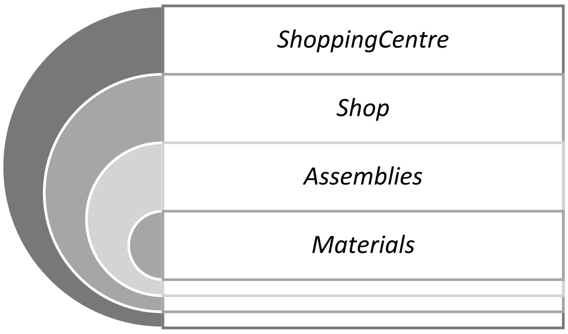


Figure 6.2: Hierarchy of databases used in the object-oriented programming sorted by comprehension

The classes in the model are linked to the databases. Data frames are used to store data inputs from databases in the Python programme. Data frames are two-dimensional, tabular data structures with rows and columns. Each class consists of at least one data frame generated from spreadsheet database (Microsoft Excel) containing the attribute values of objects in the class. Detailed descriptions of databases are provided under the next sub-headings.

6.3.2.1 Materials

The *Materials* database is the core database in the model. Materials provide the basis for assemblies to be used to construct shops, and therefore, the shopping centre itself. This database includes the properties of all materials used in the model. The values of different properties of materials are defined under nine fields in the database (refer to Table 6.2).

The values stored in these fields are crucial for embodied energy and material cost calculations on assembly, shop and shopping centre levels. Each material entered in the database is given a unique identification number (*material_id*) to ease access to materials at later stages in the model. A few key fields used in the database are listed below with a description of values entered and its data type (full list attached as Appendix 3).

Table 6.2: Fields in the Materials database used as input to the model

Field name	Type	Description
material_id	string	Unique ID given to each material (i.e. M01,…,M_n)
material_name	string	Name of the material (i.e. concrete, insulation, etc)
material_type	string	Type of the material (i.e. 25 MPa, Glass wool, etc)
material_unit	string	Functional unit of the material (i.e. m^3, m^2, etc)
material_eec	float	Embodied energy coefficient in GJ/unit (i.e. concrete 25 MPa: 5.01 GJ/m^3)
material_unit_price	float	Price per unit quantity in AU$ (i.e. concrete 25 MPa: 341.00 AU$/$m^3$)
material_lifespan	integer	Lifespan of material in years (i.e. concrete 25 MPa: 100)
wastage_coefficient	float	Wastage coefficient of the material (i.e. concrete 25 MPa: 0.05)
description	string	Description of the material (i.e. concrete 25 MPa with 14 mm aggregate)

The *material_eec* and *material_unit_price* values are fundamental to calculate the LCEE and LCMC of the shops and the shopping centres in the model. However, before that, the material properties are used to calculate assembly EEC and assembly unit prices in the *Assemblies* class along with data extracted from the *Assemblies* database. Different materials that can be used to construct subregional shopping centres in Australia are identified through industry document analysis, supplier details, and observations of case studies, as stated in Chapter 5. Details on innovative low embodied energy materials are obtained from research findings, suppliers, industry research and development documents and most importantly from Eco Specifier website. Eco Specifier is an accessible open database which provides details on environmentally sensitive materials. One material is created as a void material with zero material EEC and zero material unit price. This material is used in void assemblies in the *Assemblies* database to create assemblies with zero EEC and unit price. The modelling approach used in this study is inspired by Stephan (2013).

Material EEC are obtained based on research by Treloar and Crawford (2010). The researchers used an input-output based hybrid life cycle inventory analysis and path exchange method to develop more comprehensive embodied energy and greenhouse gas (GHG) emission coefficients of building materials and assemblies. The selection of data for EEC is explained in detail and justified in Section 4.7.2.1. Where EEC were unavailable, the researcher used proxy values based on a similar material.

In most cases, unit prices of materials are obtained from Rawlinson's construction cost guide (2019) and Cordell construction cost guide (2019). When cost details were unavailable in those mentioned sources, different suppliers were contacted and cost details were obtained. If unreachable from any of those methods, internet sources were used (supplier websites). For details, refer to Section 4.7.2.3. The material lifespan was determined based on the findings of existing research studies. For some materials, lifespan was accessed through supplier details. Wastage coefficients of different materials were also obtained from existing research and where inaccessible, details were requested from suppliers.

Different materials identified in the *Materials* database were then used in the *Assemblies* database as input. Details on the *Assemblies* database are discussed in the following section.

6.3.2.2 Assemblies

Building assemblies are defined as one level above materials. In the context of this research, assemblies are considered combinations of one or more building materials. Similar to materials in the *Materials* database, each assembly in the *Assemblies* database is given a unique identification number (*assembly_id*) for ease of access. Assembly data are stored under 6 key fields and include up to 10 input materials with respective quantities per unit quantity of the assembly to be stored for an assembly. The key fields, data types and a description of the data stored in the *Assemblies* database are provided in Table 6.3 (full list attached as Appendix 4).

Table 6.3: Fields in Assemblies database used as input to the model

Field name	Type	Description
assembly_id	string	Unique assembly ID (i.e. column: CL01, CL02)
assembly_type	string	Type of element assembly is constructed into (i.e. foundation, column)
assembly_name	string	Name of the assembly (i.e. reinforced concrete column)
assembly_unit	string	Functional unit of the assembly (i.e. m^3, m^2, m, t, no)
assembly_lifespan	integer	Lifespan of assembly in years (i.e. CL01: 50)
assembly_description	string	Details of the assembly (i.e. 9.4 m x 16.5 m column grid, 33.9 kg/m)

Each assembly is defined as a combination of materials with specified quantities of individual materials that go into a unit quantity of the assembly. The values of the fields of each assembly are obtained from similar sources as mentioned in the previous section. Measurement units of building assemblies are based on the assembly type and follow the Australian standard method of measurement of building works 6th edition published by AIQS (2016). The database includes void assemblies for each assembly type which are constructed using the void materials defined in the *Materials* database. These void assemblies were used as dummies in situations where a shop defined in the *Shop* class does not have a building element (i.e. clothing shop type does not come with a foundation assembly). The use of these assemblies is demonstrated clearly in Section 6.3.3.2.

The materials that go into each assembly were stored in the database with their identification numbers (*material_id*). The database provides flexibility to enter up to ten *material_ids* along with the quantity of each material required to build a unit quantity of the assembly. For instance, to build a unit quantity (1 m^2) of floor finish assembly FF03: Vinyl planks, the following two materials are required in respective quantities.

M42: Vinyl tiles – 1 m^2

M75: Plastic water barrier – 1 m^2

Similarly, all assemblies were defined with materials and quantities used to build per unit quantity of the assembly. All together 116 assemblies of different types were entered into the database. The quantities of materials required to build a unit quantity of the assembly were determined based on the Rawlinson's construction cost guide (2019) and Cordell construction cost guide (2019). Furthermore, research studies were used where details were unavailable. Suppliers were also contacted in situations where all sources were unreachable. These material quantities in the *Assemblies* database were later used in the *Assembly* class to quantify assembly EEC and assembly unit price. The calculation process is further explained in detail in Section 6.4 and the significance of the results are discussed thoroughly in Chapter 7. The following level of databases, *shops_catalogue* is described below.

6.3.2.3 Shops catalogue

Shops_catalogue is the database with details of different types of shops in the shopping centres. The database of *shops_catalogue* consists of 16 different fields. From these, 13 fields were allocated to define the default assemblies that are used to construct the shop type at each assembly type level. Some of the field details are presented in Table 6.4. The full list is attached as Appendix 10.

Table 6.4: Fields in Shops_catalogue database used as input to the model

Field name	Type	Description
shop_type_id	string	Unique shop type ID (i.e. CL_01_RF_5)
shop_type_name	string	Name of the shop type (i.e. clothing)
refurbishment_frequency	integer	Refurbishment frequency (i.e. 5, 10, 15 years)
ceiling_finish	string	ID of the assembly used to construct the element in default scenarios of the shop type (i.e. CF01)

The classification of shop types in a subregional shopping centre is determined by the tenant mix, as described in Chapter 5. The clusters of shops identified in case studies were used as shop types to develop the database. When identifying different shop types, the shopping centre was considered as of shell and internal fit-out. The shopping centre shell is considered as a separate shop type for the ease of energy and financial flow quantification rather than considering structural elements as parts of specialty and anchor shops. Accordingly, shop types include 11 specialty shops, two anchor shops, common areas, toilets and sanitary, and centre structure. In the context of this research, a shopping centre is considered as a combination of rectangular-shaped shops. Hence, a shop is considered as a rectangle box with a length, width and height as described in Chapter 5 (shoe-box scenario). All shops are considered to follow the shoe-box scenario together with common areas, toilets and sanitary areas and *centre structure* as well. At the end of the classification, the shopping centre was defined to have 16 different types of shops, as mentioned above.

The refurbishment frequencies of different types of shops were from the empirical study findings, as mentioned in Chapter 5. Moreover, the *shops_catalogue* database contains details of the building assemblies of each shop type in its most common scenario, as identified in Chapter 5. This information on each shop type is later used to compute the LCEE and LCMC values of the shops in the shopping centre. Next, the shops' geometric values are defined in the case study shopping centres to obtain assembly type quantities in each shop, in order to quantify the LCEE and the LCMC.

6.3.2.4 Shops

The *Shops* database links all other databases to the shopping centre scenario. This database contains shop geometry values and the location of each shop in the shopping centre. The shoe-box concept is used to define shop geometries. Accordingly, a shop is considered as a box with length (L), width (W) and height (H) (Figure 6.3).

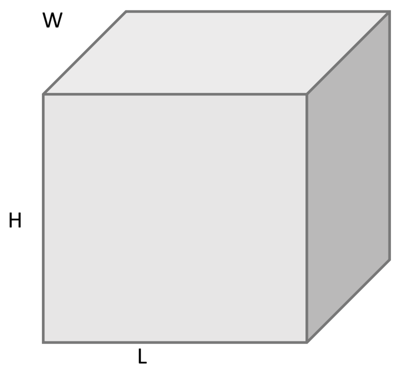


Figure 6.3: Shoe-box scenario used in the object-oriented model to define shop geometries

This technique provides flexibility to the model to modify the shop geometry at any time and thus allows the model to upgrade in the future. The parametric shop designs are, therefore regarded as a representative method to define the shopping centre at the shop level. The *Shops* database consists of 7 fields to define each shop. Table 6.5 provides an understanding of the key fields, types of data entered as values, and a brief description of each field.

The *Shops* database uses lists of shops created using shopping centre geometries of case studies as inputs. Each shop is given a unique identification number followed by the *shop_type_id, refurbishment_frequency, length, width* and *height* (i.e. CL_01_RF_5_5_11_5).

Table 6.5: Fields in the Shops database defined in the object-oriented model

Field name	Type	Description
shop_id	string	Unique shop ID (i.e. CL_01_RF_5_5_11_5)
shop_type_id	string	Shop type ID (i.e. CL_01_RF_5)
length	float	Length of the shop in m (i.e. 5)
width	float	Width of the shop in m (i.e. 8)
height	float	Height of the shop in m (i.e. 5)
span	float	Span of the shop in m (i.e. 4). This is only applicable to centre_structure shop type
location	string	Location of shop in the shopping centre (i.e. S_S_01)

Each shop is also categorised under a shop type based on its business profile. The location of each shop is given based on the shop layout drawing. The locations of the shops in the shopping centre affect the quantity calculations of internal walls and other building elements which are explained in detail later in Section 6.6.

6.3.2.5 Shopping centres

The *Shopping_centre* database stores data on different shopping centres used for analysis. As mentioned in Chapter 5, three case study shopping centres were used in the model. The *Shopping_centre* database is the largest in terms of number of fields since it has more than 150 fields. This database follows a similar structure to the *Assemblies* database with *shop_id*s and quantities. It contains all the shops' data in the shopping centre. Shops with different IDs in the shopping centre are stored with the number of shops of similar ID. Since a shopping centre includes at least 50 shops, the database becomes larger when all three case study data are stored. Other key fields in the database are as follows in Table 6.6.

Table 6.6: Fields in the Shopping_centre database defined in the object-oriented model

Field name	Type	Description
shopping_centre_id	string	Unique shopping centre ID (i.e. SC1)
shopping_centre_name	string	Name of the shopping centre (i.e. shopping_centre_average)
period_of_analysis	integer	Expected service life of the building (i.e. 50 years)
num_of_major	integer	Number of major tenants
num_of_specialty	integer	Number of specialty tenants
base_case_name	string	Name of the case study shopping centre
location	string	Location: Suburb, postcode

A period of analysis is required to quantify the LCEE and LCMC of the shopping centres, as mentioned in Sections 4.7.3 and 4.7.4. Typically, it is equal to the expected service life of the building. Since in most scenarios a building service life is taken as 50 years, the period of analysis of the shopping centres was also fixed at 50 years.

6.3.3 Computing core - Classes

The computing core consists of different classes developed to quantify the LCEE and LCMC of the shopping centres. As mentioned in Section 6.2.1, four classes are created to perform calculations at each level in order to achieve the aim of the model. For more details on the relationships of the classes, refer to the unified modelling language diagram (Figure 6.1). The *ShoppingCentre* class is at the core of the model, and all other classes are linked to it. Detailed descriptions of classes are presented in the following sections.

6.3.3.1 Materials

The *Materials* class is essential since it provides the source data for computing EEC and unit prices at the assembly level and LCEE and LCMC at the shop and shopping centre levels. This class does not contain any methods, only attributes (i.e. material_id, material_name, material_eec, etc). These attributes are quite similar to the fields in the *Materials* database. The attribute values of each material are extracted from the database. Material instances are created at the *Materials* class using database field values. The purpose of the *Materials* class is to create material objects which can later be used in LCEE and LCMC quantification processes.

6.3.3.2 Assemblies

The *Assemblies* class import data from Assemblies database to create assembly objects. Class attributes include key field names of the database (i.e. assembly_id, assembly_name, etc). Other than that, each assembly object created in the class has a dictionary of materials with respective quantities. Python dictionaries are stored as 'key: value' pairs, so that material ID in the assembly are given as keys and the quantities of each material in the assembly are given as values. This dictionary contains material IDs which can be linked to the material objects created at the *Materials* class. Therefore, material EEC values are accessible at the *Assemblies* class. One of the primary functions of the *Assemblies* class is to create assembly objects. The assembly objects, however, have few more variables stored than the attributes. This class carries methods to quantify assembly EEC and assembly unit price which are not defined at the database level. The method uses a dictionary of materials to calculate the embodied energy coefficient of an assembly. These material EEC values together with the material quantities mentioned in the dictionary of materials are used to calculate assembly EEC. These coefficients are calculated for a unit quantity of assembly; hence attention is given to the unit differences of materials and assemblies. A similar method is used to quantify the assembly unit price using material unit price values. These two calculated variable values were stored within each *Assembly* object to be used to quantify shop LCEE and LCMC.

6.3.3.3 Shop

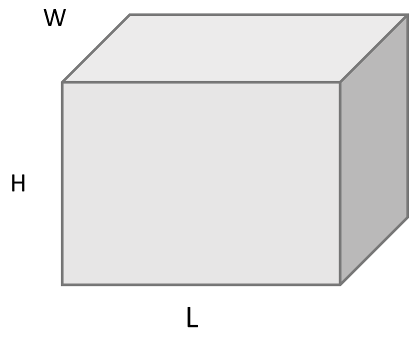
The *Shop* class is the largest in the computing core. It has 27 different methods to compute different variable values and to create shop objects. At the *Shop* class, data are imported from the two databases of *Shops* and *Shops_catalogue*. As in the *Assemblies* class, the *Shop* class creates *Shop* objects based on shops defined in databases. When creating a *Shop* object, an auto-generated BOQ of each shop is prepared and stored in the object. Quantity calculations are performed based on the parametric values of the shops defined in the *Shops* database. The primary three geometry values are used to calculate quantities of building elements. The quantification process is further explained in detail in Section 6.4. The quantities generated are used to quantify IEE, REE and LCEE. Similarly, financial flow is calculated. Energy flow calculations are done using the quantities of each element and the assembly EEC of each assembly used to construct the building element as defined in the *Shops_catalogue* database. As each shop has a shop type ID and each shop type has a default pre-defined most common assembly combination for the construction of building elements of the shop, these data are used to access the EEC of the assemblies used in the shop. Quantities of each building element and the EEC of the assembly ID defined in the *Shops_catalogue* database is used to calculate energy figures. Shop class quantifies LCEE and LCMC by aggregating values of different assemblies in the shops. Life cycle embodied greenhouse gas emissions (LCEGHGE) are also calculated based on the LCEE values, which are later converted to monetary values using carbon tax component.

6.3.3.4 ShoppingCentre

The class *ShoppingCentre* is at the core of the model since it generates the results. Different shopping centres in the database are created into objects at the shopping centre class level, and finally, LCEE and LCMC are calculated. Implications of carbon tax are also assessed in terms of LCEGHGE. The *ShoppingCentre* class uses the objects created at the *Shop* class to extract energy and cost figures of different shops in the shopping centres. Since the *Shop* class creates the BOQ and LCEE and LCMC of each shop, the *ShoppingCentre* class simply sums the existing values of its contributing shops.

6.4 SAMPLE CALCULATION PROCESS OF THE LIFE CYCLE EMBODIED ENERGY AND LIFE CYCLE MATERIAL COST OF A SHOP

This section provides details of a sample of a typical LCEE calculation process of a shop performed in the model.



Consider a clothing shop; ID: CL_01 of L = 12; W = 10; H = 4

The *Shops* database defines this shop with geometry values and shop type. When the shop ID is provided as input to the model, it retrieves the data for the clothing shop type. The data on the types of assemblies used in the shop are extracted from *Shops_catalogue* data frame in the *Shop* class.

Therefore, the CL_01 shop has the assemblies of IW for internal wall, WF for wall finish, FF for floor finish and CF for ceiling finish. All other assembly types contain void assemblies. So, in the *Shop* object LCEE of CL_01 is calculated as follows.

$$LCEE_{CL\_01} = LCEE_{IW} + LCEE_{WF} + LCEE_{FF} + LCEE_{CF}$$

Where,

$LCEE_{CL\_01}$ = *Life cycle embodied energy of CL_01 shop, in GJ*

$LCEE_{IW}$ = *Life cycle embodied energy of the internal wall of CL_01 shop, in GJ*

$LCEE_{WF}$ = *Life cycle embodied energy of the wall finishes of CL_01 shop, in GJ*

$LCEE_{FF}$ = *Life cycle embodied energy of the floor finishes of CL_01 shop, in GJ*

$LCEE_{CF}$ = *Life cycle embodied energy of the ceiling finishes of CL_01 shop, in GJ*

For demonstration purposes $LCEE_{FF}$ quantification process is considered.

$$LCEE_{FF} = IEE_{FF} + REE_{FF}$$

Where,

IEE_{FF} = *Initial embodied energy of the floor finishes of CL_01 shop, in GJ*

REE_{FF} = *Recurrent embodied energy of the floor finishes of CL_01 shop, in GJ*

$$IEE_{FF} = EEC_{FF} \times Q_{FF}$$

Where,

EEC_{FF} = *Embodied energy coefficient of the floor finish assembly, in GJ/unit*

Q_{FF} = *Quantity of the floor finish assembly, in CL_01 shop, in units*

To quantify IEE_{FF} ; IEE of floor finish assembly, EEC of assembly FF and quantity of assembly FF in CL_01 shop are required.

EEC_{FF} is retrieved from the *Assemblies* class. To calculate EEC_{FF}, the *Assemblies* class uses data inputs from the *Materials* class.

$$EEC_{FF} = \sum_{m=1}^{M} EEC_m \times Q_m$$

Where,

EEC_m = *Embodied energy coefficient of the materials in floor finish assembly, in GJ/unit*

Q_m = *Quantity of the materials in floor finish assembly, in CL_01 shop, in units*

Considering assembly FF consists of two materials as m1 and m2 with quantities q1 and q2,

$$EEC_{FF} = (EEC_{m1} \times q1) + (EEC_{m2} \times q2)$$

Where,

$q1$ = *Quantity of the material m1 in floor finish assembly, in units*

EEC of materials m1 and m2 are obtained from the *Materials* class and the quantities q1 and q2 are taken from the Assemblies class. Then EEC_{FF} is calculated and stored in the *Assemblies* class.

The quantity of FF assembly Q_{FF} is calculated using the geometry values in the *Shop* class and stored in the BOQ of the *Shop* object.

$$Q_{FF} = L \times W$$

Where,

L = *Length of the shop, in m*

W = *Width of the shop, in m*

Therefore IEE_{FF} is calculated using the above values. The calculation of REE_{FF} uses the IEE_{FF} value stored in the *Shop* object along with the replacement rate; RR.

$$REE_{FF} = IEE_{FF} \times RR$$

Where,

RR = *Replacement rate of the floor finish in the shop, in years*

RR is quantified using the refurbishment frequency of the *Shop* object, the service life value of the *Assembly* object and the period of analysis of the *ShoppingCentre* object.

$LCEE_{FF}$ is calculated using IEE_{FF} and REE_{FF}. Similarly, $LCEE_{WF}$, $LCEE_{IW}$, and $LCEE_{CF}$ are quantified and summed to obtain the $LCEE_{CL\_01}$

A similar process is used to quantify LCMC of the shops and shopping centres in the model.

6.5 IMPACT OF CARBON PRICING ON THE SELECTION OF BUILDING MATERIALS AND ASSEMBLIES

The model analyses the impact of carbon pricing on building materials selection as well. A carbon tax or carbon pricing is the application of a tax scheme based on the carbon emissions. In the model, LCEGHGE are considered for tax purposes. To quantify the carbon tax throughout the life cycle, first, the total amount of EGHGE needs to be measured. A conversion factor is used to convert embodied energy to EGHGE values. Considering the conversion factor for life cycle embodied GHG emission is 58.78 kg CO_2e/GJ (Langston et al., 2018), the LCEGHGE are calculated for shops and shopping centres. The carbon tax scheme was introduced in 2012 in Australia and repealed in 2014. According to clean energy regulator, carbon price in the 2013–2014 financial year was AU$ 24.15 per tonne CO_2 emissions. This figure is used in the model factoring in annual escalation of 1.9 % and as for the financial year 2019-2020, the carbon price is estimated as AU$ 32.36. Using this value, the model quantifies the total LCMC variable with carbon tax with an annual real price escalation rate of 1.9 %.

6.6 THE CALCULATION PROCESS OF MATERIAL QUANTITIES

The preparation of a BOQ is crucial for embodied energy and financial flow calculations over the life cycle of a building. At the shop level, the generation of a BOQ is the most significant aspect since the quantities of building elements are the key inputs for energy and cost calculations. In the *Shop* class, BOQ are created using the basic geometry of parametric shop designs described in Section 6.3.3.3. This process is critical since the quantification of building elements can affect the ultimate findings of the study. Furthermore, this automated BOQ generation provides the researcher ease of quantification and 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. Selected quantities of assemblies which are calculated using this process are listed below in Table 6.7. For the complete detailed list, please refer to Appendix 11.

Table 6.7: Details of quantity variables defined in the Shop class of the object-oriented model

Variable name	Unit	Data type	Description
quantity_gross_floor_area	m^2	float	Gross floor area of the building
quantity_foundation	m^2	float	Area of the foundation
quantity_column	m	float	Quantity of the column in linear m

Different quantity variables are used to quantify different building elements. All building elements are quantified using the fundamental geometry values of the shops. However, the reliability of the results generated through the automated BOQ process needed to be checked. Therefore, a BOQ for a single case study was prepared manually by the researcher and the automated values are compared with the real values. The relative error limit was set at ±10%. If the automated values are within the margin they are considered accurate, and if not, modifications are carried out to alter the quantification algorithms presented in Section 6.6.

Each element is quantified using a different algorithm using the geometric variables of length, width, height or span. The location of each shop is considered when quantifying building elements as it would affect the quantities. Based on the location each shop would be designed with either one or two sides of internal walls. The calculation of the quantities of building elements based on the main building components is presented under the following headings.

6.6.1 Structural elements

The structural elements of a shop consist of foundation, column, roof structure and structural wall. However, in the model it was established that only the *centre structure* (CS) shop type has structural elements. As mentioned in the previous sections, a shopping centre is combined as main components: shell and the internal fit-outs. The shell is considered as an individual shop type, and the internal fit-out is considered as other shops. Hence the structural element calculation is only carried out when shop type id starts with 'CS'. If not, the quantities for structural elements are considered as zero.

6.6.1.1 Foundation quantity

The quantity of foundation of a shop is considered equal to the gross floor area of a shop. This method is used to ease the process of calculation of foundation quantities and to minimise the arithmetical errors. It is a complicated process since any foundation is typically inclusive of many sub-elements that are measured in different units of measurements. Therefore, in this model, the foundation is considered as a whole system inclusive of all sub-elements. For instance, all building material components with their respective quantities to form a unit quantity (m^2) of a slab on grade foundation system are as follows.

Specification:

Foundation type 1: Concrete foundation (slab-on-grade) 150 mm thick provide SL92 fabric top, poured on PVC damp proof membrane lapped and tapped at joints on 50 mm bedding sand with left in formwork. Pad footings to be 2300 mm × 2300 mm × 500 mm with N169-250 mm each way. Strip footings to be 450 mm × 400 mm with 4L11-TM10 top and bottom, and R10-45011 ties. Concrete grade: N32.

The foundation quantity for the entire system was calculated manually using the shopping centre geometry values of the average shopping centre case study (length:280 m, width:88 m). The material quantities of concrete for foundation slab and ground beams, reinforcement and formwork for concrete, insulation and damp-proof membrane were included in the assembly. Then per unit area quantities were calculated by dividing the total quantities of materials by foundation surface area (280 m × 88 m). Those quantities were entered as material quantity inputs in the *Assemblies* database.

For all three foundation systems, the manual calculations were carried out, and the assembly EEC and unit prices were quantified by the model per unit area of the foundation surface. Those per square meter values were then used to quantify the LCEE and LCMC. The unit of measurement for foundation is therefore in square metres (m^2). The quantity of foundation is obtained using the following Equation 6.1.

Equation 6.1: Algorithm for calculating gross floor area of a shop

$$GFA_S = l_S \times w_S$$

Where;

GFA_S =*Gross floor area of the shop S, in* m^2

$l_S =$ *Length of the shop S, in m*

$w_S =$ *Width of the shop S, in m*

Equation 6.2: Algorithm for calculating foundation quantity of a shop

$$QFD_S = GFA_S$$

Where,

QFD_S = *Quantity of foundation of the shop S, in* m^2.

6.6.1.2 Column quantity

The average span is used to calculate the quantity of columns in the shop. Only if either the length and/or width of the shop are separately greater than the span of the shop, the shop is considered to have columns. The calculation is staged as follows. The number of columns is counted along the length and width of the shop, and then the total lengths of columns are calculated by multiplying the count by the height of the shop. The quantity of columns is measured in linear meters (m).

Equation 6.3: Algorithm for calculating the number of columns along the length of a shop

$$CAL_S = \frac{w_S}{s_S}$$

Equation 6.4: Algorithm for calculating the number of columns along the width of a shop

$$CAW_S = \frac{l_S}{s_S}$$

Where,

$CAL_S =$ *Number of columns along the length of the shop S*

$CAW_S =$ *Number of columns along the width of the shop S*

$s_S =$ *Span of the shop S, in m*

$h_S =$ *Height of the shop S, in m*

Equation 6.5: Algorithm for calculating the column quantity of a shop

$$QCL_S = CAL_S \times CAW_S \times h_S$$

Where,

QCL_S = *Quantity of columns of the shop S, in m.*

6.6.1.3 Roof quantity

The roof is one of the most complex items in buildings. However, in this model, the roof element is considered to have a limited number of geometrics similar to the foundation quantities calculations. In the *Assemblies* database quantities of the building materials required to form a unit quantity of the roof structure and coverings are included. It also has reflective insulation installed to reduce radiant heat gain. For instance, the assembly steel truss roof includes the sub-elements of roof trusses and other roof structural components, roof covering, roof beams and any other sundry items.

Specification:

Roof structure with steel beams 530UB92, purlins C30024, bracings and steel truss and Colourbond sheets (530UB92 primary beams at 9.4 m along 240 m length, C30024 purlins at 1.2 m along 87.5 m width, laps added 900 mm at 6 m lengths of purlins).

Similar to the foundation quantity calculations, the total quantities of materials required to construct the roof assemblies for the average case study shopping centre were calculated. Quantities per unit flat roof area were then obtained. Hence, the quantity of roof is taken to be equal to the quantity of foundation and is measured in square metres (m^2).

Equation 6.6: Algorithm for calculating the roof quantity of a shop

$$QRS_S = QFD_S$$

Where,

QRS_S = *Quantity of roof of the shop S, in* m^2

QFD_S = *Quantity of foundation of the shop S, in* m^2

6.6.2 Envelope elements

The envelope elements considered in the model involve structural walls, internal walls, windows, lintels and waterproofing where defined. At least one of these elements is included in all the shop types defined in the study. As for the structural elements, the calculations are conducted based on the shop type. This is because different types of shops have different settings of the elements and the calculations need to be tailored to accept those differences.

6.6.2.1 Structural wall quantity

Structural walls are components of *centre structure* and anchor shop types. Both the supermarket and discount department store shops are considered to have external structural wall components. Structural walls are considered with all the insulation (within cavities, within stud frames, on the outside of stud frames, on the inside or outside of solid walls), bracings and moisture retainers (considering wind loads and other loads). Calculating the quantity of structural walls is carried out in two stages. First, the total quantity of the wall area is calculated without any deductions for openings.

Equation 6.7: Algorithm for calculating gross structural wall area quantity for centre structure shop type

$$GSW_{S_{CS}} = \left(l_{S_{CS}} + w_{S_{CS}}\right) \times 2 \times h_{S_{CS}}$$

Where,

$GSW_{S_{CS}} =$	*Gross structural wall quantity of the centre structure shop, in m²*
$l_{S_{CS}} =$	*Length of centre structure shop, in m*
$w_{S_{CS}} =$	*Width of centre structure shop, in m*
$h_{S_{CS}} =$	*Height of centre structure shop, in m*

However, for *anchor shops*, *structural wall* quantity calculation involves only two sides of wall components considering they are located at corners of the shopping centre as demonstrated in Figure 6.4.

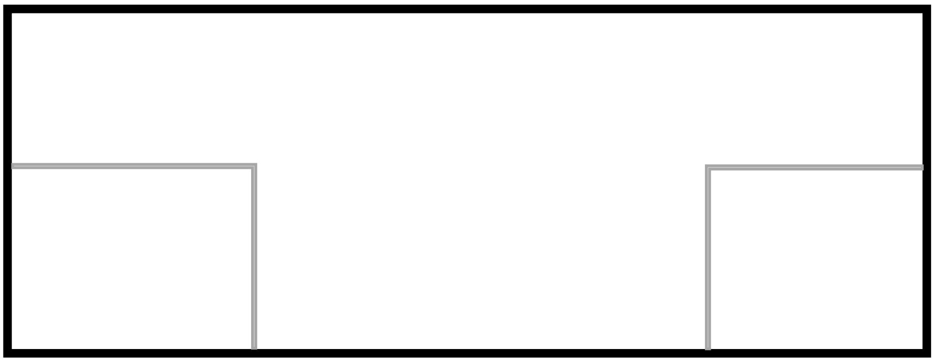


Figure 6.4: Location of anchor shops in the shopping centre: Demonstration for structural wall quantity calculation purpose in the model

Therefore, the quantification algorithm for gross structural wall area of anchor shops is as follows.

Equation 6.8: Algorithm for calculating gross structural wall area quantity for anchor shop types

$$GSW_{S_A} = \left(l_{S_A} + w_{S_A}\right) \times h_{S_A}$$

Adjustments are then made to the gross quantity to account for openings. Openings can be considered as any open areas in the structural wall of the building as shop front openings, openings for doors and windows, or any display items. The opening in structural wall quantity is considered as 10% of the floor area of the shop as per the standard of the Australian Building Codes Board (2015) for the minimum requirement for lighting and ventilation. Hence, the opening area calculation is followed by the equation below, measured in square metres (m^2).

Equation 6.9: Algorithm for calculating wall opening area quantity of centre structure and anchor shops

$$OSW_S = (0.1 \times GFA_S)$$

Where,

$OSW_S =$ *Opening structural wall quantity of the shop S, in m^2*

$GFA_S =$ *Gross floor area quantity of the shop S, in m^2*

Finally, the quantity of the structural wall area of a shop is quantified using the following equation.

Equation 6.10: Algorithm for calculating structural wall quantity of centre structure and anchor shops

$$QSW_S = GSW_S - OSW_S$$

Where,

$QSW_S =$ *Quantity of structural wall of the shop S, in m^2.*

6.6.2.2 Internal wall quantity

Calculating the quantity of internal walls of different shops is a lengthy programmatic process since the quantities of internal walls of shops differ based on the location of the shops in the shopping centres. Hence the calculation is presented here for shops with two sides of internal walls. The following demonstration of shops in the shopping centres is used to quantify the internal wall quantities based on the shop locations.

Based on the shop layout in Figure 6.5, two types of shop internal wall combinations were identified (blue colour-with two internal wall components; red colour-with one internal wall component).

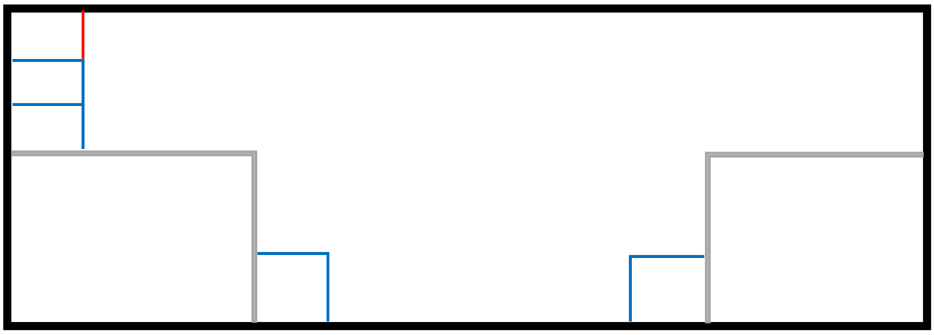


Figure 6.5: Possible locations of shops in the shopping centre: Demonstration for internal wall quantity calculation purpose in the model

However, the majority of the shops were considered to have internal walls with two sides of length and width. Therefore, the calculation process of the shop internal walls is considered as follows, measured in square metres (m^2).

Equation 6.11: Algorithm for calculating gross internal wall area quantity of a shop

$$GIW_S = (l_S + w_S) \times h_S$$

Where,

$GIW_S =$	*Gross internal wall area of a shop S, in m^2*
$l_S =$	*Length of a shop S, in m*
$w_S =$	*Width of a shop S, in m*
$h_S =$	*Height of a shop S, in m*

Adjustments were carried out to account for openings for doors (shops are considered not to have any other opening, except for *centre structure*). The opening is considered to be 10% of the floor area, as mentioned in Section 6.6.2.1 as per the Australian Building Codes Board (2015).

Equation 6.12: Algorithm for calculating net internal wall area quantity

$$QIW_S = GIW_S - (0.1 \times GFA_S)$$

Where,

$QIW_S =$	*Quantity of internal wall area of a shop S, in m^2*

However, as mentioned earlier, internal wall quantity calculations are subjected to several conditions, respective locations, and layout of the shops.

6.6.2.3 Window quantity

The quantity of window areas in the shops was calculated using the opening to wall ratios defined in Section 6.6.2.1. Windows are considered only as a part of the *centre structure* shop type. Following equation 6.13 represents the quantification algorithm for windows, measured in square metres (m^2).

Equation 6.13: Algorithm for calculating window quantity

$$QWI_S = (0.1 \times GFA_S)$$

Where,

$QWI_S =$	*Quantity of window area of a shop S, in m^2*
$GFA_S =$	*Quantity of gross floor area of a shop S, in m^2*

6.6.2.4 Lintel quantity

The process of calculating the quantity of lintels in *centre structure* shop type incorporating the quantity of window areas. Equation 6.14 was used to quantify lintels, measured in linear metres (m).

Equation 6.14: Algorithm for calculating lintel quantity

$$QLI_S = (QWI_S / h_S)$$

Where,

$QLI_S =$ *Quantity of lintel of a shop S, in m*

$QWI_S =$ *Quantity of window area of a shop S, in* m^2

$h_S =$ *Height of a shop S, in m*

6.6.2.5 Waterproofing quantity

The quantification of waterproofing quantity was carried out for toilets and sanitary shop types only. Equation 6.15 was used to quantify waterproofing, measured in square metres (m^2).

Equation 6.15: Algorithm for calculating waterproofing quantity

$$QWP_S = GFA_S$$

Where,

$QWP_S =$ *Quantity of waterproofing of a shop S, in* m^2

$GFA_S =$ *Gross floor area of a shop S, in* m^2

6.6.3 Finishing elements

Shop finishes were also calculated using shop geometries. Three types of finishes were included in the model: wall finish, floor finish and ceiling finish. All shops have at least one of these finishes. The *centre structure* shop is considered to have a structural wall finish, whereas, for other shops, the internal wall is finished. The algorithm for calculating wall finishes in shops is presented in the next section.

6.6.3.1 Wall finish quantity

The gross wall finish quantity is calculated using the length, width and height of the shop, measured in square metres (m^2). Since the geometries of the shops are considered the centre line measurements, direct geometry values are used in the quantifying process. As mentioned earlier, the internal wall finishes of shops are considered as wall finish in all shop types except for the *centre structure* where the external finish is considered as the wall finish quantity.

Equation 6.16: Algorithm for calculating gross wall finish quantity of Scenario 1 in Figure 6.6

$$GWF_S = (l_S + w_S) \times 2 \times h_S$$

Where,

$GWF_S =$	*Gross wall finishes quantity of Scenario 1 shops, in m²*
$l_S =$	*Length of Scenario 1 shops, in m*
$w_S =$	*Width of Scenario 1 shops, in m*
$h_S =$	*Height of Scenario 1 shops, in m*

Adjustments are made to account for openings in the wall areas. Furthermore, the small quantities of rebates and sides of openings are not included in the quantities but covered under unit prices of the assemblies.

Equation 6.17: Algorithm for calculating net wall finish quantity of Scenario 1 in Figure 6.6

$$QWF_S = GWF_S - (0.1 \times GFA_S)$$

Where,

$QWF_S =$	*Quantity of wall finishes of Scenario 1 shops, in m²*
$GFA_S =$	*Gross floor area quantity of Scenario 1 shops, in m²*

Figure 6.6 demonstrates the different shop settings used to quantify wall finish quantities.

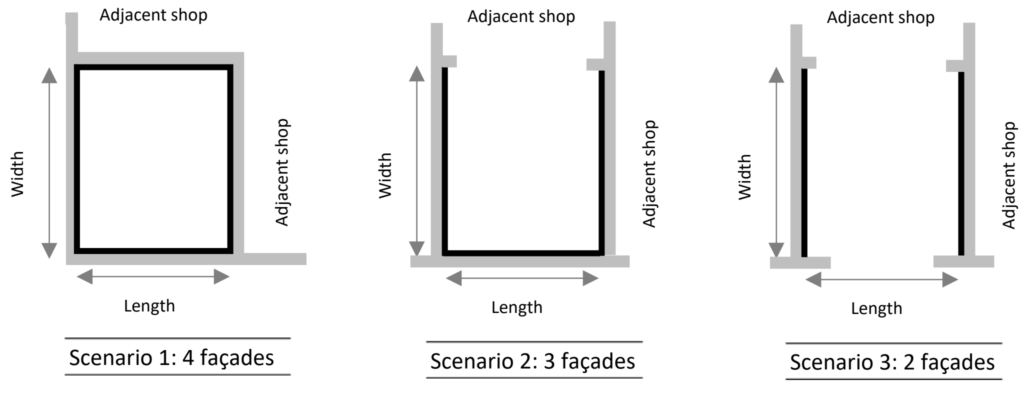


Figure 6.6: Demonstration of wall settings for wall finishes quantifying algorithm selection in the model

Table 6.8: Algorithms for wall finish quantities of other wall setting scenarios

Scenario	**Algorithm for quantity of wall finishes (QWF_S)**
Scenario 2	$(l_S + 2w_S) \times h_S$
Scenario 3	$2w_S \times h_S$

Algorithms for different shop types are presented in Table 6.8, based on the shop settings in the above figure. The appropriate algorithms are selected based on the locations of the shops in the shopping centre layout.

6.6.3.2 Floor finish quantity

The quantity of floor finishes is calculated using the length and width geometries of a shop. Unit of measurement is square metres (m^2). All shop types except the *centre structure* are considered to have the floor finish assembly type since floor finishes of other shops cover it.

Equation 6.18: Algorithm for calculating floor finish quantity

$$QFF_S = l_S \times w_S$$

Where,

$QFF_S =$ *Quantity of floor finishes of the shop S, in* m^2

$l_S =$ *Length of the shop S, in m*

$w_S =$ *Width of the shop S, in m*

6.6.3.3 Ceiling finish quantity

The ceiling finishes quantity is obtained by multiplying the shop length and width. Ceiling finishes are considered to have insulation between the joists to reduce heat gain and loss. Hence ceiling quantity is as floor finish quantity and measured in the same unit.

Equation 6.19: Algorithm for calculating ceiling finish quantity

$$QCF_S = QFF_S$$

Where,

$QFF_S =$ *Quantity of floor finishes of the shop S, in* m^2

$QCF_S =$ *Quantity of ceiling finishes of the shop S, in* m^2

The automated BOQ is generated based on these algorithms in Python programming script and are stored in shop objects. Once shop objects are created with BOQs for the default scenario of assembly combinations, the next step is to develop the alternative assembly scenarios for different shop types. This process is described in the subsequent section.

6.7 COMBINATIONS DEVELOPMENT

This section details the process of developing alternative building assembly combinations for different shop types. The research aim was to identify combinations of assemblies for shopping centres with minimum LCEE and LCMC for subregional shopping centres. As described in Section 6.3.3.3, each shop object developed in the model consists of combinations of assemblies to construct its default scenario. However, to unveil the best combinations with minimum LCEE and LCMC, all possible alternative combinations of assemblies are required. The process of developing assemblies combinations was carried out using specific functions in Python such as a *list of lists* and *itertools.product*. Shop-assembly compatibility matrix and assembly compatibility matrix were compiled and used in the process of developing alternative combinations, which are further discussed in Section 6.7.

From an arithmetical perspective, this study relies on permutations, not combinations. A permutation is defined as an arrangement of objects in a certain order (Bóna, 2012). The order in which they are arranged is crucial. Mathematically, the number of permutations on a set of *n* elements is denoted by *n!* (i.e. for 5 elements, 5! = 120). For each shop type defined in the *shops_catalogue* database (see Section 6.3.3.3), a list of all possible permutations of different assembly mixes are created. For different shop types different numbers of permutations are generated based on the number of assemblies that can be used in each element in the shop. The possible assemblies for each shop type are obtained through industry document analysis, empirical data through observations at case study sites, and details provided by material suppliers. A demonstration of a sample shop type is presented below in Table 6.9.

Table 6.9: Demonstration of assemblies of different types for clothing shop type to develop assemblies combinations

Shop type	Assembly type	Identification numbers	Number of assemblies
Clothing	Ceiling finish	CF01, CF02, CF03, CF04, CF05, CF06	6
	Column	CL03	1
	Structural wall	EW04	1
	Floor finish	FF01, FF05, FF06, FF11, FF12	7
	Foundation	FD04	1
	Internal wall	IW01, IW02, IW03, IW04, IW05, IW06	6
	Lintel	LT04	1
	Roof structure	RS03	1
	Wall finish	WF02, WF04, WF06, WF07, WF09, WF10	6
	Window	WD03	1
	Waterproofing	WF02	1

All possible assemblies that can be used in a building element in a clothing shop are entered in a list of assemblies list. Lists of assembly types that go into different shops were created. These lists are created based on the shop assembly compatibility matrix. Once the final list of lists is created for a shop type, alternative scenarios are created and saved to a CSV file.

While creating permutations of assembly mixes for each shop type, the possible scenarios are run through constraint matrices to assess reliability and reality aspects of the model are met. The constraint matrices are linked to the model in the form of matrices that scan all permutations generated for a shop type and remove any impossible permutations, based on the constraints (Section 6.8). Only the clean permutations are exported into CSV files.

The 'clean' permutation files are imported to the model, and the LCEE and LCMC are calculated for each alternative scenario using the assembly EEC and assembly unit prices of each element. The constraint matrices mentioned above are explained in detail under the next heading.

6.8 CONSTRAINTS OF THE MODEL

Any mathematical model has restrictions to its process where the behaviour and state of the inputs are restricted using pre-defined constraints (Caldwell & Douglas, 2004). These constraints can be in any form and can profoundly affect the results of the model. None of the real-life problems are unconstrained (Heiliö, 2016), nor are the problems studied in this research. When developing permutations of assemblies or alternative scenarios, only the shop assembly compatibility is used as a constraint. Assembly compatibility constraints are further added to the alternative scenarios pool as filters. In the model, while developing assembly scenarios for each shop type, assembly compatibility constraints and shop assembly compatibility constraints are incorporated.

The shop assembly compatibility matrix is a database which stores data on the compatibility of each assembly with different shop types (see Table 6.10 for a sample shop type).

Empirical observations show that different types of shops have different types of assemblies, used to construct different elements based on the business profile, the scale of the shop and target customer niche. Hence, the selection of assemblies for each shop type is constrained when developing permutations. The shop assembly compatibility matrix is created to define the assemblies that can be used in different types of shops for different assembly types. The matrix has the potential to input up to 10 assembly IDs for an individual assembly type. The complete matrix consists of 12 columns and 177 rows of data points.

For instance, for shop type 'Household' all assemblies for each assembly type that can be used are defined. Each assembly type can have up to 10 different assembly IDs from assembly_id0 to assembly_id9, as demonstrated in Table 6.10. It provides a fraction of the entire database for a single shop type (The complete database is available in Appendix 8).

Table 6.10: Sample of shop assembly compatibility matrix

Shop type	Assembly type	Assembly ID0	Assembly ID1	Assembly ID2	Assembly ID3	Assembly ID4	Assembly ID5	Assembly ID6	Assembly ID7	Assembly ID8	Assembly ID9
Household	Ceiling finish	CF01	CF02	CF03	CF04	CF05	CF06				
	Column	CL03									
	Structural wall	EW04									
	Floor finish	FF01	FF02	FF03	FF04	FF05	FF06	FF07			
	Foundation	FD04									
	Internal wall	IW01	IW02	IW03	IW04	IW05	IW06				
	Lintel	LT04									
	Roof structure	RS03									
	Wall finish	WF02	WF03	WF04	WF06						
	Window	WD03									
	Waterproofing	WP02									

The first set of permutations was developed based on this matrix, followed by filtrations according to the assembly compatibility matrix.

The assembly compatibility matrix is a database defining the structural compatibility of assemblies with each other (refer following Table 6.11 for the structure of the database).

Table 6.11: Sample demonstration of the assembly compatibility matrix used in the model

	RS01	**RS02**	**RS03**	**CF01**	**CF02**	**CF03**	**CF04**	**CF05**	**CF06**	**CF07**
RS01	TRUE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
RS02	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
RS03	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
CF01	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
CF02	TRUE	TRUE	TRUE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
CF03	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE
CF04	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE
CF05	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
CF06	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
CF07	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE

As mentioned in the table, the compatibility of an assembly with all other assemblies are stated in the matrix. For instance, three possible assemblies can be used to construct the roof of the shopping centre (identified as RS01, RS02 and RS03). If in a shop type one of these assemblies is used, then other roof structure assemblies cannot be used since the roof structure is already constructed. Other than being the same assembly type, there are situations where assemblies are incompatible with each other, i.e. roof structure with timber beams is not compatible with glue-laminated timber columns. All these incompatibilities are entered in the matrix to provide a more realistic set of solutions. The complete matrix consists of 64 × 64 datapoints (full matrix is attached in Appendix 12).

Permutations developed incorporating these constraint matrices are stored in CSV files as 'clean' combinations. The alternative shop scenarios created based on permutations are also created as objects in the model and LCEE and LCMC are calculated. These alternative shop objects are analysed to discover the minimum LCEE and LCMC scenarios at the shop level and shopping centre level.

6.9 FINDING MULTI-OBJECTIVE OPTIMAL SOLUTIONS

The research problem contains three objective functions to be resolved. Minimising LCEE, minimising LCMC, and minimising both the LCEE and LCMC of subregional shopping centres in Australia. The scenarios responsible for minimum LCEE and LCMC of shop types are obtained by sorting the LCEE and LCMC values of shop objects to find the minimum. Since the model quantifies LCEE and LCMC for all scenarios of all shop types following the processes mentioned above, the shop objects carry the values of the objective variables that need to be minimised. Therefore, finding the combinations achieving objective functions 1 and 2 stated in Section 4.7.7.1 is straightforward.

However, unveiling multi-objective optimal solution achieving objective function three is complicated. The research follows Pareto frontier development with the weighted sum method (WSM) to find the optimal solution as described in Section 4.7.7.4. Since the objective function values have been calculated in Python objects (shops and shopping centres), the Pareto front was drawn using those values. The following Figure 6.7 shows the use of WSM method to find the most preferred solution on the Pareto frontier based on the decision maker's preference.

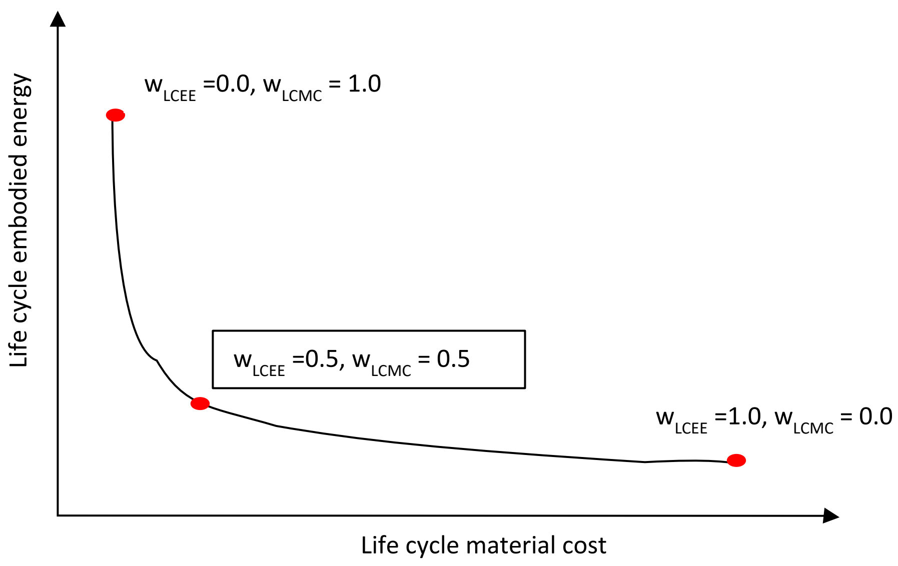


Figure 6.7: Sample Pareto frontier display to demonstrate the process of finding the optimal solution on the graph

The two axes in the graph are LCEE function values and LCMC function values. Then the calculated points are located from a scatter diagram, and the line that is fitted to the points is taken as the Pareto front. The Pareto frontier is considered the best to find the optimal solution for objective function 3 using WSM if it is convex, minimising both functions. As for this study, both objective functions were minimisations and therefore were suitable for the method carried out. Following this process, multi-objective optimal solutions are found for shop and shopping centre scenarios.

6.10 VERIFICATION OF MODEL RESULTS

The results generated from the model were verified at different stages to increase their accuracy and transparency. The verification of the results generated is a critical step in any mathematical model development. The details on model verification are provided below.

6.10.1 Shop quantities

Quantities in the automated BOQ were verified using a manually created BOQ for a case study shopping centre. The researcher's competency as a professional quantity surveyor was advantageous and effective to this end. The results of the automated BOQ were compared with the real values to check discrepancies between the quantities. The relative error limit was set at ±10%. If the automated values were within the margin they were considered accurate, and if not, modifications were carried out to alter the quantification algorithms demonstrated in Section 6.6.

6.10.2 Shop embodied energy and material cost

As the second step of the verification process embodied energy figures at the shop level were verified. IEE, REE and LCEE are calculated manually for ten randomly selected shop permutations, and results were cross-checked with the answers generated by the model. The relative error limit was set at ±10%. If the automated values were within the margin they were considered accurate, and if not, the model process is scanned for any possible mistakes and revised accordingly. In all cases, it was made sure that the difference between the model-generated results and the manual results is lower than ±10%. When verifying recurrent embodied energy (REE) figures, replacement rates were also verified.

A similar process was conducted to verify material cost results of the model. Verification of material cost-in-use included confirming the net present value figures generated in the model as well. The replacement factor calculation based on the growth rate and interest rate, as mentioned in Sections 4.7.3.2 and 4.7.4.2, was also verified.

6.10.3 Use of case studies for verification

The model results are generated for case study shopping centres. Case study 2 and 3 were selected to compare the embodied energy and material cost values over the life cycle based on gross lettable area (GLA), size and number of shops in the shopping centre. Case study 2 and 3 were referred to as the 'small' and the 'large' shopping centres, respectively. Shops from all three case studies were also used for the verification process of the model for increased precision and accuracy.

However, the designs of the modelled case study shopping centres did not follow the same layout and design of the actual building. Several modifications were made in the designs to simplify the creation of automated shop BOQ (rectangular shaped shops and shopping centres – shoe-box scenario). Comparative shopping centre floor plans are attached in Appendix 13. Nevertheless, the tenant mix, GLA and the volume of building materials and assemblies of the shopping centres were maintained as with the actual shopping centres. Only the locations of the shops were slightly changed to represent a less complicated, more typical rectangular-shaped building. The quantities of the shops might be different from the actual scenarios, yet the results are comparable since the tenant mix and GLA proportion were maintained throughout the process.

The verification of the results is critical for the reliability of the model. Once the results were verified and necessary adjustments are made to the model to generate outcomes as reliable and comprehensive as possible, the model development was completed. Then results generated are analysed to discuss the significance and to ascertain the aim and the objectives of the study are achieved.

6.11 SUMMARY

This chapter discussed the process of mathematical model development using OOP in Python and verified the developed model. The use of Python as the programming language, OOP as the programming paradigm, development and reliance on databases, and computing core are the key features of the model. The interactions between the databases and the computing core is the primary function of the model. This reliance on databases provides ease of access to data and greater flexibility to the model and potential for future advancements.

The process of verification involved verifying the data inputs, algorithms used in the model, and the results generated. Arithmetical consistency of the algorithms was tested, and the calculations were compared with manual workings. The deviations of model calculations from the manual calculations were verified to be less than 0.001%.

The model was then used to answer the research question of '*how can building material and assembly selection reduce life cycle embodied energy and material cost of shopping centres in Australia?'*. The process of LCEE and LCMC quantification and development of permutations of shops and shopping centre scenarios are the most critical characteristics of the model alongside the application of constraint matrices to obtain more reliable and realistic results. With the previous research question being answered, the verified model can be used to analyse the impacts of material selection on embodied energy and material cost of subregional shopping centres and to evaluate potential assemblies combinations that can lead to reduced impacts. Therefore, using the model, the next few sub-research questions can be answered, as presented in Chapter 7.

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7 RESULTS AND ANALYSIS

7.1 INTRODUCTION

The previous chapter discussed the process of developing the model, stating the quantification methods of life cycle embodied energy (LCEE), embodied greenhouse gas emissions (LCEGHGE), and material cost with and without carbon tax (LCMCWT and LCMC), input attribute values, and possible visual outputs. This chapter aims to present the results generated for the three case study shopping centres used to test the model. These results are analysed at the assembly, shop and shopping centre levels, comparing the different scenarios to identify low embodied energy and material cost solutions and then interpreted in Chapter 8. This chapter starts with the results at the assembly level, which is the smallest unit of analysis in the study. Then analysis is presented at the shop level comparing different scenarios of different shop types in the shopping centres. Finally, shopping centre level analysis is offered with comparisons of different scenarios and establishing the relationships between LCEE and LCMC with gross lettable areas (GLA) of shopping centres.

7.2 ANALYSIS AT ASSEMBLY LEVEL

This section presents the results at the assembly level including embodied energy coefficients (EEC) and unit prices developed at the *Assemblies* class. Assembly types are differentiated under subcategories of structure, envelope and finishes as defined in Chapter 6. Structural assemblies include *foundation*, *column*, and *roof structure,* whereas the envelope consists of *structural wall* or *internal wall* based on the shop type, and *lintel* and *window*. The finishes category contains *floor finish*, *wall finish* and *ceiling finish*. Assembly EEC and unit prices are compared based on the types of assemblies to identify the best solutions with the lowest values. The analysis begins by comparing structural assemblies in the next section.

7.2.1 Structural assemblies

As described in Chapter 6, the structural assembly category includes *foundation*, *column* and *roof structure* as assembly types. As defined in the model, the *centre structure* is the only shop type that contains the structural assemblies. These structural assemblies have a significant impact on the LCEE and LCMC of the shopping centres. This effect is predominantly due to the initial embodied energy (IEE) and capital cost (CC), since most of these assemblies have a service life considered equal to the period of analysis of the building and therefore, replacements are not required. Selecting the optimal structural assemblies are significant to reduce LCEE and LCMC in shopping centres.

Table 7.1 shows the summary of the most used and environmentally responsive assemblies alongside their EEC and unit prices, quantified using the model.

Detailed assembly descriptions are presented in Appendix 4 (*Assemblies* database) with material inputs and their respective quantities in each assembly. Furthermore, assembly specifications are also provided stating the maximum pressure load requirements and other structural and architectural design requirements.

Table 7.1: Embodied energy coefficient and unit price of structural assemblies identified in the study

Assembly name	Assembly type	Unit	Assembly embodied energy coefficient (GJ/unit)	Assembly unit price (AU$/unit)
Concrete foundation (slab-on-grade)	Foundation	m^2	2.448	98.23
Waffle raft slab	Foundation	m^2	4.320	170.16
Concrete foundation (slab-on-grade) with 40% fly ash cement	Foundation	m^2	2.085	89.06
Glue-laminated timber columns	Column	m	0.057	47.72
Steel columns	Column	m	3.187	95.23
Roof structure with structural steel and Colourbond sheet covering	Roof structure	m^2	6.914	801.96
Roof structure with engineered and structural timber and Colourbond sheet covering	Roof structure	m^2	4.097	805.42

Figure 7.1 exhibits an overview of the EEC and unit prices of assemblies (excluding installation costs) in a comparative parallel coordinates graph. What stands out in Figure 7.1 is that among different structure assemblies, *glue-laminated timber (GLT) column* has the lowest EEC *(0.057 GJ/m^2)* and unit price *(AU$ 47.72 /m^2)*. The *engineered timber roof structure* is the only assembly that has a lower EEC *(4.097 GJ/m^2)* and higher unit price *(AU$ 805.42 /m^2)* and all other assemblies have higher EEC and lower unit prices.

Waffle raft slab has the highest EEC *(4.320 GJ/m^2)* and unit price *(AU$ 170.16 /m^2)* whereas *slab-on-grade with 40% fly ash cement* has the lowest *(2.085 GJ/m^2, AU$ 89.06 /m^2)*. The expanded polystyrene (EPS) form systems in waffle slabs provide better thermal insulation but contain highly detrimental GHG which increase embodied energy (Department of Industry Innovation and Science, 2016). On the contrary, the use of fly ash cement in the slab-on-grade reduces the embodied energy considerably. *Slab-on-grade with general purpose Portland cement* falls between and only differs by less than 10% from the lowest *(2.448 GJ/m^2, AU$ 98.23 /m^2)*. Therefore, *slab-on-grade with 40% fly ash cement* is identified as the best solution of the three options for shopping centres achieving both environmental and financial aspects of a project.

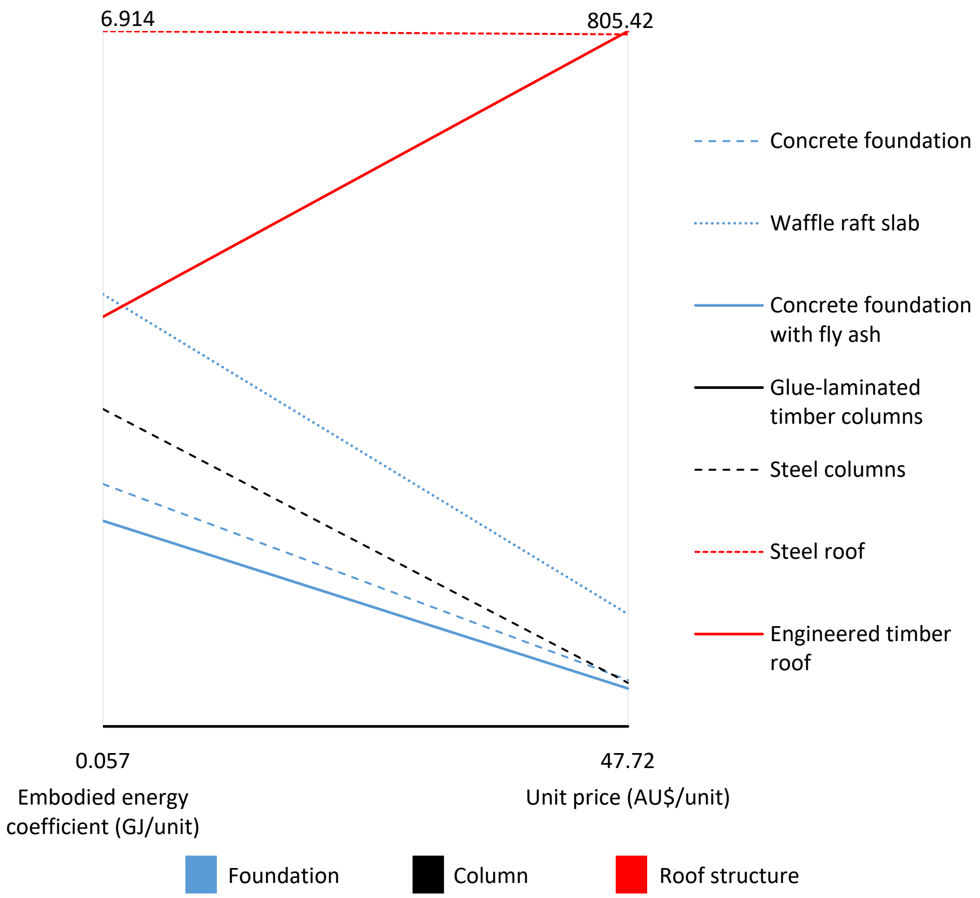


Figure 7.1: Parallel coordinates graph of embodied energy coefficients and unit prices of structural assemblies

Nevertheless, it should be noted that the model incorporates only material inputs for calculations, and if labour inputs were accounted for, these findings could change. For instance, waffle slab is considered as a cost-effective foundation system in terms of labour requirement due to minimal earthworks required and increased workability (Hes & Bates, 2003). The inclusion of labour inputs could alter the results yet is external to the scope of this research. However, the effect of labour input is discussed in Section 8.6.2 along with means to address this limitation in future research.

The comparison of *column* alternatives reveals that even though the industry is dominated by *structural steel* (ANCR, 2019; PCA, 2019), *GLT* is a better assembly solution both in terms of EEC and unit price. This engineered timber product is often adopted as a visually expressed, strong structural support in beams, columns, roof trusses and portal frames. Further details of *GLT* are discussed in Section 8.4.1.1, identifying its benefits and suitability for shopping centres. However, the use of *GLT* in shopping centres is not common as the Building Codes Australia only approved its use in Class 6 buildings (shops or shopping centres) in

2019. However, it is identified as a better alternative to *steel columns* and needs to be promoted among the developers.

Among alternative *roof structure* assemblies, the *steel roof structure* was found to have a lower unit price *(AU$ 801.96 /m^2)* when compared with the *timber roof structure (AU$ 805.42 /m^2)*. When EEC values are assessed, the *timber roof structure (4.097 GJ/m^2)* is preferred over the *steel roof structure (6.914 GJ/m^2)*. Therefore, the *steel roof structure* is proved more cost-efficient, but with a difference of just *AU$ 4 /m^2* against an embodied energy saving of *2.817 GJ/m^2*. Hence, the *timber roof structure* is recognised as a better solution to achieve substantial environmental benefits with only a minimal financial loss.

7.2.2 Envelope assemblies

The building envelope includes four different assembly types namely; *structural walls*, *internal walls*, *windows* and *lintels*. Only the *centre structure* and *anchor shops* are defined to have *structural walls* (refer Chapter 6). All other shop types have *internal walls*. The *centre structure* is also defined to have *windows* and *lintels* meeting the lighting and ventilation requirements. Table 7.2 provides the summary of EEC and unit prices (excluding installation costs) of the envelope assemblies.

Table 7.2: Embodied energy coefficients and unit prices of envelope assemblies identified in the study

Assembly name	Assembly type	Unit	Assembly embodied energy coefficient (GJ/unit)	Assembly unit price (AU$/unit)
Precast concrete wall panel	Structural wall	m^2	1.124	403.55
Insulated precast sandwich panel	Structural wall	m^2	1.319	378.35
Cross-laminated timber wall panel	Structural wall	m^2	1.285	464.04
Clay brick wall (110 mm)	Internal wall	m^2	0.535	41.82
Concrete block wall (140 mm)	Internal wall	m^2	0.807	53.88
Gypsum block wall (500 × 500 × 100 mm)	Internal wall	m^2	0.564	4.76
Steel stud frame wall (welded)	Internal wall	m^2	0.293	28.11
Calcium Silicate brickwork (110 mm)	Internal wall	m^2	0.481	73.93
Timber stud frame wall (90 × 45 mm)	Internal wall	m^2	0.409	36.18
Metal framed glass window	Window	m^2	7.386	117.17
Timber framed glass window	Window	m^2	7.162	119.74
Steel lintel (2400 × 150 × 100 × 6 mm galvanised angle)	Lintel	m	0.951	18.92
Concrete lintel	Lintel	m	0.312	12.69
Timber lintel	Lintel	m	0.011	0.44

Figure 7.2 presents the parallel coordinates plot of the envelope assemblies. Only the *timber lintel* has a low EEC and a unit price. *Cross-laminated timber (CLT) wall panel, precast concrete wall panel, insulated precast sandwich wall panel, calcium silicate brick wall, concrete block wall, clay brick wall, timber stud frame wall* and *steel stud frame wall* have low EEC and high unit prices. Furthermore, *timber framed glass window, metal framed glass window, steel lintel, concrete lintel and gypsum block wall* have high EEC and low unit prices.

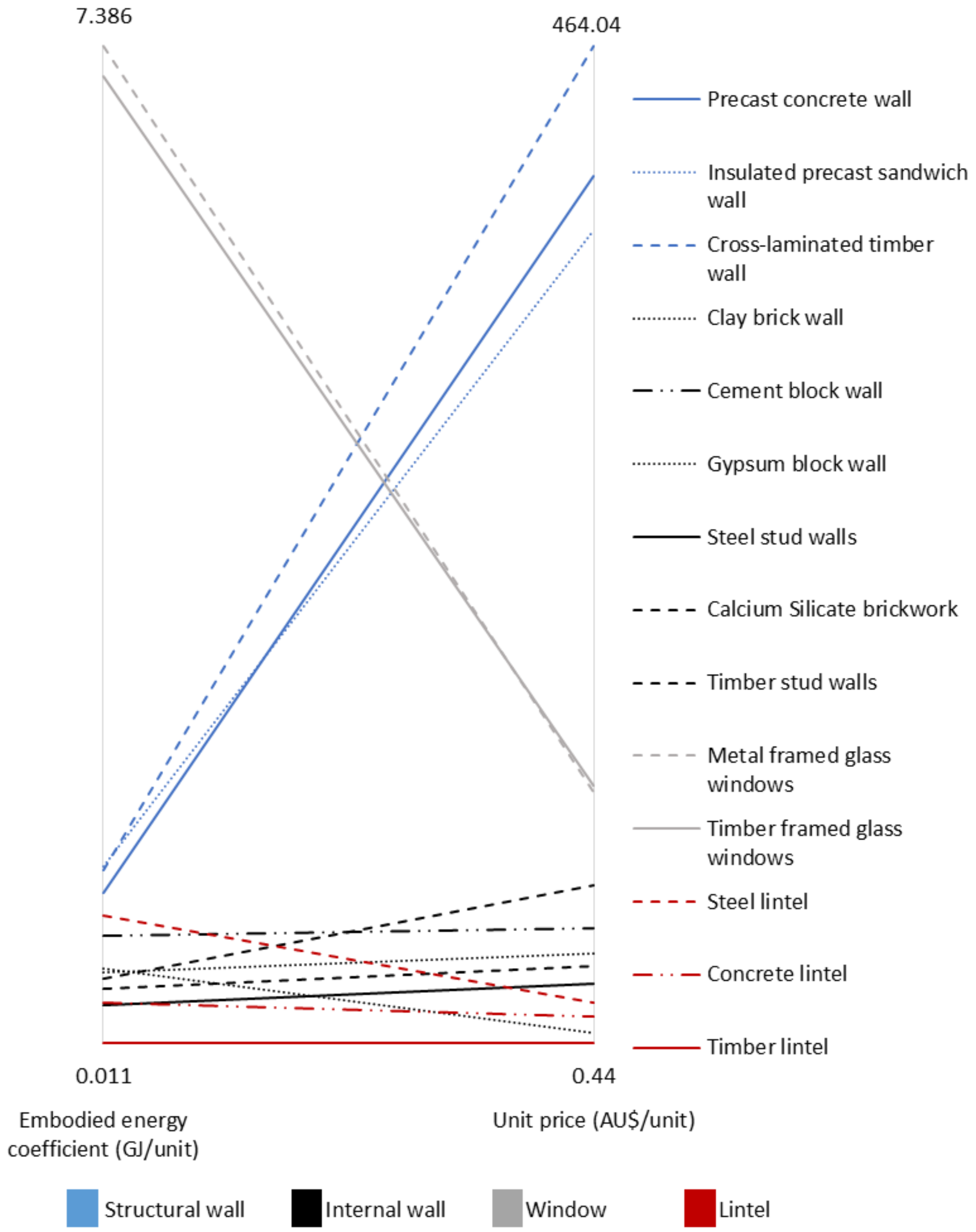


Figure 7.2: Parallel coordinates graph of embodied energy coefficients and unit prices of the envelope assemblies

Figure 7.2 is subdivided to illustrate structural and non-structural assemblies separately and presented in Appendix 20.

Closer inspection of the *structural walls* reveals that the *precast concrete wall panel* has the lowest EEC *(1.124 GJ/m^2)* and *insulated precast sandwich wall panel* have the lowest unit price *(AU$ 378.35 /m^2)*. *CLT wall panel* has the second lowest EEC *(1.285 GJ/m^2)* but the highest unit price *(AU$ 464.04 /m^2)*. However, *CLT* is developed from timber, which is a renewable resource. It is relatively lightweight, and thus foundation sizes can be reduced compared to *precast reinforced concrete wall panel* construction in specific soil situations (i.e. sandy soils), as discussed in Section 8.4. Hence, the selection should not predominantly base on EEC and unit price per Figure 7.2, but on the total LCEE and LCMC of that assembly choice at the shopping centre level. However, based on the results of the model, *precast reinforced concrete panel* appears to be a better choice considering both EEC and unit price followed by *CLT* for *structural walls*.

The comparison of *internal walls* reveals that *steel stud frame wall* has the lowest EEC *(0.293 GJ/m^2)* while the *gypsum block wall* has the lowest unit price *(AU$ 4.76 /m^2)*. *Steel stud frame wall* is further recognised as the optimal solution minimising both EEC and unit price. The analysis of *windows* identified *metal framed glass window* has the lowest unit price *(AU$ 117.17 /m^2)* whereas *timber framed glass window* has the lowest EEC *(7.162 GJ/m^2)*. *Timber framed glass window* is identified as the optimal solution which minimises both EEC and unit price equally. Similarly for lintels, *timber lintel* is identified as the most preferred solution within the considered assemblies.

7.2.3 Finishes assemblies

The finishes category consists of three assembly types namely; *wall finish, floor finish* and *ceiling finish* as defined in Chapter 6. Table 7.3 provides the EEC and unit prices of finishes assemblies quantified using the model to support the determination of the best assembly solutions with minimum EEC and unit price.

Figure 7.3 depicts the assemblies along with their EEC and unit prices (excluding installation costs) for comparison purposes. Accordingly, *cement mortar screed with white putty* has the lowest EEC *(0.021 GJ/m^2)* and unit price *(AU$ 7.70 /m^2)*. Among other *wall finish* assemblies, *ceramic tiling on cement mortar, compressed fibre cement panels, terrazzo tiles on mortar, timber board cladding* and *bamboo panels on timber frame* are identified to have low EEC but high unit prices. Conversely, *sheet metal cladding, vinyl tiled walls, water-based paint on plasterboard, oil-based paint on cement mortar* and *water-based paint on cement mortar* assemblies have high EEC and low unit prices.

In comparison with finishes assemblies, all *ceiling finishes* have low EEC and high unit prices. *Floor finish* assembly comparison identified *terracotta tiles, polypropylene carpet, vinyl planks, linoleum flooring, ceramic tiles* and *corkboard flooring* have high EEC and low unit prices. On the contrary, *wool* and n*ylon carpets, terrazzo, bamboo planks, porcelain tiles, laminated timber flooring,* and *polished exposed aggregate flooring* have low EEC and high unit prices.

Table 7.3: Embodied energy coefficients and unit prices of finishes assemblies identified in the study

Assembly name	Assembly type	Unit	Embodied energy coefficient (GJ/unit)	Unit price (AU$/unit)
Plasterboard lining with paint on timber frame	Ceiling finish	m^2	0.734	45.59
Wood planks with paint on timber frame	Ceiling finish	m^2	0.404	91.17
Plasterboard lining with paint on metal frame	Ceiling finish	m^2	0.648	44.32
Metal frame ceiling with metal tiles	Ceiling finish	m^2	0.577	69.26
Metal frame ceiling with cork tiles	Ceiling finish	m^2	0.306	52.64
Metal frame ceiling with vinyl tiles	Ceiling finish	m^2	0.974	53.44
Vinyl planks with water barrier underlay	Floor finish	m^2	1.285	30.60
Corkboards with water barrier underlay	Floor finish	m^2	0.617	29.80
Linoleum sheets with water barrier underlay	Floor finish	m^2	0.945	35.91
Rubber carpet with double-sided tape	Floor finish	m^2	0.915	32.52
Nylon carpet with underlay	Floor finish	m^2	1.230	81.88
Wool carpet with underlay	Floor finish	m^2	1.291	139.26
Polypropylene carpet with underlay	Floor finish	m^2	1.334	40.61
Ceramic tiling on 10 mm thick cement mortar screed	Floor finish	m^2	0.900	32.59
Terracotta tiles 10 mm thick cement mortar screed	Floor finish	m^2	2.939	104.15
Terrazzo with 100 mm infill slab 20 MPa	Floor finish	m^2	0.028	112.65
Bamboo planks	Floor finish	m^2	0.725	98.91
Laminated timber	Floor finish	m^2	0.629	67.06
Polished exposed aggregate concrete	Floor finish	m^2	0.466	52.50
Porcelain tiles 800 × 800 mm	Floor finish	m^2	0.441	71.54
Sheet metal cladding on metal frame - external	Wall finish	m^2	1.202	60.17
Water-based paint on 10 mm thick cement mortar screed with white putty	Wall finish	m^2	0.133	11.63
10 mm thick cement mortar screed with white putty	Wall finish	m^2	0.021	7.70
Oil-based paint on 10 mm thick cement mortar screed with white putty	Wall finish	m^2	0.138	11.24
Terrazzo tiles on 10 mm thick cement mortar screed	Wall finish	m^2	0.028	51.76
Water-based paint on 10 mm plasterboard	Wall finish	m^2	0.330	9.28
Timber board cladding	Wall finish	m^2	0.045	64.35
Ceramic tiling on 10 mm thick cement mortar screed	Wall finish	m^2	0.358	30.65
Bamboo panels with panelling adhesives and finishing nails on timber frame	Wall finish	m^2	0.141	96.20
Vinyl tiles	Wall finish	m^2	0.715	33.90
Compressed fibre cement façade panel – external	Wall finish	m^2	0.329	53.88

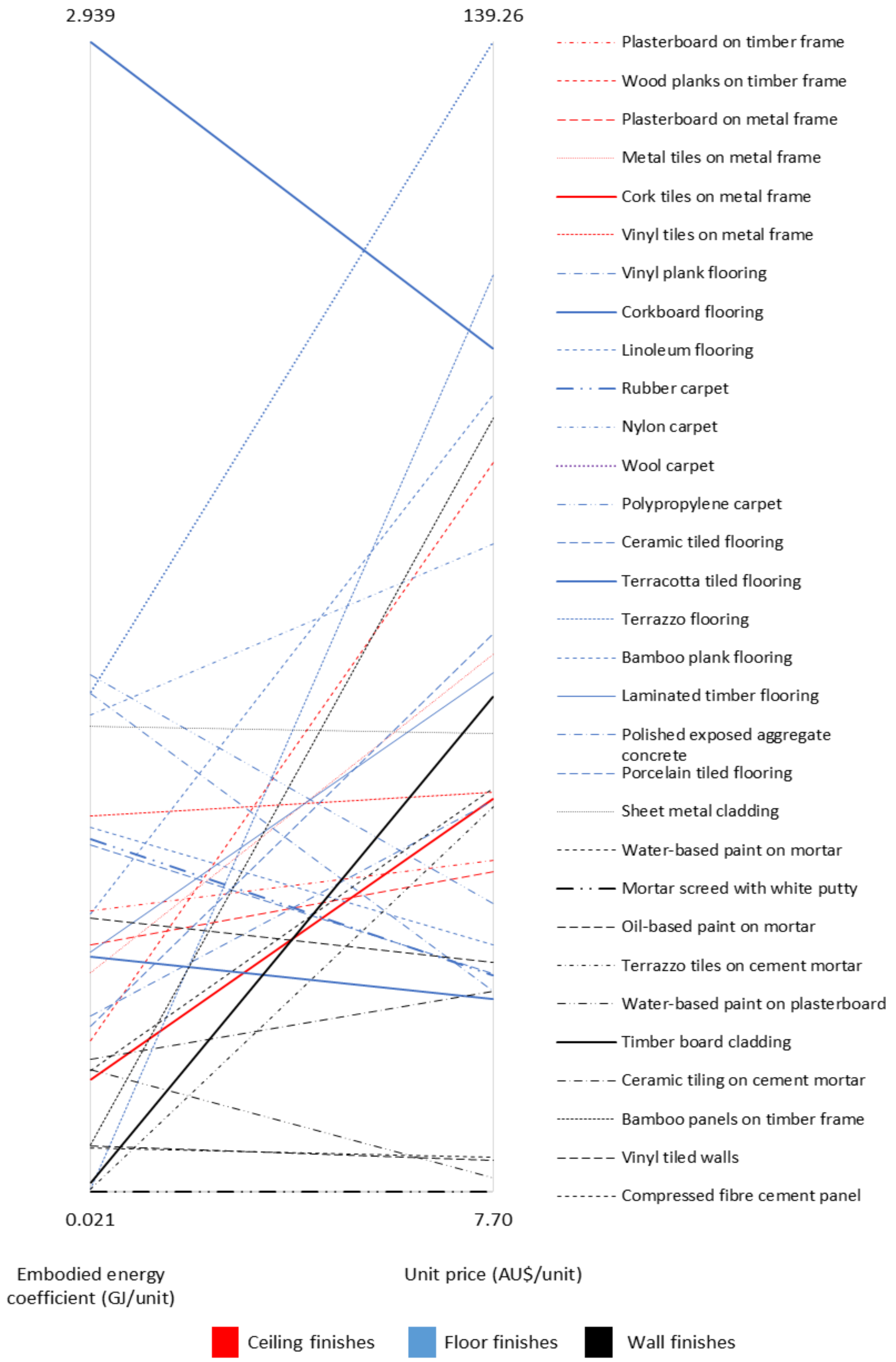


Figure 7.3: Parallel coordinates graph of embodied energy coefficients and unit prices of the finishes assemblies

Figure 7.3 is subdivided to illustrate ceiling finishes, floor finishes, and wall finishes separately and is presented in Appendix 20.

The optimal *ceiling finishes* with minimum EEC and unit prices are *metal framed ceiling with cork tiles (0.306 GJ/m², AU$ 52.64 /m²)* and *plasterboard with paint on metal frame (0.648 GJ/m², AU$ 44.32 /m²)*. According to the analysis of *floor finishes* data outlined in Table 7.3, it can be seen that the optimal solutions are *cork board flooring (0.617 GJ/m², AU$ 29.80/m²)* and *polished exposed aggregate with infill slab (0.466 GJ/m², AU$ 52.50 /m²)*. The optimal solutions minimising both EEC and unit price for *structural wall finishes* are *timber board cladding (0.045 GJ/m², AU$ 64.35 /m²)* followed by *compressed fibre cement (CFC) façade panels (0.329 GJ/m², AU$ 53.88 /m²)*. The results further demonstrate *cement mortar screed with white putty (0.021 GJ/m², AU$ 7.70 /m²)* as the optimal solution for *internal wall finishes* followed by *water-based paint on cement mortar and white putty (0.133 GJ/m², AU$ 11.63 /m²)*.

7.2.4 Summary at assembly level

The analysis at assembly level identified best solutions for different assembly types minimising EEC and unit prices. Table 7.4 below illustrates the summary of the assembly level analysis.

Table 7.4: Assemblies that achieve objective functions of minimising embodied energy coefficients and unit prices

Assembly type	Minimum embodied energy coefficient	Minimum unit price	Optimal solution
Foundation	Slab-on-grade with 40%fly ash cement	Slab-on-grade with 40% fly ash cement	Slab-on-grade with 40% fly ash cement
Column	Glue-laminated timber	Glue-laminated timber	Glue-laminated timber
Roof structure	Roof structure with structural steel and Colourbond sheet covering	Roof structure with engineered and structural timber and Colourbond sheet covering	Roof structure with engineered and structural timber and Colourbond sheet covering
Structural wall	150 mm thick precast panel	Insulated precast sandwich wall panels 220 mm thick	150 mm thick precast panel
Internal wall	Steel stud wall	Gypsum block wall	Steel stud wall
Window	Timber framed glass window	Metal framed glass window	Timber framed glass window
Lintel	Timber lintel	Timber lintel	Timber lintel
Ceiling finish	Metal frame ceiling with cork tiles	Plasterboard lining with paint on metal frame	Metal frame ceiling with cork tiles
Floor finish	Terrazzo with infill slab	Corkboards with water barrier underlay	Corkboards with water barrier underlay
Wall finish - External	Timber board cladding on metal frame	Compressed fibre cement façade panel	Timber board cladding on metal frame
Wall finish - Internal	Water cement mortar screed with putty	Water-based paint on plasterboard	Water cement mortar screed with putty

Since the EEC and unit prices of assemblies have a positive linear relationship with the IEE and CC of a shop, this analysis can be extended to the next level by stating the identified assembly solutions are the most suitable solutions minimising initial effects. However, when assembly combinations are generated at the shop level, assembly selection is constrained by structural and design compatibility, which could change the most suitable assemblies for different shop types.

The next section compares the LCEE, LCEGHGE, LCMC and LCMCWT across shop types identified in shopping centres.

7.3 ANALYSIS AT THE SHOP LEVEL

The assembly level analysis identified the building assemblies with minimum EEC and unit prices for all assembly types defined in the model. However, these results could be changed when assemblies are integrated with others to form different types of shops. As explained in Chapter 5, 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 earlier section. Shop types are grouped into three major categories based on the typical refurbishment frequencies as the *centre structure* (shell), *specialty shops* and *anchor shops*. As described in earlier chapters, the *centre structure* consists of the *foundation, columns, roof structure, structural walls*, *structural wall finishes, external windows and lintels*. *Specialty shops* in the model are designed using *internal walls, ceiling finishes, wall finishes*, and *floor finishes* only. *Anchor shops* are designed using *structural walls, ceiling finishes, wall finishes* and *floor finishes*. The assembly combinations of the shop variations are used to determine the combinations minimising LCEE, LCEGHGE, LCMC and LCMCWT. This section presents the findings at the shop level providing analysis of four different scenarios, hereinafter referred to as; *minimum life cycle embodied energy (LCEE), minimum life cycle material cost (LCMC), minimum life cycle material cost with tax (LCMCWT)* and *optimal* (which minimises both LCEE 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 *shop_categories* database.

7.3.1 Centre structure

The *centre structure* is the largest shop type in the shopping centre as defined in the model. The building shell was considered as the *centre structure* for modelling purposes. Therefore, the *centre structure* consists of 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 five scenarios are discussed identifying differences in assembly selection resulting in embodied energy and material cost variations. The refurbishment frequency of the *centre structure* is considered equal to the period of analysis of the building (50 years). However, the assembly service life values are also considered when determining the number of replacements to quantify recurrent embodied energy (REE) and material cost-in-use (CIU) during the use phase (refer Section 4.7). Thus, several envelope and finishes assemblies might have replacements over the period of analysis depending on their service life values even if the shop itself is not refurbished.

As outlined in Section 5.3.1, the *centre structure* used for the analysis is 240 m long, 88 m wide, 10 m high and has a structural span of 9 m. The total GLA of the *centre structure* is 22,498 m^2. Table 7.5 presents an overview of the embodied energy and material cost values of the *centre structure* across the different scenarios.

Table 7.5: Comparison of different scenarios of the centre structure

Criteria	Scenarios				
	Business as usual	**Minimum LCEE**	**Minimum LCMC**	**Optimal**	**Minimum LCMCWT**
Initial embodied energy ('000 GJ)	232.48	151.11	157.60	151.98	151.98
Recurrent embodied energy ('000 GJ)	20.95	15.73	20.95	15.73	15.73
Life cycle embodied energy ('000 GJ)	253.43	166.84	178.55	167.70	167.70
Capital cost (million AU$)	21.58	21.36	21.22	21.25	21.25
Cost-in-use (million AU$)	0.32	0.71	0.32	0.71	0.71
Life cycle material cost (million AU$)	21.90	22.07	21.54	21.99	21.96
Life cycle embodied greenhouse gas emission (tonne CO_2e)	14,896.80	9,806.54	10,495.06	9,857.56	9,857.56
Life cycle material cost with carbon tax (million AU$)	38.91	33.27	33.52	33.21	33.21

LCEE: Life cycle embodied energy; LCMC: Life cycle material cost; LCMCWT: Life cycle material cost with carbon tax

What is interesting about the data in this table is that even though the *BAU* scenario uses 253.43 TJ of embodied energy over the 50 years, it is possible to achieve up to 34% LCEE reductions with the use of specific assembly combinations. However, closer inspection of the table also shows that the maximum reduction that can be achieved in LCMC is only 2%. This figure indicates that the typical design of shopping centres is a representation of lower LCMC solutions. Further analysis of the scenarios is provided in the subsequent sections.

The following figures (7.4, 7.5, 7.6) present the LCEE, LCMC and LCMCWT comparisons of the *centre structure* scenarios. Accordingly, it can be observed that the IEE represents a larger share of LCEE in the *centre structure* across all scenarios (90% - 95%). This is because of the 50 year refurbishment frequency, which is less than the service life values of most structural assemblies used in the *centre structure* resulting in lower REE.

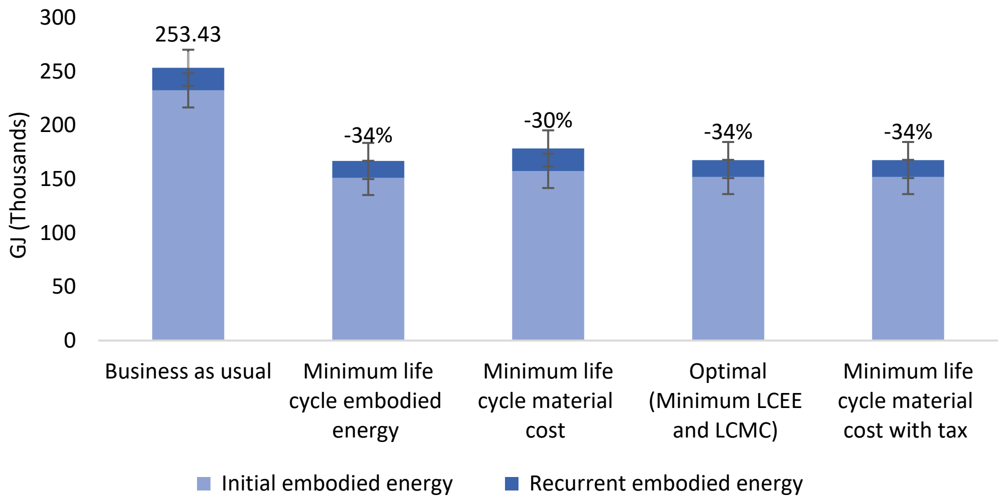


Figure 7.4: Comparison of life cycle embodied energy across different scenarios of the centre structure

A similar observation can be made on the CC contribution in the LCMC component. CC consists of around 96-99% of the LCMC across all scenarios as displayed in Figure 7.5. In the centre structure, roof structure accounts for almost 80% of LCMC. The study identified only two alternative assemblies for roof structure where the difference in cost is less than 1%. This causes the minimal change in LCMC across scenarios as depicted below.

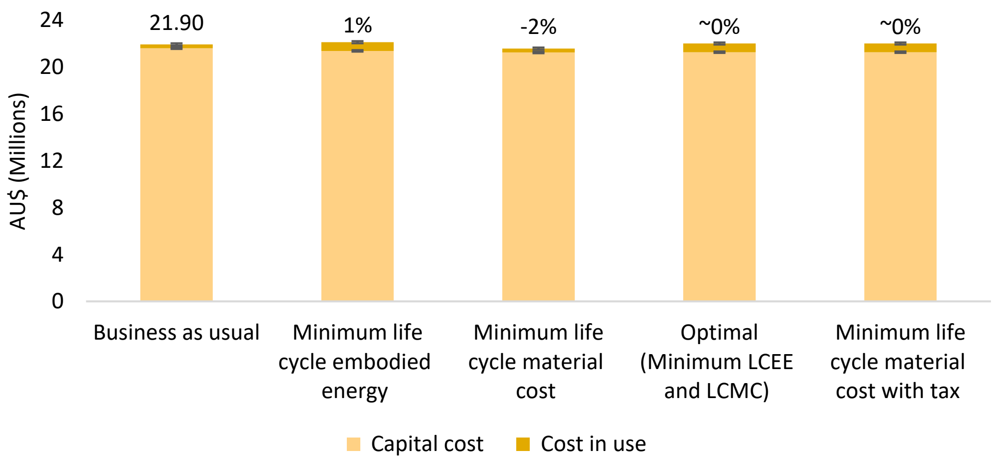


Figure 7.5: Comparison of life cycle material cost across different scenarios of the centre structure

Results also reveal that when the carbon tax component is incorporated, material costs increase (Figure 7.6). However, selecting lower embodied energy solutions can result in smaller cost increments rather than choosing typical assemblies for larger cost increments.

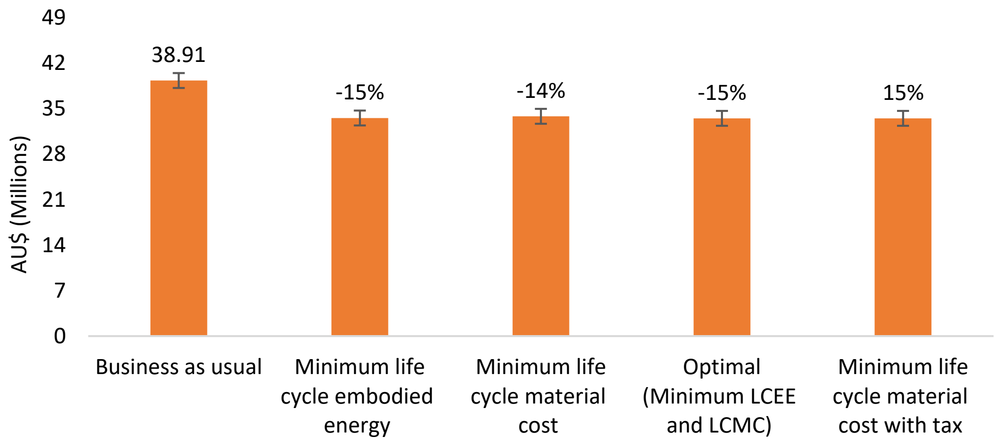


Figure 7.6: Comparison of life cycle material cost with carbon tax across different scenarios of the centre structure

The scenarios are analysed in detail in the following sub-sections to demonstrate the effects of assembly combinations on LCEE, LCMC and LCMCWT of the *centre structure*.

7.3.1.1 Business as usual scenario

The *BAU* scenario of the *centre structure* is designed using the typical assemblies used in the industry at present (refer Chapter 5). It has a *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*. This was identified as a generic *centre structure* design in Australia based on data collected through interviews and document analysis. The findings of the model demonstrate that the CC intensity of the *centre structure* in the *BAU* scenario is AU$ 960.00 /m^2 and IEE intensity is 10.33 GJ/m^2. IEE and CC distribution across assembly types in the *centre structure* are shown in Figure 7.7.

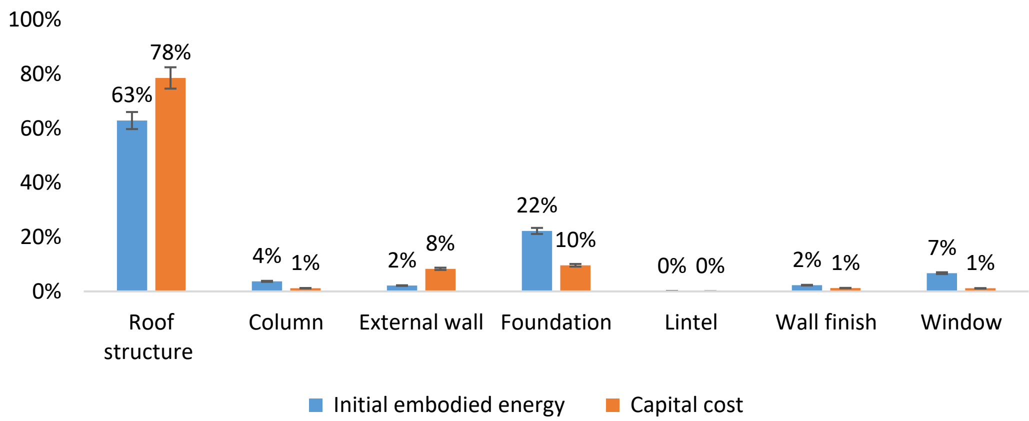


Figure 7.7: Centre structure assembly initial embodied energy and capital cost distribution across assembly types

It can be observed that the *roof structure (63%)* is responsible for the largest share of the total IEE in the *BAU* scenario of the *centre structure* followed by the *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 of the *BAU* scenario follows a similar pattern as IEE distribution where the *roof structure (78%)* has the highest cost, followed by the *foundation (10%)*. The *structural wall* represents 8% of the total. All other assembly types represent only around 4% of the CC. The CIU and REE of the *centre structure* are significantly lower when compared to IEE and CC because only the *finishes* assemblies are replaced over the period of analysis. The REE intensity is 0.93 GJ/m^2, and the CIU intensity is AU$ 14.00 /m^2. Hence the LCEE and LCMC intensities of the *centre structure* are quantified as 11.26 GJ/m^2 and AU$ 970.00 /m^2 respectively, dominated by IEE and CC. Therefore, the LCEE and LCMC distribution across assembly types can be interpreted in the same manner as IEE and CC in the *centre structure*. However, the LCMCWT intensity of the *BAU* scenario is significantly higher, as accounted for AU$ 1,730.00 /m^2. This higher value indicates that the choice of assemblies in the *BAU* scenario is questionable when considering their environmental effects.

7.3.1.2 Minimum life cycle embodied energy scenario

The assembly combination of the *minimum LCEE* scenario is different from the *BAU* scenario in several aspects. The analysis reveals that the *centre structure* with *minimum LCEE* consists of a *slab-on-grade foundation with 40% fly ash cement*, *glue-laminated timber columns, timber roof structure with Colourbond roof sheets, precast concrete panel walls, timber framed glass windows, concrete lintels* and *timber board cladding on metal frame wall finish*. In this scenario, only the *wall finish* and *window* assembly types are replaced over the period of analysis.

The analysis identifies that the LCEE intensity of this scenario is 7.42 GJ/m^2, which is a 34% reduction in comparison to the *BAU* scenario. However, LCMC intensity of this scenario is slightly higher (<+1%) than the *BAU* scenario with AU$ 980.00 /m^2. Nevertheless, the LCMCWT intensity is considerably lower in comparison to the *BAU* scenario with AU$ 1,480.00 /m^2, making a reduction of almost 15%. This LCMCWT reduction demonstrates the effectiveness of pricing GHG emissions as a means of encouraging the construction sector towards environmentally sensitive material selection.

7.3.1.3 Minimum life cycle material cost scenario

The *minimum LCMC* scenario of the *centre structure* is designed using *a slab-on-grade foundation with 40% fly ash cement, glue-laminated timber columns, timber roof structure with Colourbond roof sheets, insulated sandwich panel walls, metal framed glass windows, concrete lintels* and *sheet metal cladding structural wall finish*. The findings of the model show that the *minimum LCMC* scenario has a LCEE intensity of 7.94 GJ/m^2 and an LCMC intensity of AU$ 960.00 /m^2. When compared to the *BAU* scenario, LCEE demonstrates a 30% reduction, whereas LCMC shows only a 2% reduction. Therefore, the assembly combination with the *minimum LCMC* is a better solution than the *BAU* scenario both in terms of LCEE and LCMC, leading to a 14% reduction in the LCMCWT.

7.3.1.4 Minimum life cycle material cost with carbon tax scenario

A comparison of the differences in material selection in the scenarios of *minimum LCMC* and *minimum LCMCWT* was conducted. The results of the model demonstrate that the combinations of assemblies are different in the two scenarios. The shop design minimising LCMCWT is constructed using *slab-on-grade foundation with 40% fly ash cement, glue-laminated timber columns, timber roof structure with Colourbond roof sheets, insulated sandwich panel walls, timber framed glass windows, concrete lintels* and *timber board cladding on metal frame wall finish*. This composition leads to significant savings in embodied energy (-34%) when compared to the *BAU* scenario with only a slight cost increment (+<1%). When compared to the *minimum LCEE* scenario, savings are reversed, where LCEE is increased (+<1%) and LCMC is reduced (-<1%). Therefore, the introduction of a carbon tax promotes the selection of assemblies with lower embodied energy with minimal additional expenses.

7.3.1.5 Optimal life cycle embodied energy and material cost scenario

Optimal scenarios of the *centre structure* are obtained based on the Pareto frontier developed in the model, as presented in Figure 7.8.

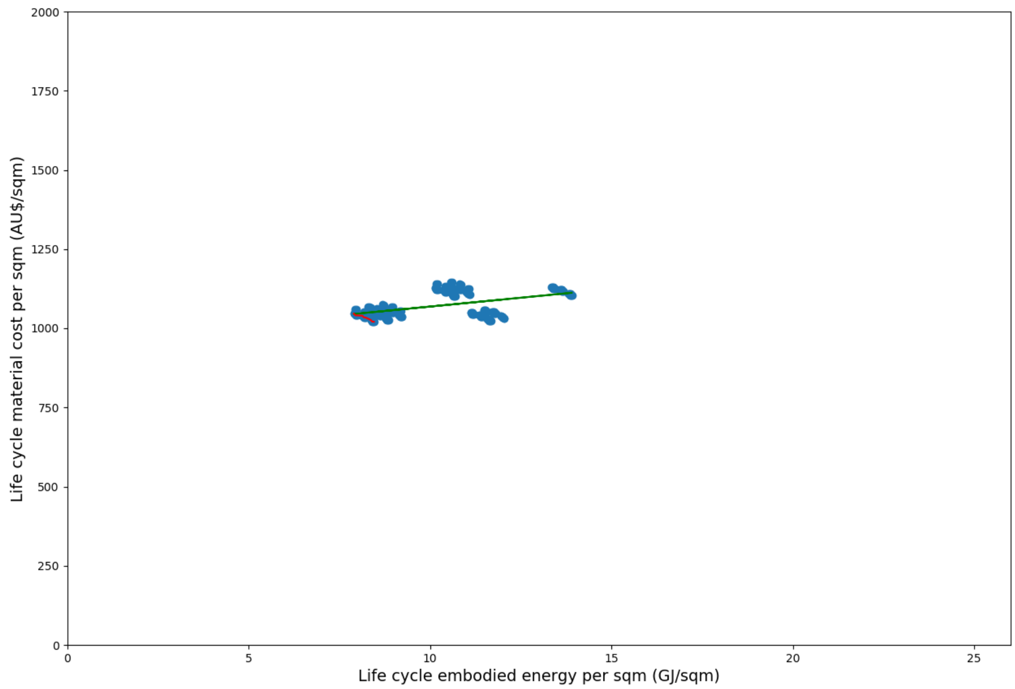


Figure 7.8: Pareto frontier of the centre structure optimal scenarios

Nine Pareto solutions were identified with objectives of minimising both LCEE and LCMC. The design space displays four clusters of combinations which are scattered. The first cluster consists of assembly combinations with lower LCEE and LCMC and is the largest among the four. Two other clusters represent medium LCEE solutions which have lower LCMC and higher LCMC separately. The last is the combinations that lead to higher LCEE and LCMC. The graph demonstrates that there is a moderately strong positive linear association between LCEE and LCMC per unit area (Pearson's correlation: 0.502). No apparent outliers are visible. Therefore, it can be observed that in the *centre structure* reducing LCEE does not necessarily increase the LCMC within the selected assembly solutions.

The Pareto optimal solutions are analysed based on the researcher's requirements on the dominance of objectives to find the most suitable solution meeting the requirements. Therefore, the decision criteria (DC) is set to find the preferable assembly combination for the *centre structure*.

DC: Minimising LCEE and LCMC are given equal weights (0.5, 0.5), and none of the objectives are considered dominant.

Accordingly, different assembly combinations are obtained, which fulfil the decision criteria. The findings reveal that the assembly combination of the optimal scenario is also the *minimum LCMCWT* scenario. This is interesting as it ascertains that the enforcement of carbon tax is an effective approach to achieve the optimal embodied emissions reductions in Australian shopping centres because construction internalises the cost of the embodied carbon emissions.

Due to the conciseness of the thesis, only the best assembly combination is presented under each scenario. The model identified series of assembly combinations that can minimise LCEE and LCMC of the *centre structure*. Appendix 15 presents the top ten combinations under each scenario. The next section presents the results of the scenario analysis of the *anchor shop* category representing *supermarkets* and *discount department stores*.

7.3.2 Anchor shops

The analysis for *anchor shops* is carried out for a *discount department store* representing the shop category. *Anchor shops* are defined to have a refurbishment frequency of 20 years (refer Chapter 6). The selected *anchor* store is 93 m long, 58 m wide and 8 m deep. The comparison of the embodied energy and material cost flows of the shop under different scenarios is presented in the table below (Table 7.6).

As found for centre structures, the comparison identifies that the *minimum LCMCWT* scenario and the *optimal s*cenario minimising both LCEE and LCMC have identical assembly combinations. The following figures (7.9, 7.10, 7.11) depict the comparisons of LCEE, LCMC and LCMCWT across different scenarios.

Table 7.6: Comparison of different scenarios of the discount department store

Criteria	Scenarios				
	Business as usual	Minimum LCEE	Minimum LCMC	Optimal	Minimum LCMCWT
Initial embodied energy ('000 GJ)	7.29	4.48	6.36	4.57	4.57
Recurrent embodied energy ('000 GJ)	14.83	7.55	11.23	7.64	7.64
Life cycle embodied energy ('000 GJ)	22.12	12.03	17.60	12.21	12.21
Capital cost (million AU$)	0.92	0.91	0.68	0.79	0.79
Cost-in-use (million AU$)	0.97	0.92	0.64	0.77	0.77
Life cycle material cost (million AU$)	1.89	1.83	1.32	1.56	1.56
Life cycle embodied greenhouse gas emission (tonne CO_2e)	1,299.97	706.98	1,034.22	717.52	717.52
Life cycle material cost with carbon tax (million AU$)	3.38	2.64	2.50	2.38	2.38

LCEE: Life cycle embodied energy; LCMC: Life cycle material cost; LCMCWT: Life cycle material cost with carbon tax

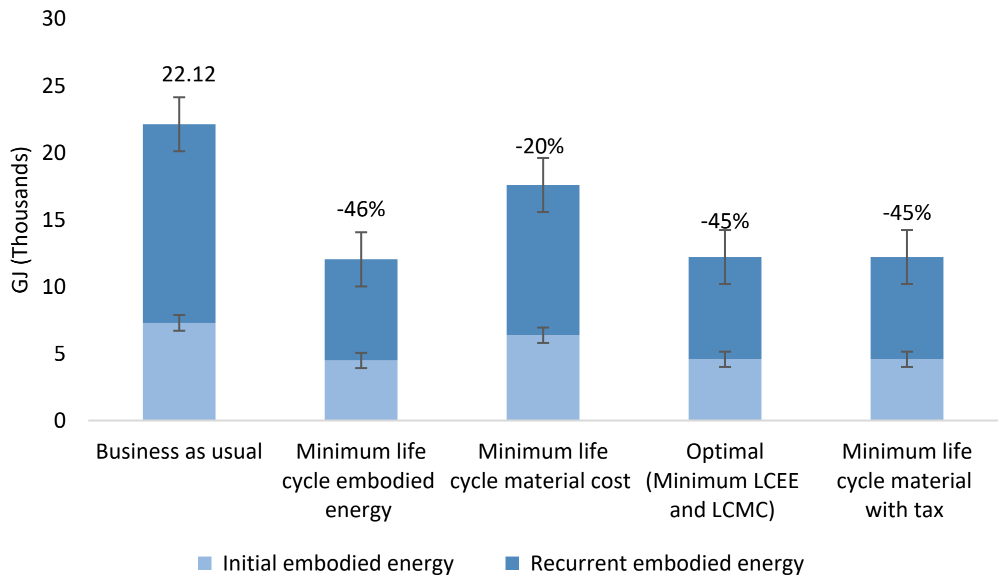


Figure 7.9: Comparison of life cycle embodied energy across different scenarios of the discount department store

Unlike in the centre structure, LCMC varies to a great extent in anchor shops as shown in Figure 7.10. This difference is identified due to the large number of assembly alternatives available for anchor shops that create a large number of scenarios with a huge range of material costs.

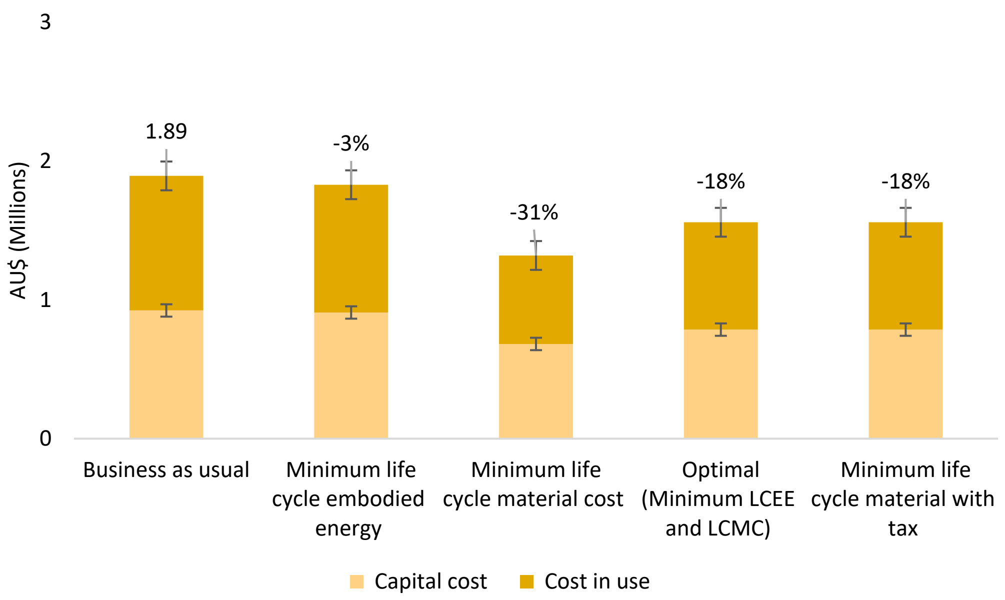


Figure 7.10: Comparison of life cycle material cost across different scenarios of the discount department store

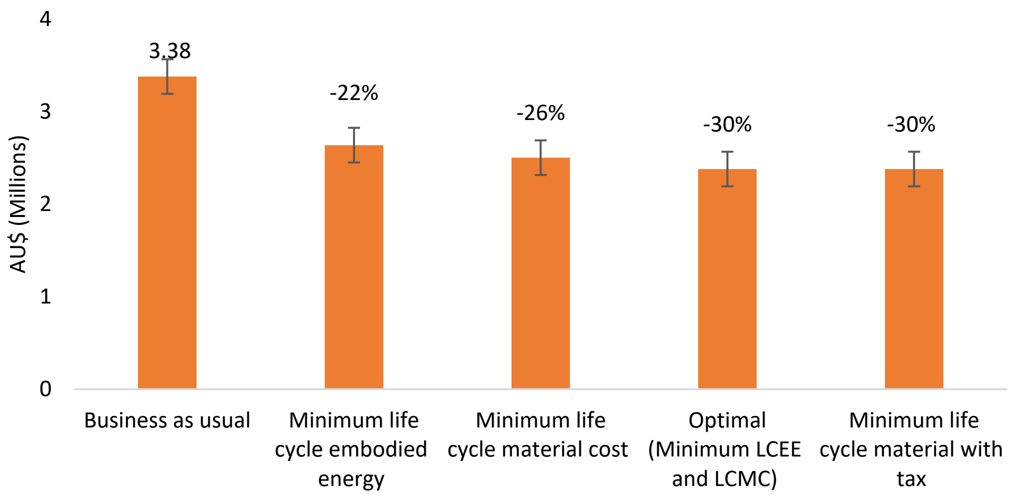


Figure 7.11: Comparison of life cycle material cost with carbon tax across different scenarios of the discount department store

As shown in the figures, in *anchor shops*, the REE and CIU are most impactful in LCEE and LCMC as their percentage contributions are 67% and 52%, respectively, across all scenarios. The detailed analysis of the scenarios is presented under the following subheadings.

7.3.2.1 Business as usual scenario

The *BAU* scenario of the *discount department store* is designed using *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*. The LCEE intensity of the *BAU* scenario is 4.10 GJ/m², and LCMC intensity is AU$ 350.00/m². The LCEGHGE of this scenario is 0.24 tonne CO_2e m^{-2}. However, after incorporating the carbon tax component, the LCMC of the shop is increased to AU$ 630.00 /m², almost doubling its value.

Figure 7.12 compares the IEE and REE as a percentage of the LCEE, and CC and CIU as a percentage of the LCMC of the *BAU* scenario of the *discount department store* by assembly type.

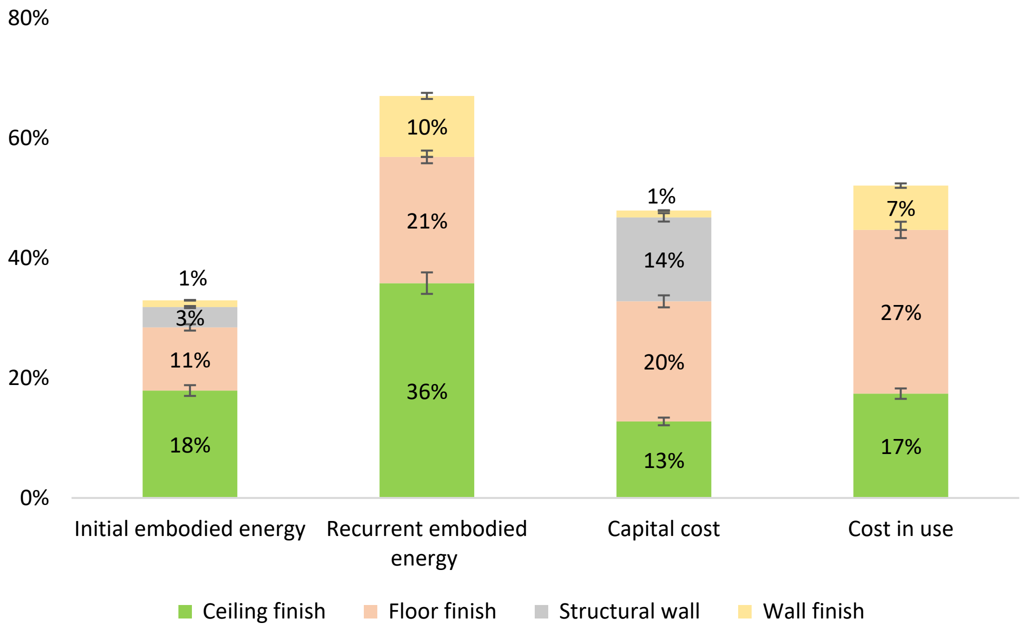


Figure 7.12: Comparison of percentage initial and recurrent embodied energy from life cycle embodied energy and capital cost and cost-in-use as a percentage of the life cycle material cost of different assemblies of the business as usual scenario of discount department store

The comparison of assembly types reveals that in the *BAU* scenario, *ceiling finishes* (54%) contributes the most to LCEE followed by *floor finish* (32%), *wall finish* (11%) and *structural wall* (3%). 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%).

7.3.2.2 Minimum life cycle embodied energy scenario

The *minimum LCEE* scenario is achieved by using *precast concrete panel walls, plasterboard lining with paint on metal frame ceiling, terrazzo flooring with infill slab* and *timber board cladding on metal frame wall finish*. The resulting LCEE intensity of the shop (2.23 GJ/m²) is a 46% reduction when compared to the *BAU* scenario. The LCMC intensity is AU$ 340.00 /m² representing a 3% reduction from the *BAU* scenario. The critical observation is that LCMCWT value of this scenario is AU$ 490.00 /m² which is a 22% reduction when compared to the *BAU* scenario.

Accordingly, the assembly combination minimising the LCEE is a better solution than the *BAU* scenario in terms of material cost as well.

7.3.2.3 Minimum life cycle material cost scenario

The *minimum LCMC* design involves *insulated precast sandwich panels, mortar screed with white putty wall finish, painted plasterboard on metal frame ceiling* and *ceramic tiled flooring*. The LCEE intensity (3.26 GJ/m^2) of this scenario is a 20% reduction from the *BAU* scenario, whereas LCMC intensity (AU$ 240.00 /m^2) results in 31% cost savings. Further, LCMCWT intensity of this scenario is valued as AU$ 460.00 /m^2, which is 26% lower than the *BAU* scenario.

7.3.2.4 Minimum life cycle material cost with carbon tax scenario

The selection of assemblies in the *minimum LCMCWT* scenario is different from the *minimum LCMC* scenario only in terms of the *floor finish*. This shop is designed using *terrazzo flooring with infill slab*. The LCEE and LCMC intensities are obtained as 2.26 GJ/m^2 and AU$ 290.00 /m^2, respectively. The embodied energy reduction and material cost increment in comparison to the *minimum LCMC* scenario is caused by the shift in *floor finish* assembly from *ceramic tiling* to *terrazzo flooring,* which is environmentally responsive yet expensive. However, the assembly combination still results in 45% LCEE reduction and 18% LCMC saving when compared to the *BAU* scenario. The LCMCWT of this scenario is AU$ 440.00 /m^2, which is the lowest among all scenarios.

7.3.2.5 Optimal life cycle embodied energy and material cost scenario

Pareto frontier solutions of the *discount department store* are provided in the figure below. The *optimal* scenario minimising both LCEE and LCMC with equal weights is with the same as the *minimum LCMCWT* scenario.

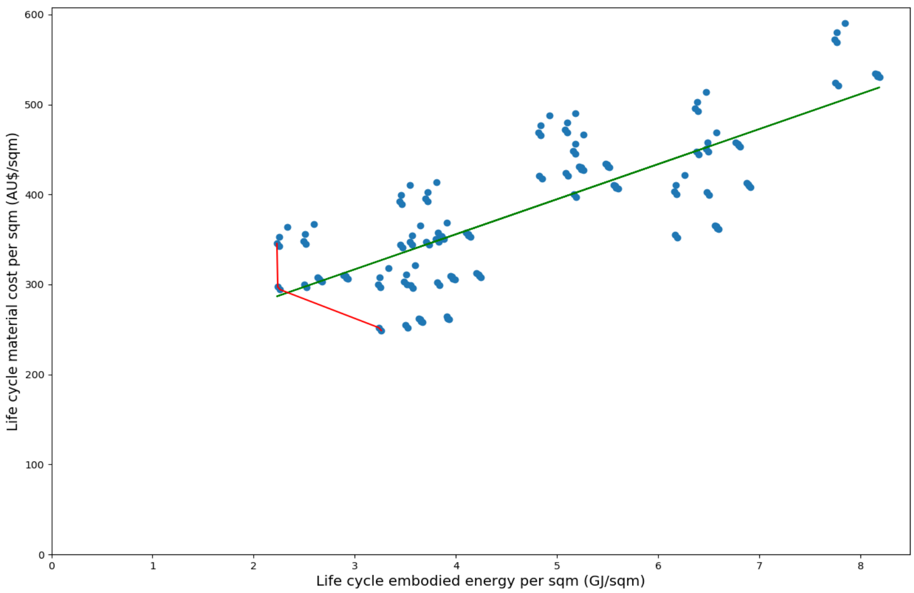


Figure 7.13: Pareto frontier solutions of the discount department store

Figure 7.13 shows that all possible combinations of assemblies for *discount department store* scatter across the design space and weighted along the intersection of the LCEE and LCMC intensities axes.

The bivariate relationship is a strong positive linear association (Pearson's correlation: 0.784). There are a few potential outliers. Hence, the figure indicates that for the *discount department store*, when LCEE intensity is reduced, material cost also reduces by significant amounts. Therefore, it can be observed that within the design space of selected assemblies it is highly possible to achieve LCEE reductions in the *discount department stores* without increasing the material costs.

7.3.3 Specialty shops

The shopping centre case studies identified ten different types of *specialty shops,* (described in Sections 5.3.1, 5.4.1 and 5.5.1). For the sake of brevity, results are presented here for just one of the *specialty* shop types to identify their significance in terms of embodied environmental impacts. However, the rest of the results are provided in Appendix 15. The comparison of different *specialty shop* types is presented later in Section 7.4 to illustrate their similarities and differences. A *services* shop was selected since they represent the largest share of GLA among *specialty shops*.

The *services* shop is 20 m long, 14 m wide, 4 m high and has a GLA of 280 m^2. Data on embodied energy, embodied GHG emissions and material costs across the scenarios are available in Table 7.7.

Table 7.7: Comparison of different scenarios of the services shop

Criteria	**Scenarios**				
	Business as usual	**Minimum LCEE**	**Minimum LCMC**	**Optimal**	**Minimum LCMCWT**
Initial embodied energy ('000 GJ)	0.57	0.15	0.42	0.16	0.16
Recurrent embodied energy ('000 GJ)	5.10	1.36	3.78	1.44	1.44
Life cycle embodied energy ('000 GJ)	5.67	1.51	4.20	1.60	1.60
Capital cost (million AU$)	0.05	0.04	0.02	0.03	0.03
Cost-in-use (million AU$)	0.30	0.25	0.15	0.20	0.20
Life cycle material cost (million AU$)	0.35	0.29	0.17	0.23	0.23
Life cycle embodied greenhouse gas emission (tonne CO_2e)	333.36	88.55	246.93	93.80	93.80
Life cycle material cost with carbon tax (million AU$)	0.73	0.39	0.45	0.34	0.34

LCEE: Life cycle embodied energy; LCMC: Life cycle material cost; LCMCWT: Life cycle material cost with carbon tax

The LCEE, LCMC and LCMCWT comparisons are graphically displayed in the Figures 7.14, 7.15 and 7.16. Across all scenarios, LCEE, LCMC and LCMCWT are lower than in the *BAU* scenario.

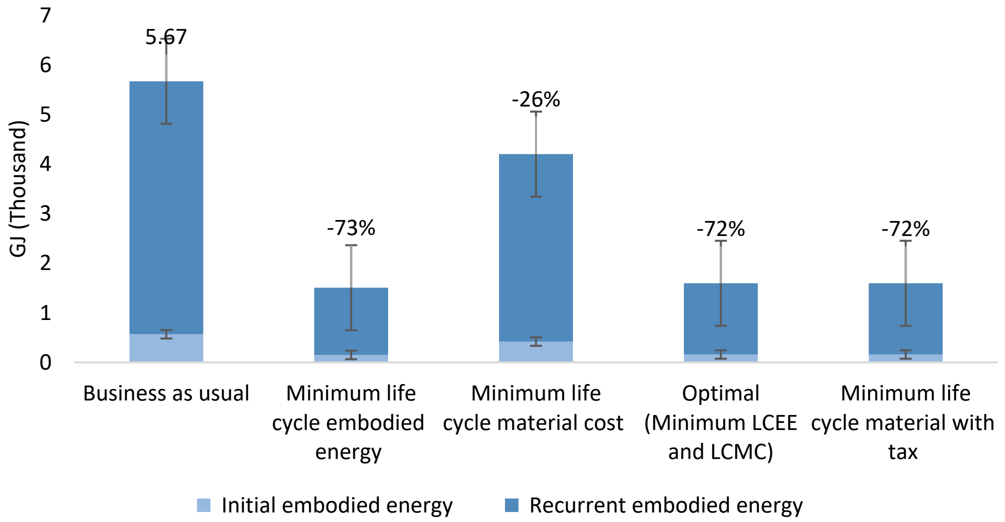


Figure 7.14: Comparison of life cycle embodied energy across different scenarios of the services shop

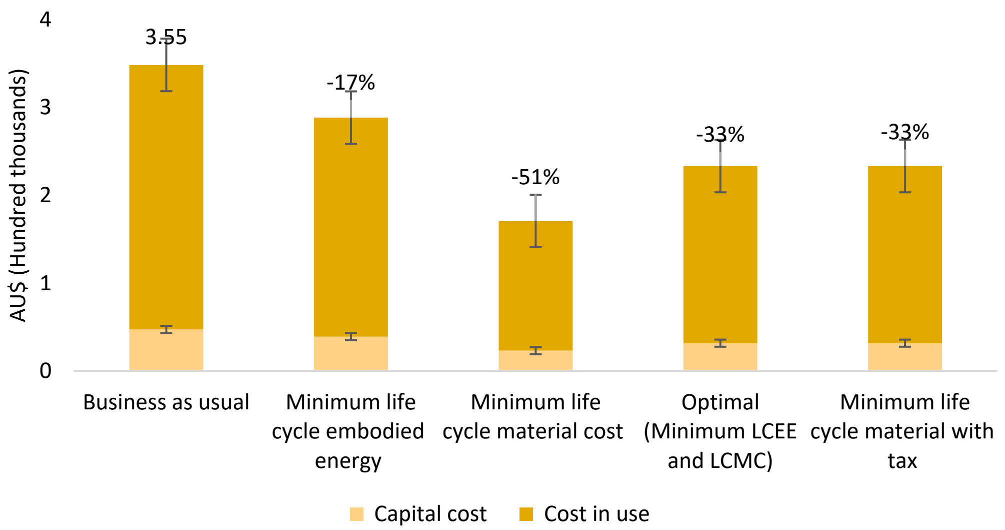


Figure 7.15: Comparison of life cycle material cost across different scenarios of the services shop

LCMC of speciality shops also vary to a great extent as in anchor shops, regards to the large number of assembly alternatives.

The comparisons reveal that the IEE and REE shares of LCEE of *services* shops across the scenarios are 10% and 90% respectively. Similarly, CC represents 13% of the LCMC, whereas CIU is responsible for 87%. This pattern is repeated across all *specialty shop* types with the refurbishment frequency of five years. The underlying reason is that when assemblies are replaced in five-year recurrences, they do not require any additional replacements in between since in all selected assemblies the expected service life is higher than five years. However, when refurbishment frequency is increased, the impacts differ and are presented in Section 7.7.Results indicate that in terms of LCEE reductions in *specialty shops*, the use phase of the building is far more critical than the initial construction phase. It is therefore imperative to devote more attention to material selection at each recurrence when considering the life cycle effects.

The LCMCWT of the scenarios are presented in Figure 7.16, identifying that the *BAU* scenario is responsible for the largest LCMCWT value followed by the *minimum LCMC* scenario.

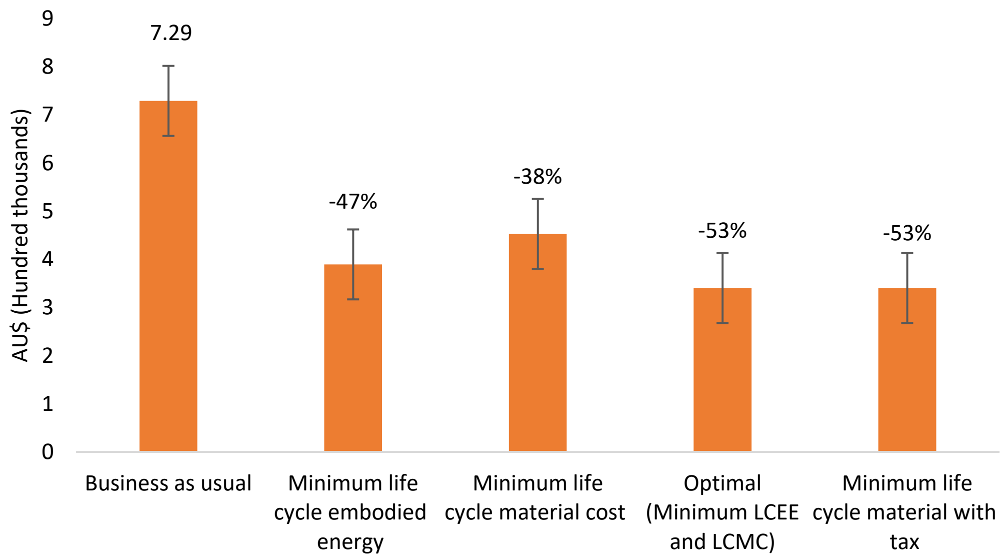


Figure 7.16: Comparison of life cycle material cost with carbon tax across different scenarios of the services shop

7.3.3.1 Business as usual scenario

The *BAU* scenario of *services* shops is constructed using *steel stud wall, water-based paint on plasterboard, timber framed plasterboard ceiling* and *terracotta tiled flooring*. This combination results in an IEE intensity of 2.04 GJ/m^2 and a CC of AU$ 180.00 /m^2. With the refurbishment frequency of five years (as described in Section 4.7.3.2), the *services* shop goes through 9 replacements throughout the 50 year analysis. Based on the notion where existing assemblies are replaced with same assemblies each time, the REE intensity of the *services* shop reaches 18.21 GJ/m^2. The CIU of the shop is also determined based on the refurbishment frequency and assembly service life values. The accounted CIU intensity of the *services* shop can, therefore, be given as AU$ 1,070.00 /m^2. The LCEE intensity of the shop is 20.25 GJ/m^2, and LCMC intensity is AU$ 1,243.38 /m^2. The LCEGHGE intensity is estimated as 1.19 tonne CO_2e /m^2, resulting in an increased LCMCWT valued as AU$ 2,600.00 /m^2.

The assembly level analysis of the *BAU* scenario is presented below in Figure 7.17. The analysis demonstrates that the *floor finishes* (44%) dominate the LCEE of *services* shop followed by *ceiling finishes* (37%), *wall finishes* (14%) and *internal walls* (6%). The LCMC distribution also indicates a similar pattern.

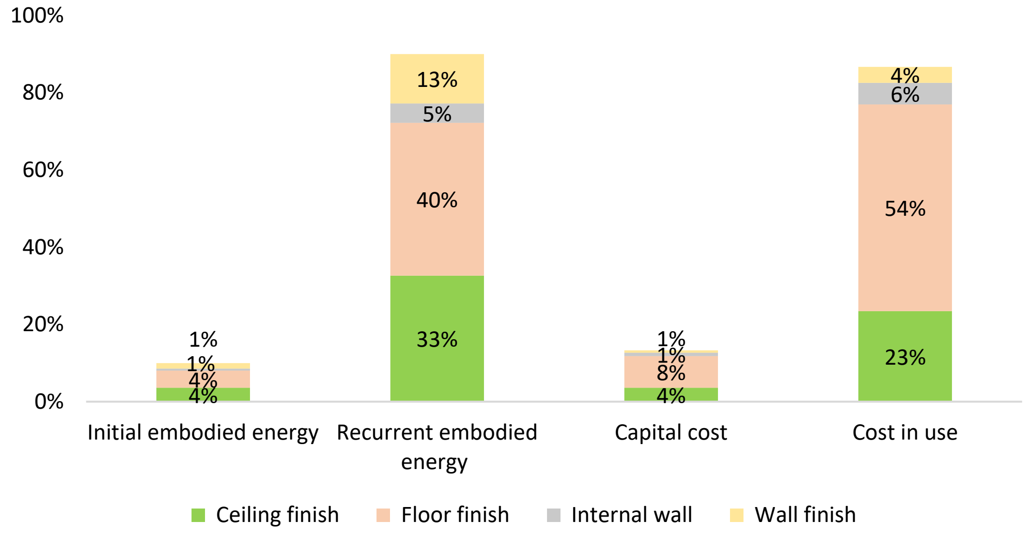


Figure 7.17: Comparison of percentage initial and recurrent embodied energy from life cycle embodied energy and capital cost and cost-in-use as a percentage of the life cycle material cost of different assemblies of the business as usual scenario of services shop

7.3.3.2 Minimum life cycle embodied energy scenario

The assembly configuration of the *minimum LCEE* scenario is constructed using *calcium silicate brick wall, cement mortar with white putty wall finish, metal framed ceiling with cork tiles* and *terrazzo flooring with infill slab*. This composition of assemblies leads to a significant reduction of LCEE (-73%) when compared to the *BAU* scenario with an estimated intensity of 5.38 GJ/m^2. LCMC intensity of the scenario (AU$ 1,030.00 /m^2) is also 17% lower than the *BAU* scenario. As a result of reduced LCEE and LCMC, the LCMCWT is also reduced by 47% in comparison to the *BAU* scenario.

7.3.3.3 Minimum life cycle material cost scenario

The assembly combination of the *minimum LCMC* scenario contains *gypsum block wall, cement mortar with white putty, plasterboard lining with paint on metal framed ceiling* and *cork board flooring*. LCEE and LCMC intensities of this scenario are estimated as 15.00 GJ/m^2, and AU$ 610.00 /m^2, respectively. The LCMC reduction compared to the *BAU* scenario is 51%, and the LCEE is also reduced by 26%. The LCMCWT (AU$ 1,620 /m^2) is also 38% lower than the *BAU* scenario, but 16% higher than the *minimum LCEE* scenario. Therefore, it can be concluded that the *minimum LCMC* scenario is a better solution than the *BAU* scenario minimising both embodied energy and material costs over the life cycle.

7.3.3.4 Minimum life cycle material cost with carbon tax scenario

The *minimum LCMCWT* scenario is constructed using a *gypsum block wall, cement mortar with white putty wall finish, metal framed ceiling with cork tiles* and *terrazzo flooring with infill slab*. This solution has the lowest LCMCWT (AU$ 1,220.00 /m^2) which reduces the *BAU* scenario's LCMCWT by 53%. LCEE and LCMC intensities of the shop are estimated as 5.70 GJ/m^2, and AU$ 830.00 /m^2, resulting in 72% and 33% reductions respectively, in comparison to the *BAU* scenario.

The assembly combination of the *optimal* scenario where LCEE and LCMC are minimised is identical to the *minimum LCMCWT* scenario, and therefore, the analysis can be applied to that scenario as well. The Pareto frontier of *services* shop solutions is demonstrated in Figure 7.18.

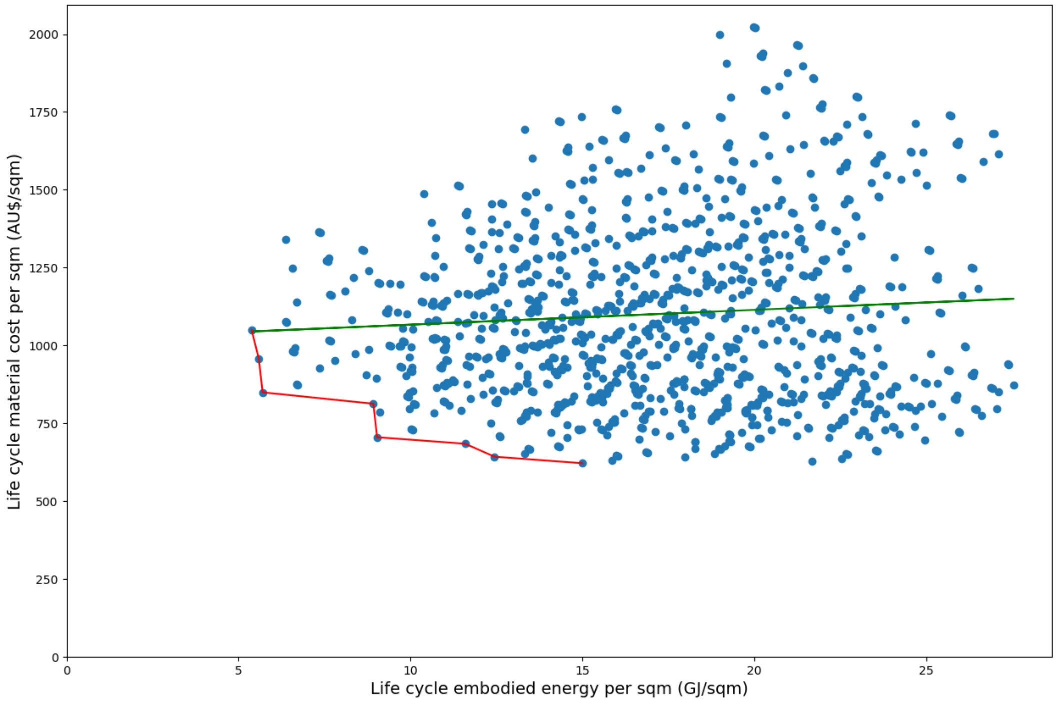


Figure 7.18: Pareto frontier solutions of the services shop

The scatter plot of all possible assembly combinations for *services* shop which graphs LCEE intensity against LCMC intensity is dispersed across the design space. There is no potential linear relationship between the variables (Pearson's correlation: 0.076). The regression line, however, shows a slight upward trend indicating a positive association between LCEE and LCMC intensities. Furthermore, it is visible that a larger number of plots lean towards higher value margins along x and y axes, which are worse than the Pareto optimal solutions.

This section compared embodied environmental effects and material costs of different shop types defined in the modelling process and identified from the case studies as described in Chapter 5. However, under *specialty shop* category only a single shop type was presented due to the conciseness of the chapter. More assembly combinations minimising LCEE and LCMC independently and combined for all shop types identified in Chapter 5 are presented in appendix as mentioned earlier. The next section offers comparisons of all *specialty shop* types defined in the model, to recognise the similarities and differences of LCEE, LCMC and LCMCWT across the scenarios.

7.4 COMPARISON OF LIFE CYCLE EMBODIED ENERGY AND MATERIAL COSTS OF DIFFERENT SPECIALTY SHOPS

Different *specialty shop* types in shopping centres have variances in material selection preferences based on a series of factors, as discussed in Chapter 5 and 6. These various assembly preferences, therefore, result in different embodied energy values and material costs over the shop life cycles. The LCEE, LCMC and LCMCWT of all *specialty shops* across all scenarios are compared in Figures 7.19, 7.20 and 7.21, respectively. The intensities are compared to improve the accuracy of the comparisons, rather than absolute values.

Figure 7.19 illustrates an overview of the LCEE intensities at the shop level. In the *BAU* scenario, LCEE intensities of the shops range between 10.26 GJ/m^2 to 24.23 GJ/m^2, where the average is 19.51 GJ/m^2. Five shop types have intensities above average, namely from the highest; *household*, *gymnasium, leisure and entertainment, services,* and *clothing.* Conversely, *café and restaurant* is identified as the most embodied energy efficient shop type in the *BAU* scenario followed by *food supplies* and *shoes*. The comparison of the *BAU* scenario further indicates that the majority of *specialty shops* are inclined towards higher LCEE intensities. In the *minimum LCEE* scenario, LCEE intensities range between 14.29 GJ/m^2 and 5.38 GJ/m^2. The average LCEE intensity is 9.84 GJ/m^2, which is almost half the average of the *BAU* scenario. As with the *BAU* scenario, five shops are leaned towards higher LCEE category led by *gymnasium*, and four shops are in the lower category where *services* shop type has the lowest intensity. A similar pattern can be observed in the *minimum LCMC* scenario, with an average of 16.25 GJ/m^2, which is 17% less than the average in the *BAU* scenario. However, in the *minimum LCMC* scenario, *clothing* shop has the highest LCEE intensity followed by *shoes*, whereas *leisure and entertainment* shop has the lowest intensity. In the *optimal* scenario, LCEE intensities range between 5.70 GJ/m^2 and 15.61 GJ/m^2. The average intensity is 10.88 GJ/m^2, which is 44% less than in the *BAU* scenario. Among different types, *services* shop has the lowest LCEE intensity.

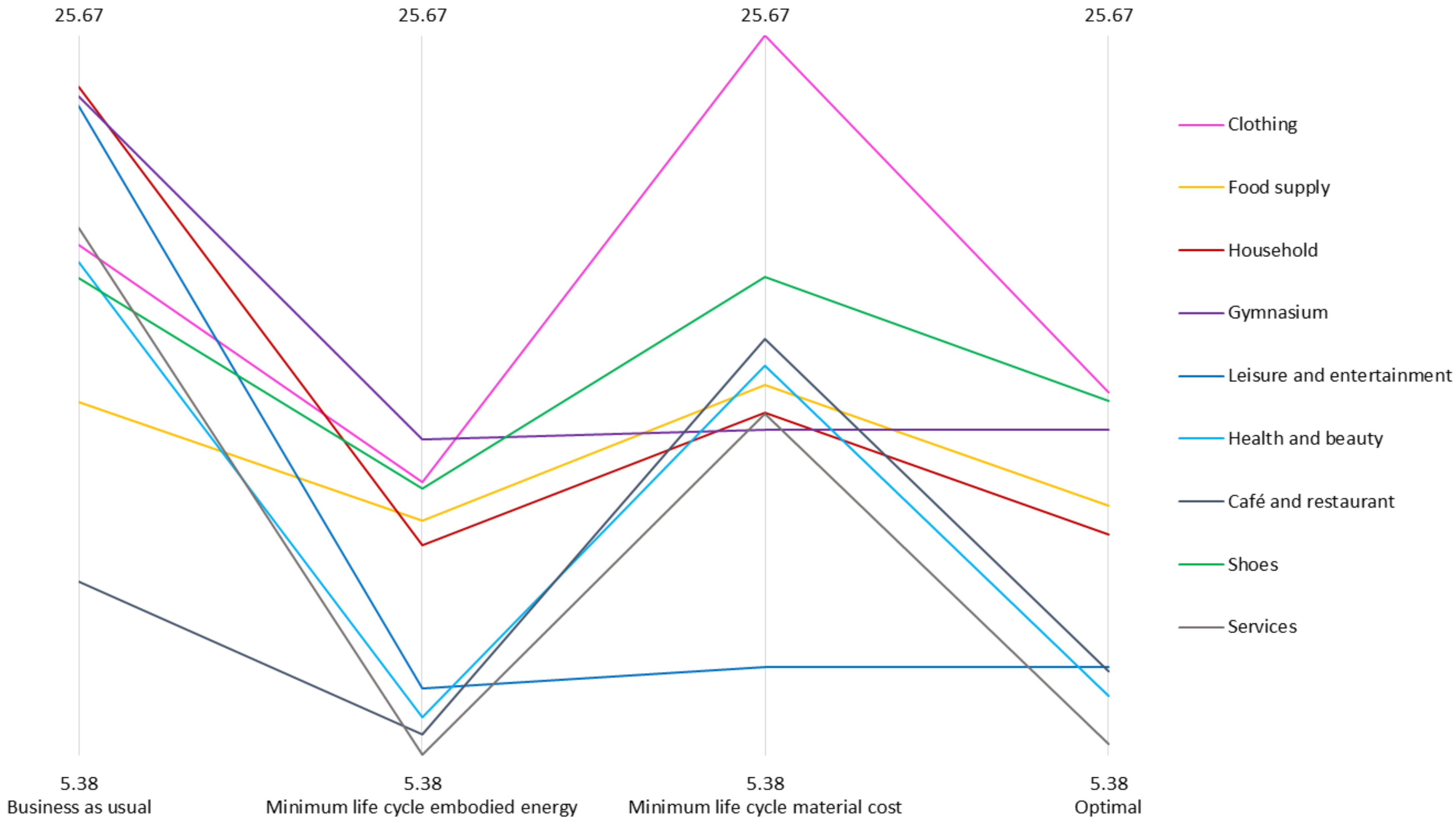


Figure 7.19: Comparison of life cycle embodied energy per unit area (in GJ/m²) of different specialty shop types in shopping centres

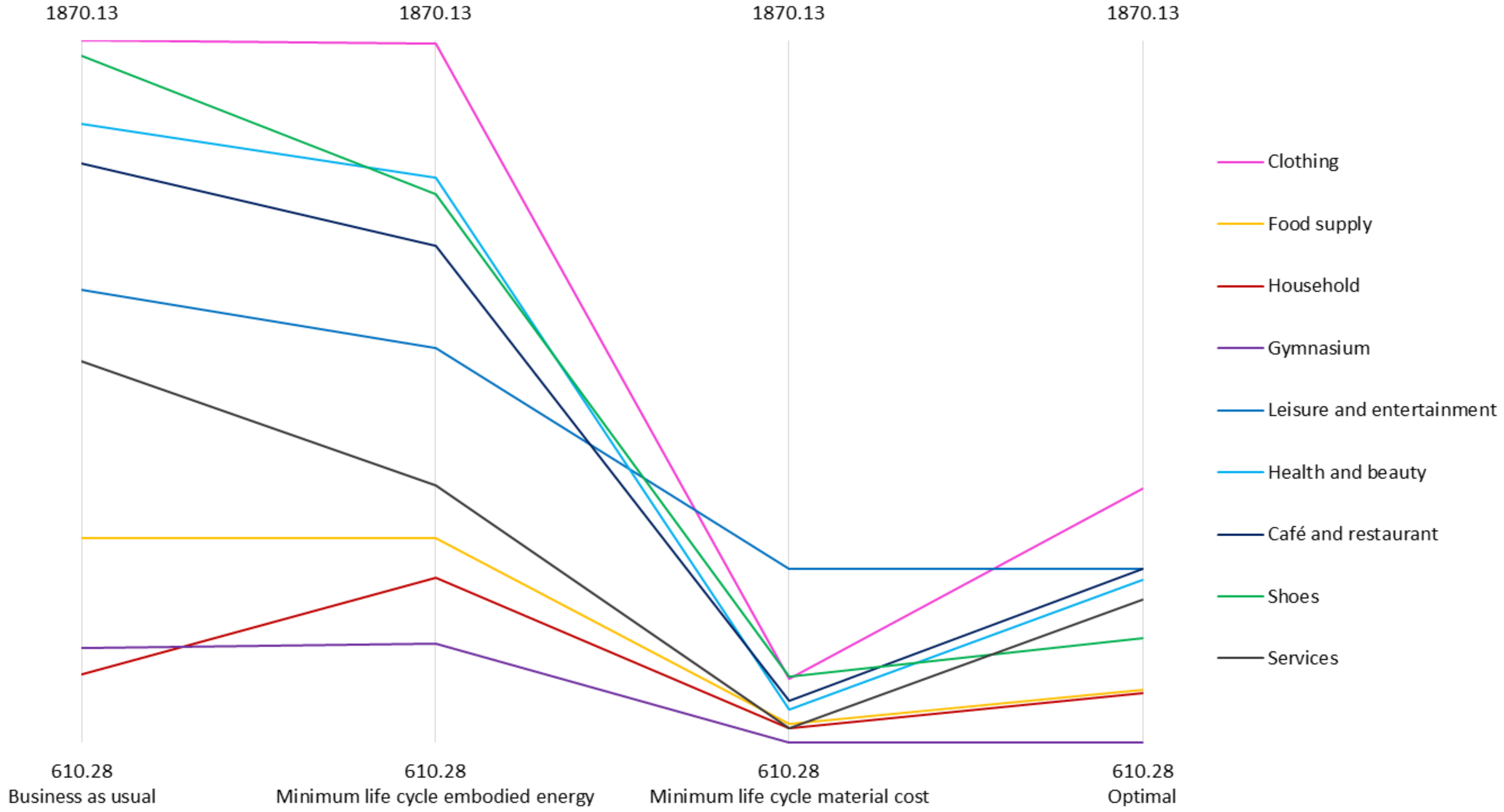


Figure 7.20: Comparison of life cycle material cost per unit area (in AU$/sqm) of different specialty shop types in shopping centre

The comparison of LCMC intensities across different scenarios is presented in Figure 7.20. Accordingly, in the *BAU* scenario, LCMC intensities range between AU$ 610.00 /m^2 and AU$ 1870.00 /m^2, accounting for an average of AU$ 1,340.00 /m^2. Amongst, *clothing* shop has the highest LCMC intensity followed by *shoes*. *Household* and *gymnasium* have the lowest material cost intensities. When *minimum LCEE* scenario is compared, *clothing* and *health and beauty* shops have the highest LCMC intensities, while *gymnasium* and *household* have the lowest intensities. LCMC intensities in this scenario vary between AU$ 770.00 /m^2 and AU$ 1860.00 /m^2, resulting in an average of AU$ 1,270.00 /m^2 which reduces the average in *BAU* scenario by 5%. The most interesting aspect of this graph is that the LCMC intensities in the *minimum LCEE* scenario in all shops are lower than in the *BAU* scenario except for *household* and *gymnasium*. In the *minimum LCMC* scenario, average LCMC intensity is AU$ 680.00 /m^2, ranging between AU$ 610.00 /m^2 and AU$ 900.00 /m^2. In comparison, it is 49% lower than the average of the *BAU* scenario, which is a massive reduction. Among different shop types*, leisure and entertainment* and *clothing* shops have the highest LCMC intensities, whereas *gymnasium* and *services* have the lowest intensities. The comparison of LCMC intensities of the *optimal* scenario identifies that even when both LCEE and LCMC reductions are considered, the average LCMC intensities of the *BAU* scenario can be reduced by 39%, valued as AU$ 820.00 /m^2. The intensities range between AU$ 610.00 /m^2 and AU$ 1,060.00 /m^2. *Clothing* and *leisure and entertainment* shops are identified to have the highest intensities and *gymnasium* and *household* to have the lowest. To conclude, across all scenarios except *minimum LCMC* scenario, *clothing* has the highest LCMC intensity, and except in the *BAU* scenario, *gymnasium* has the lowest LCMC intensity.

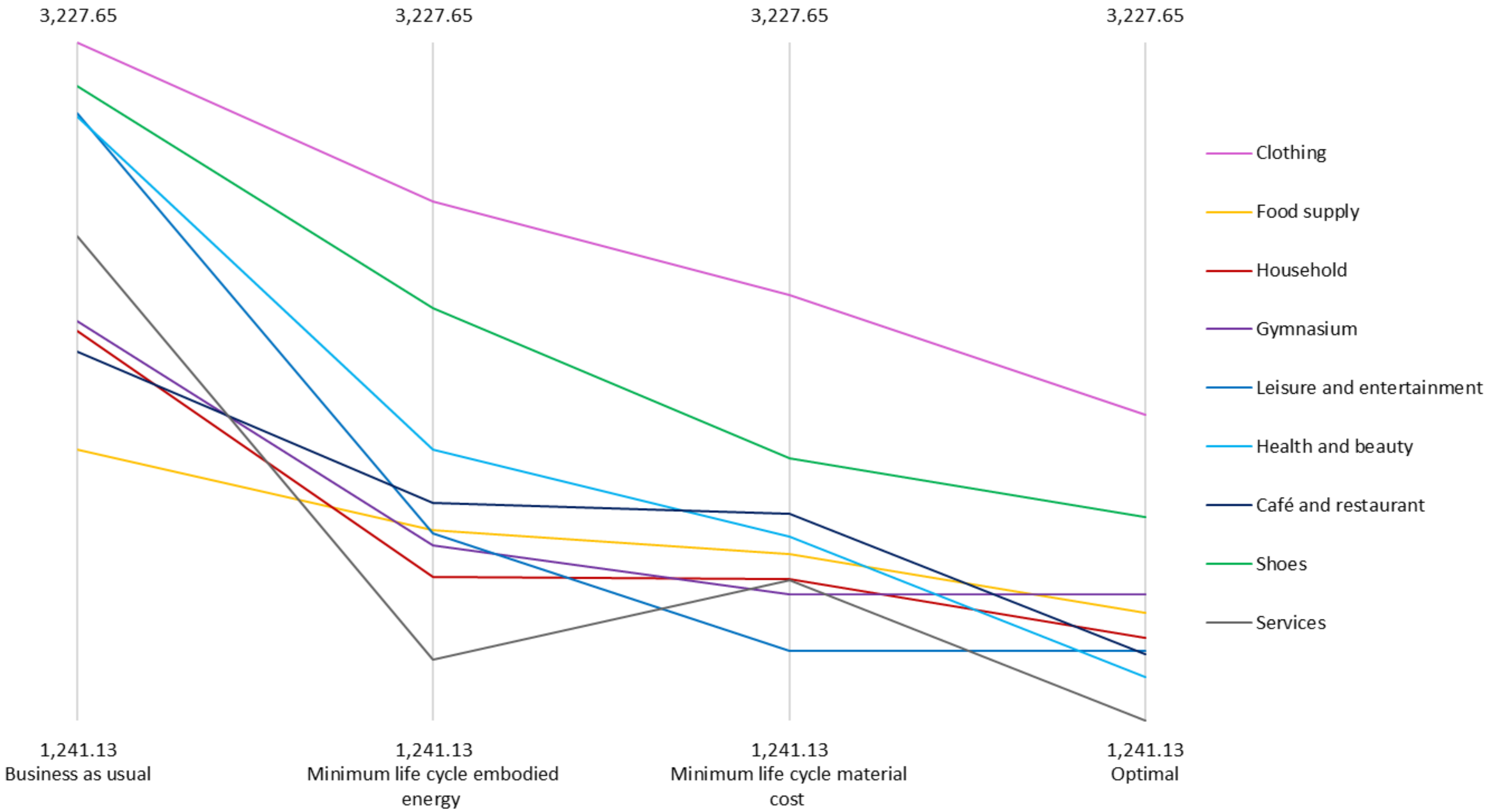


Figure 7.21: Comparison of life cycle material cost with carbon tax per unit area (in AU$/sqm) of different specialty shop types in shopping centres

However, the situation changes when a carbon tax is aggregated to the material cost of the shops. The comparison of LCMCWT in Figure 7.21 indicates that across all scenarios *clothing* and *shoes* shops have the highest intensities. The LCMCWT value ranges between AU$ 2,030.00 /m^2 (*food supply*) and AU$ 3,230.00 /m^2 (*clothing*) in the *BAU* scenario accounting for an average of AU$ 2,690.00 /m^2. The *minimum LCEE* scenario shows that LCMCWT value spans between AU$ 1,420.00 /m^2 (*services*) and AU$ 2,760.00 /m^2 (*clothing*). The average LCMCWT of all *specialty shops* is estimated as AU$ 1,950.00 /m^2, which is 27% lower than the *BAU* scenario. The comparison of the *minimum LCMC* scenario shows an average of AU$ 1,800.00 /m^2, resulting in a 33% reduction from the *BAU* scenario. The values range in between AU$ 1,440.00 /m^2 (*leisure and entertainment*) and AU$ 2,490.00 /m^2 (*clothing*). In the *optimal* scenario, LCMCWT of the shops range from AU$ 1,240.00 /m^2 (*services*) and AU$ 2,140.00 /m^2 (*clothing*). The average intensity is AU$ 1,570.00 /m^2, which is 42% lower than in the *BAU* scenario.

The most interesting observation that can be made from the graph is that the LCMCWT of all shops reaches their lowest values in the *optimal* scenario where both LCEE and LCMC are equally minimised. Therefore, it is recognised that the enforcement of a carbon tax could direct developers towards the *optimal* solutions while they minimise the LCMCWT.

7.5 COMPARISON OF PARETO DISTRIBUTIONS OF DIFFERENT SPECIALTY SHOPS

The LCEE and LCMC intensities of different assembly combinations of all specialty shop types are graphed in Figures 7.22, and 7.23. Shops with positive bivariate relationships are displayed in Figure 7.22, whereas negative relationships are presented in Figure 7.23. The scatter plot graphs can be described in terms of form, direction, and strength, along with the existence of outliers to identify the association of the variables of LCEE and LCMC intensities. No correlation was analysed between embodied emissions (LCEGHGE) and cost (LCMC) because emission is a scalar multiplication of energy and thus the relationship is similar. Pearson's correlation coefficient is used to determine the strength of the relationship between the variables.

Accordingly, the results demonstrate that among different specialty shops, *health and beauty, leisure and entertainment, gymnasium* and *household* shops indicate a positive association of LCEE and LCMC intensities (refer Figure 7.22). It signifies that the reductions of LCEE intensities can result in LCMC reductions as well. However, the strength of the association is different for each shop type.

In *health and beauty* shop, the scatter plot shows that the dots are dispersed across the design space resulting in no linear relationship with a PCC of 0.040. The Pareto frontier identified eight Pareto *optimal* points of which the solution minimising both LCEE and LCMC equally, is as with the *minimum LCMC* with carbon tax solution.

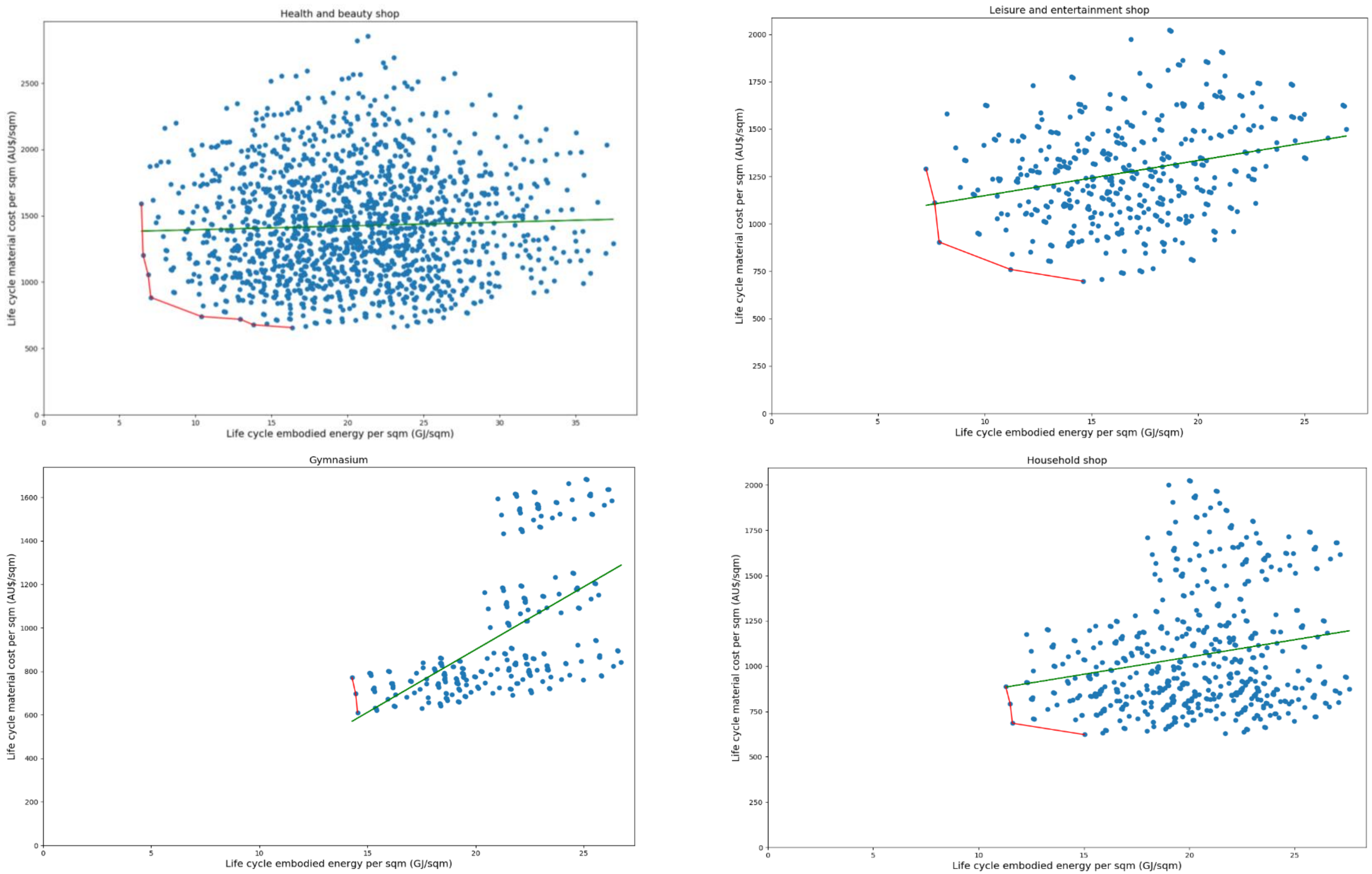


Figure 7.22: Pareto frontier solutions and design space distribution of different specialty shops with positive bivariate relationship

The scatterplot graph of *leisure and entertainment* shop shows a similar pattern in the dispersion of the dots. However, here the number of dots is less than in *health and beauty* shop indicating that a lesser number of assembly combinations are available for *leisure and entertainment* shop within the selected assembly solutions. The scatter plot indicates a weak positive linear relationship (PCC: 0.272) between LCEE and LCMC intensities, with several potential outliers. The Pareto frontier shows five *optimal* points where the solution minimising both LCEE and LCMC equally is identical to the *minimum LCMCWT* solution.

Graphical representation of the LCEE and LCMC intensities of *gymnasium* shows a strong positive relationship between the variables with a PCC of 0.558. However, the scatterplot reveals a large cluster of outliers of the regression line. Furthermore, the number of solutions in the graph is far less than in any other shops presented in Figure 7.22. The distribution ponders towards larger values of LCEE indicating the majority of the solutions are worse than the Pareto *optimal* solutions. The Pareto frontier identified only three *optimal* solutions. As with other *specialty shops*, the solution minimising LCEE and LCMC equally is identical to the *minimum LCMCWT* solution.

Household shop demonstrates a weak positive relationship between the variables in the scatterplot graph with a PCC of 0.202. Several potential outliers are visible in the distribution. The solutions are dispersed through the design space weighing more towards higher values of LCEE intensities. Pareto frontier identified four points of which the *optimal* solution with equal weights is as with the *minimum LCMCWT* solution.

Figure 7.23 presents the graphical representation of LCEE and LCMC intensities of assembly combinations of *shoes, food supply, café and restaurant* and *clothing* shops. They show a negative association between the variables which signifies that the reductions of LCEE intensities can result in increased LCMC intensities. However, for different shop types the strength of the association is different.

The scatterplot graph of *shoes* shop type shows a dispersal of the dots across the design space with a PCC of -0.048, indicating no linear relationship between the two variables. The solutions start far from the Y-axis, between the LCEE intensities of 10 GJ/m^2 and 15 GJ/m^2, which is similarly followed in *food supply* and *clothing* shops. The Pareto frontier shows ten solutions where the *optimal* solution minimising both LCEE and LCMC equally is identical to the *minimum LCMCWT* solution.

In *food supply* shop, the graph shows no linear relationship with a PCC of -0.077. The number of dots in the design space is less than in the *shoes* shop. The Pareto frontier identified four Pareto *optimal* points of which the solution minimising both LCEE and LCMC equally is as with the *minimum LCMCWT* solution.

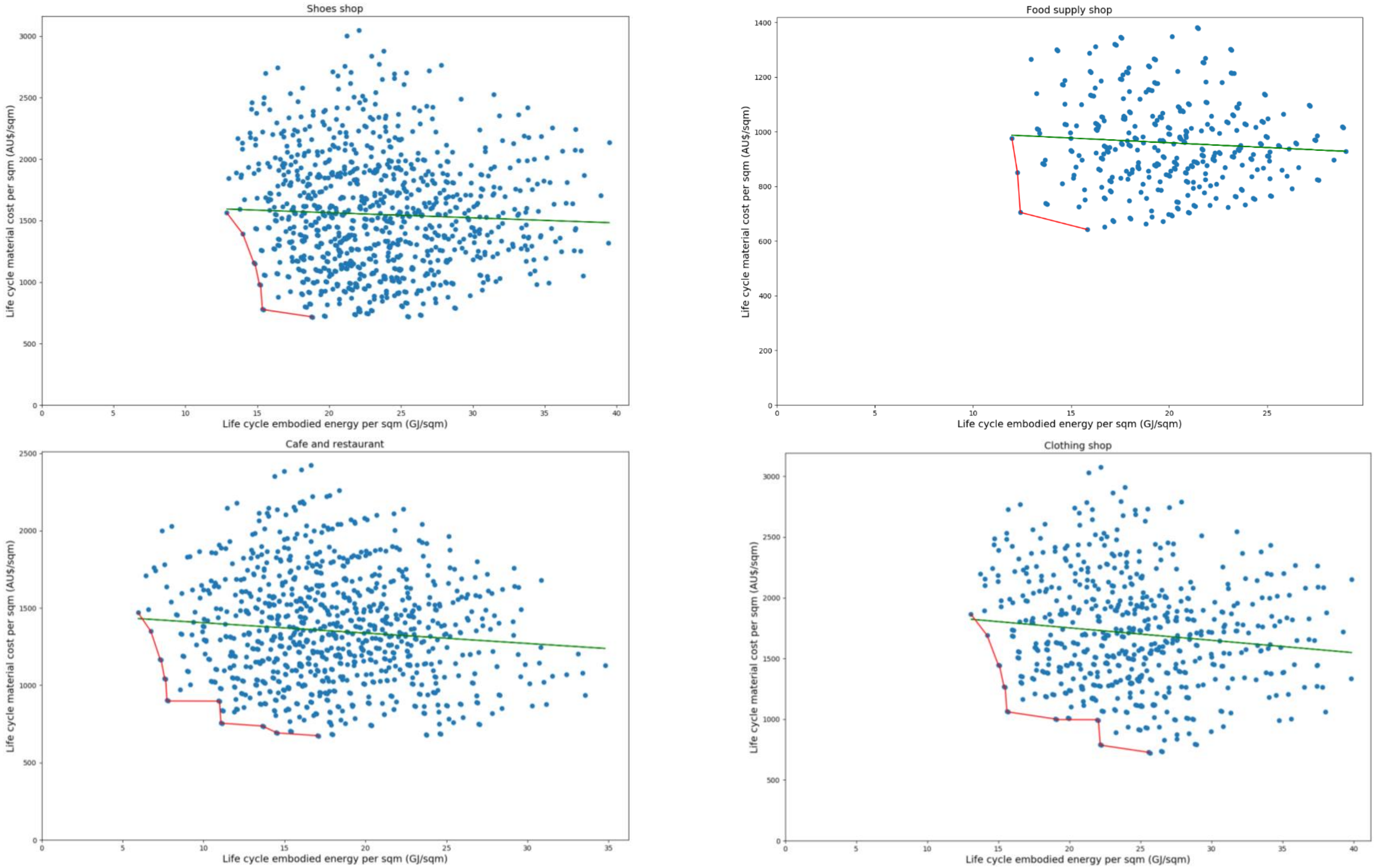


Figure 7.23: Pareto frontier solutions and design space distribution of different specialty shops with negative bivariate relationships

The graphical presentation of *café and restaurant* also indicates no linear relationship between the variables. The PCC between the variables is -0.097. The dots are more dispersed across the design space, starting closer to the Y-axis between LCEE intensities of 5 GJ/m^2 and 10 GJ/m^2. The Pareto frontier disclosed 17 *optimal* solutions which is the largest number of *optimal* solutions identified in a *specialty shop* type. Amongst, the solution minimising both LCEE and LCMC equally, is as with the *minimum LCMCWT* solution.

The results of *clothing* shop reveal a weak negative relationship between LCEE and LCMC intensities with a PCC of -0.122. From the 16 Pareto *optimal* solutions identified, the *minimum LCMCWT* solution is established as the *optimal* solution minimising both LCEE and LCMC intensities.

This section offered the similarities and differences of the distribution of LCEE and LCMC intensities of assembly combinations of different *specialty shops*, while acknowledging their significance in terms of reducing embodied environmental effects.

7.6 SUMMARY OF ASSEMBLY AT THE SHOP LEVEL

Assemblies have different LCEE intensities depending on the type of shop they are installed. This is due to different refurbishment frequencies of shop types and assembly service life values. As explained in Section 4.7, the number of assembly replacements of a shop over the period of analysis of a shopping centre is quantified based on the RF and assembly service life values. This number of replacements of assemblies, therefore, vary for different types of shops and ultimately trigger variable LCEE values.

Figure 7.24 illustrates the LCEE intensities of finishes assembly types across shop types. Here shop types are assigned their typical refurbishment frequencies as specialty shops: 5 years, anchor shops: 20 years, common areas: 10 years and toilets and sanitary areas: 10 years.

It is apparent from the figure that most finishes assembly types have varying LCEE values for different categories of shop types. The LCEE values of assemblies are higher in shop types with lower RF values than the ones with higher RF values since the number of replacements is more in the former. However, in certain shop types, even though the RF is higher than others, several assemblies have higher LCEE values since they are required to be replaced more times due to lower service life values. Appendix 14 provides more detailed information on LCEE and LCMC intensities of assembly types when they are installed in different shop types.

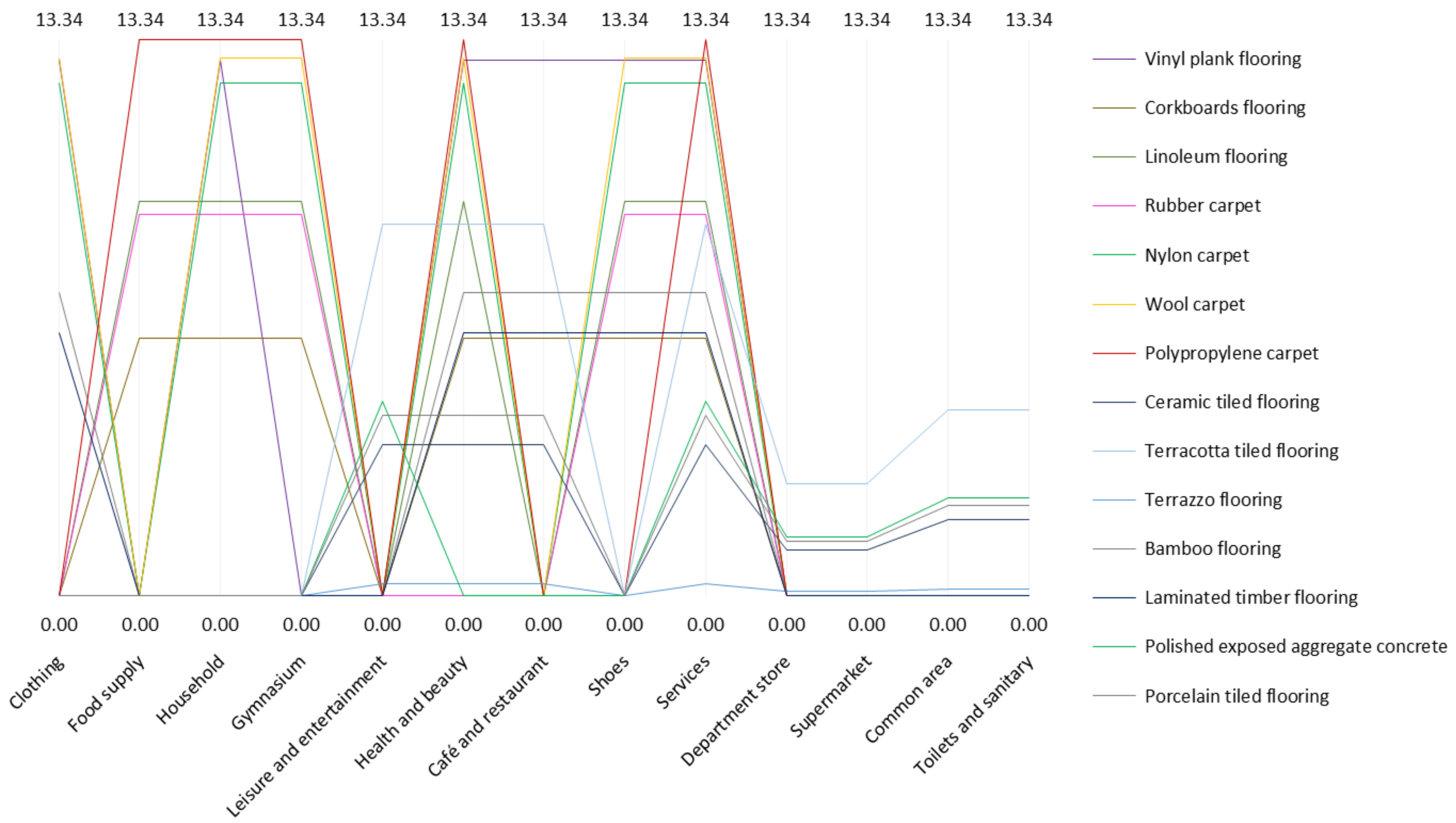


Figure 7.24: Parallel coordinates graph of life cycle embodied energy intensities of floor finishes assemblies across different shop types in the shopping centre

7.7 THE INFLUENCE OF THE REFURBISHMENT FREQUENCY ON LIFE CYCLE EMBODIED ENERGY OF DIFFERENT SHOP TYPES

The previous analysis in Section 7.4 compared LCEE intensities of shop types across the scenarios. These scenarios were analysed for a pre-defined refurbishment frequency of a shop. This section presents how LCEE of shop types would respond to changes in the refurbishment frequencies. Three types of shops are selected for the analysis, namely; *services shop* representing *specialty shops*, *discount department store* representing *anchor shops* and *common area* since they represent the largest shares of GLA in shopping centres. The refurbishment frequencies are changed from 5 to 10 years (*speciality*), from 20 to 15 (*anchor)* years*,* and from 10 to 15 (*common areas*) years. The increments and decrements are determined based on the findings of semi-structured interviews with the centre managers. Variations in LCEE across the scenarios are compared. Figure 7.25 illustrates the comparisons of LCEE values of the shops with different refurbishment frequencies.

Results demonstrate that increasing the refurbishment frequency of *speciality shops* by 100% would result in around 50% reduction in the embodied energy and material cost. Similarly, in *common areas* raising refurbishment frequency by 25% reduces LCEE by 16% while LCMC is reduced by 19%. However, in *anchor shops* lowering refurbishment frequency by 25% cause 28% LCEE increments and 23% LCMC increments. These results indicate that changing the increments and decrements in refurbishment frequencies have different effects on the levels of impact in terms of LCEE and LCMC.

The analysis also discovered that when refurbishment frequencies are altered the model identified some different assembly combinations to minimise LCEE, LCMC and LCMCWT. Table 7.8 presents the changes observed in assembly selection in the *optimal* scenario of the *services* shop when refurbishment frequency is increased by 100%, from 5 to 10 years.

Table 7.8: Changes in assembly selection when refurbishment frequency is increased in services shop optimal scenario

Assembly type	Refurbishment frequency 5 years	Refurbishment frequency 10 years
Ceiling finish	Metal frame ceiling with cork tiles	Metal frame ceiling with cork tiles
Floor finish	Terrazzo flooring with infill slab	Terrazzo flooring with infill slab
Internal wall	Gypsum block wall (500 × 500 × 100 mm)	Brick walls (110 mm)
Wall finish	10 mm cement mortar screed with white putty	10 mm cement mortar screed with white putty

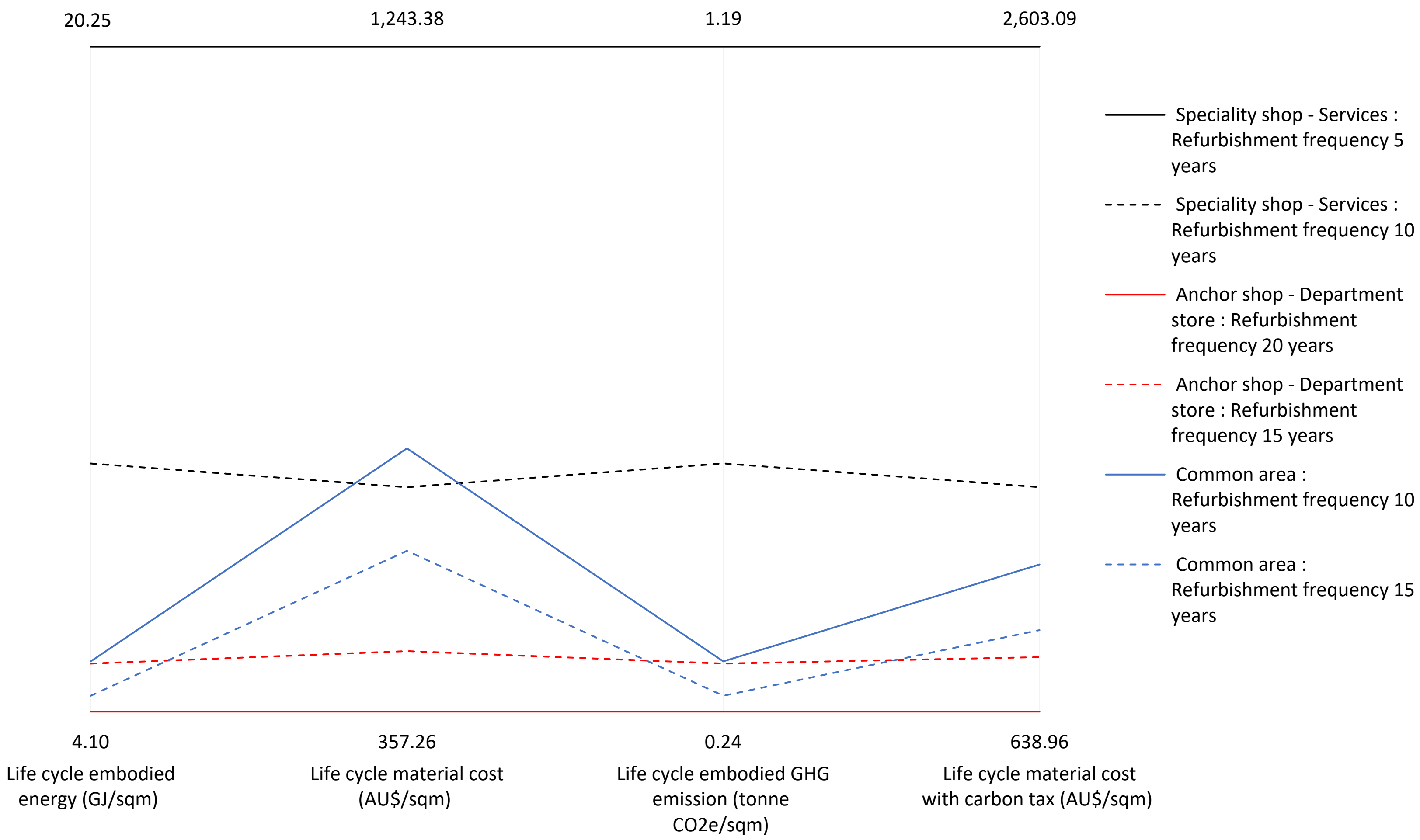


Figure 7.25: Life cycle embodied energy, embodied greenhouse gas emission and material cost with and without carbon tax at different refurbishment frequencies parallel coordinates diagram

The results indicate that 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. Furthermore, as would be expected increasing the refurbishment frequencies result in LCEE, LCMC and LCMCWT value reductions as a result of the decreased number of replacements.

7.8 ANALYSIS AT THE SHOPPING CENTRE LEVEL

This section presents the analysis of LCEE and LCMC of the average shopping centre across five scenarios of *BAU, minimum LCEE, minimum LCMC with and without the carbon tax,* and the *optimal*. The analysis incorporates average shopping centre design with minor modifications to the building morphology as defined in Chapter 5. An overview of the profile of shops in the average shopping centre is presented in Table 7.9.

Table 7.9: Profile of shops in the shopping centre

Shop type	No of shops	Gross lettable area (m^2)
Supermarket	2	5,304.00
Discount department store	1	5,394.00
Clothing	3	401.00
Food supplies	7	1,290.00
Household	4	2,323.00
Gymnasium	1	400.00
Leisure and entertainment	1	90.00
Health and beauty	8	976.00
Coffee and restaurant	8	884.00
Shoes	1	112.00
Services	9	788.00

The combinations of building materials and assemblies used to construct the shops are defined based on the type of shop (refer Chapters 5 and 6). Common areas, toilets and sanitary, and the centre structure are also considered as shop types for modelling purposes as defined in Chapter 6. Accordingly, 14 different shop types were identified in the average shopping centre.

All possible assembly combinations that can be used to design different types of shops have been discussed in Section 7.3. Combinations of shops which can be used to design the shopping centre are then generated using those different assembly combinations for each shop type. The number of assembly combinations that can be used to design a shop type is limited to a maximum of thousand. Since the shopping centre has 45 shops, the number of different combinations of shops is more than a trillion unmanageable scenarios. The selection of shop solutions to assess LCEE and LCMC of shopping centres across the scenarios is explained below.

*Take **food supply** shop type, for example.*

Number of combinations** of assemblies of the shop type: **576

*Since the shopping centre has **seven food supply** shops, each shop has the possibility of choosing any combination out of the 576. So, the total number of combinations of **food supply shops** with different assembly combinations in the shopping centre can be presented as;*

***Number of food supply shop combinations**: 576^7 = 21,035,720,123,168,600,000*

Since this number is just for seven shops, the possible number of shop combinations for all 45 shops is beyond current capacity of the model.

Due to this substantial number of possible shop combinations for designing a shopping centre, the study only focuses on the best 50 shop combinations that minimise the LCEE and LCMC and the optimal. The shop level analysis identified that the assembly combination with minimum LCMC with carbon tax is as with the *optimal* assembly combination. As a result of this outcome, the shopping centre analysis disregards the LCMCWT scenario. Therefore, a total of 150 shop combinations are analysed using the model to determine the most preferred combinations that fulfil the requirements. The selection of the best 50 combinations of shops minimising LCEE, LCMC or both was carried out based on the results of Section 7.3. For instance, to select the best 50 shop combinations minimising LCEE of the shopping centre, the model first selected the best three combinations of assemblies minimising LCEE for each shop type. This selection was limited to shop type to generate a manageable number of possible combinations. Therefore, three assembly combinations with minimum LCEE were selected from each shop type in the shopping centre and the number of combinations generated is as follows.

***Number of shop combinations** minimising LCEE: 3^14 = 4,782,969*

The same process is followed for the other objectives and the results were analysed. This process is acceptable since the LCEE and LCMC of the shopping centre are the sums of LCEE and LCMC of all individual shops. The following mathematical notation further justifies this approach.

If; $x = a + b + c$

$$\min(x) = \min(a) + \min(b) + \min(c)$$

Because $x{:} \rightarrow \min\,(x)$ *is a bijective function in* $\mathbb{R}$

Therefore, by selecting the top three combinations of assemblies for shops, the model set boundaries to the selection of combinations of shops without affecting the best combination that achieves each objective. The linearity between the shopping centre LCEE and LCMC with shops' allows the model to execute the process without complications.

The analysis below presents the four scenarios of the shopping centre, identifying the effects of assembly selection at the whole shopping centre level. Table 7.10 offers an overview of the embodied energy and material cost values of the scenarios.

Table 7.10: Comparison of different scenarios of the shopping centre

Criteria	**Scenarios**			
	Business as usual	**Minimum LCEE**	**Minimum LCMC**	**Optimal**
Initial embodied energy ('000 GJ)	268.41	169.89	256.86	170.17
Recurrent embodied energy ('000 GJ)	217.28	105.02	178.51	108.73
Life cycle embodied energy ('000 GJ)	485.69	274.91	435.38	278.90
Capital cost (million AU$)	25.54	25.37	24.08	24.85
Cost-in-use (million AU$)	12.51	12.36	7.57	10.38
Life cycle material cost (million AU$)	38.05	37.73	31.65	35.23
Life cycle embodied greenhouse gas emission (tonne CO_2e)	28,548.72	16,159.24	25,591.41	16,393.67
Life cycle material cost with carbon tax (million AU$)	70.59	56.18	60.88	53.95

LCEE: Life cycle embodied energy; LCMC: Life cycle material cost

Figure 7.26 compares the absolute values of LCEE and LCMC across the scenarios. Accordingly, the *minimum LCEE* scenario has the least LCEE followed by the *optimal* scenario. Also, *minimum LCMC* scenario has the least LCMC followed by the *optimal* scenario. Furthermore, it can be noted that the fluctuations in LCEE are more significant than in LCMC across different shopping centre scenarios.

Figure 7.27 illustrates the distribution of LCEE (IEE and REE) and LCMC (CC and CIU) across the scenarios. Accordingly, it can be observed that the IEE contribution fluctuates between 55% and 62% of the LCEE. The largest share of IEE is observed in the *minimum LCEE* scenario, valued as 62%. The LCMC composition across the scenarios indicates a pattern of CC representing 67% to 76% of the total, where the maximum is reached in the *minimum LCMC* scenario.

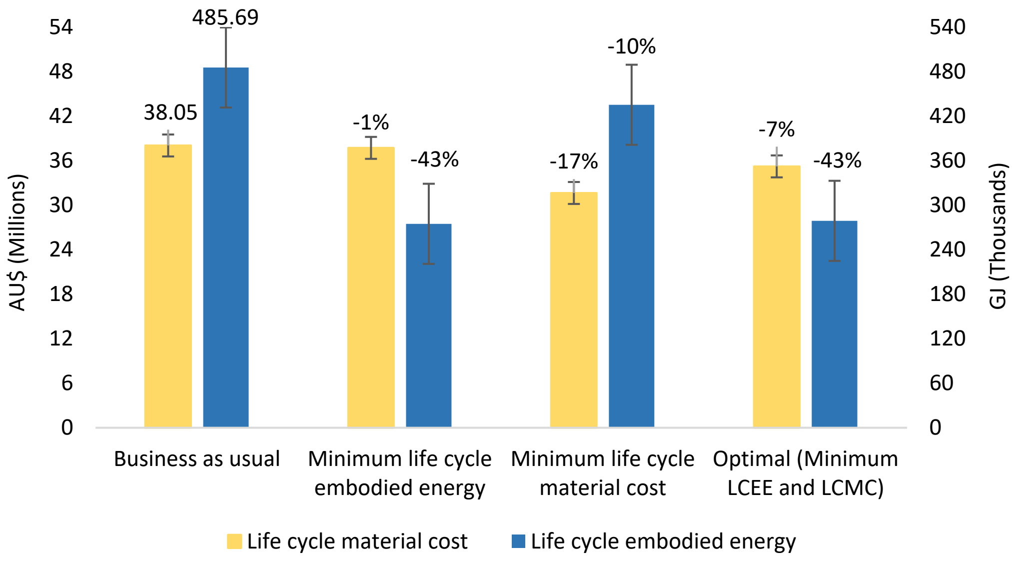


Figure 7.26: Comparison of life cycle embodied energy and material cost across shopping centre scenarios (absolute values)

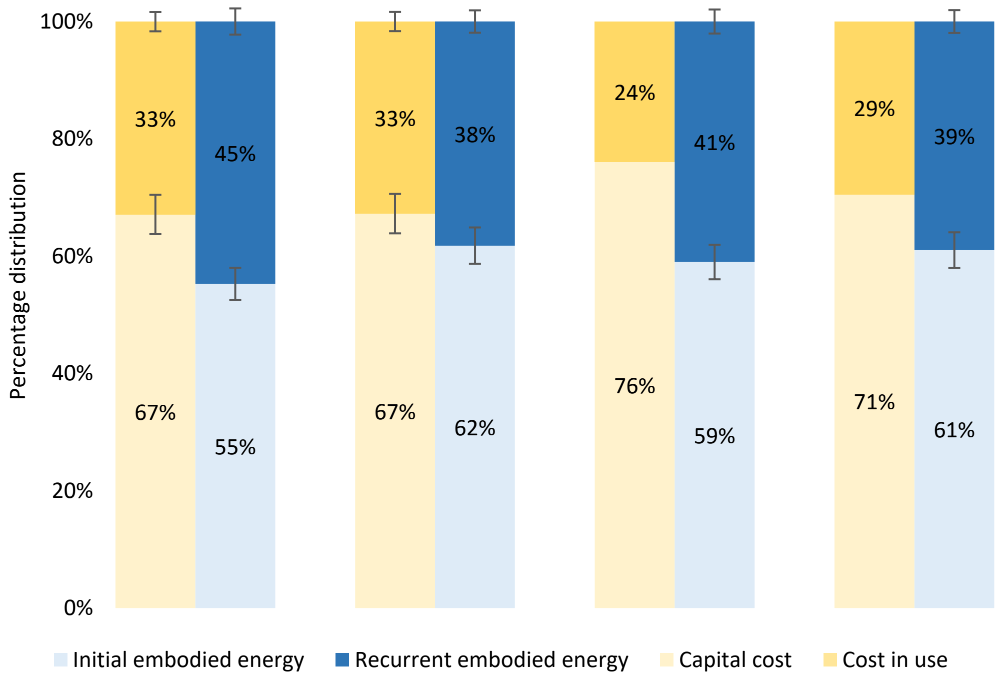


Figure 7.27: Comparison of life cycle embodied energy and material cost across shopping centre scenarios (percentages)

The most intriguing observation that can be made of the graph is that in order to minimise the LCMC of a shopping centre, the emphasis should be majorly on the CC, but for LCEE minimisation, it is vital to pay attention towards both IEE and REE.

The following sections provide the detailed analysis of the scenarios identifying their variations in embodied energy and material cost values.

7.8.1 Business as usual scenario

The typical shopping centre or the *BAU* scenario is an aggregation of the *BAU* scenarios of shop types described in Section 7.3. The scenario analysis was carried out based on the premise that shops belonging to the same type have an identical assembly combination. For instance, in a shop combination, all three *clothing* shops in the shopping centre are presumed to have an identical assembly combination.

The LCEE of the *BAU* scenario is 485,687.63 GJ, accounting for an intensity of 21.59 GJ/m^2. REE represents 45% from LCEE, resulting in an significantly higher annual value of 193.15 MJ/m^2/year, when compared to other property types in the construction context. Rauf and Crawford (2013) estimated that the annual REE intensity of an Australian house is 160 MJ/m^2/year, over a 50-year service life. Stephan and Stephan (2014) also found that a house in Lebanon accounts for an annual REE of 168.6 MJ/m^2/year, over 50 years. Both these studies use the same hybrid EEC compiled by Treloar and Crawford (2010) and have around 15% lower annual REE intensities than in shopping centres.

As discussed in Chapter 5, different types of shops account for various GLA percentages in a shopping centre. Based on the GLA and selection of building assemblies, percentage LCEE representation of each shop type is different. Figure 7.28 presents how LCEE is distributed across shop types in the shopping centre *BAU* scenario. Accordingly, the LCEE of the *centre structure* accounts for 52% of the LCEE of the shopping centre, followed by *household (11%), supermarket (8%), services (5%)* and *discount department stores (5%)*. The least impact towards LCEE is from *toilets and sanitary (~0%), shoes (~0%)* and *leisure and entertainment (~0%)* shops. The significant observation of the analysis is that even though the *centre structure* seems dominant regards to LCEE, all other shops combined represent 48% of the total, which is equally significant.

The LCMC of the *BAU* scenario is AU$ 38.05 million, where CC contributions cause 67 % of the total. The LCMC intensity of the shopping centre can be presented as AU$ 1,690.00 /m^2. The distribution of LCMC across shop types is illustrated in Figure 7.29 demonstrates that the *centre structure* accounts for 57% of the total, followed by *supermarket (7%), common areas (7%), discount department store (5%)* and others. The shops with least LCMC contributions are as before, where *toilets and sanitary areas (~0%)* has the lowest followed by *leisure and entertainment (~0%)* and *shoes (1%)* shops.

LCMCWT of the *BAU* scenario is estimated as AU$ 3,140.00/m^2. Figure 7.30 offers the comparison of LCMCWT contributions by shop types. The distribution shows that the *centre structure* is responsible for 55% of the LCMCWT followed by *anchor* *supermarket (7%)*, *household* (7%) and other shops. This pattern demonstrates that when the carbon tax is added, the percentage contributions of shop types are different than in the LCMC distribution. The changes in percentage contributions of LCMC indicates the significance of embodied energy effects of the shop types. Accordingly, it can be observed that the shop types with higher increments from LCMC indicate they have comparatively higher embodied energy effects and the ones with lower increments from LCMC have relatively lower LCEE effects.

The difference in contributions of LCEE and LCMC of shop types can be due to several reasons as, 1) the choice of materials and assemblies, 2) refurbishment frequencies, and 3) their respective GLA. This will be discussed in Chapter 8. Nevertheless, when absolute values are compared, the *centre structure* is responsible for the largest share of both LCEE and LCMC, making it the most significant for material selection decision making. For instance, shifting assemblies in the *BAU* scenario with the *minimum LCEE* assembly combination for the *centre structure* as described in Section 7.3.1.2 solely, can lead to 18% LCEE reductions of the shopping centre.

However, the comparison of LCEE and LCMC contributions of different shop types at the whole shopping centre level needs to be compared with the intensities per unit area to identify the relative significance. These intensities provide the understanding of LCEE and LCMC of shop types irrespective of their GLA in the shopping centre. Furthermore, the analysis presents the intensities of LCEGHGE and LCMCWT as well.

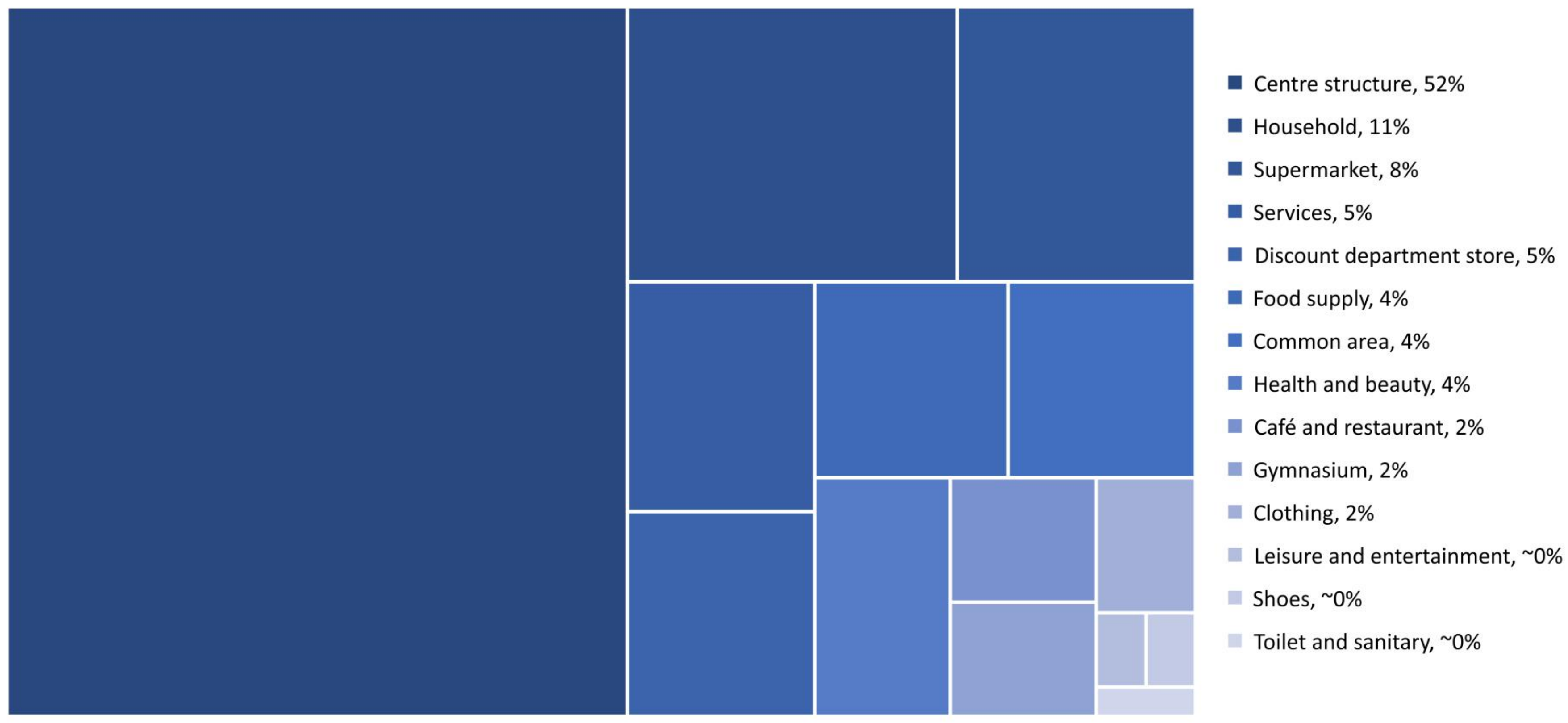


Figure 7.28: Life cycle embodied energy distribution across different shop types in the shopping centre business as usual scenario

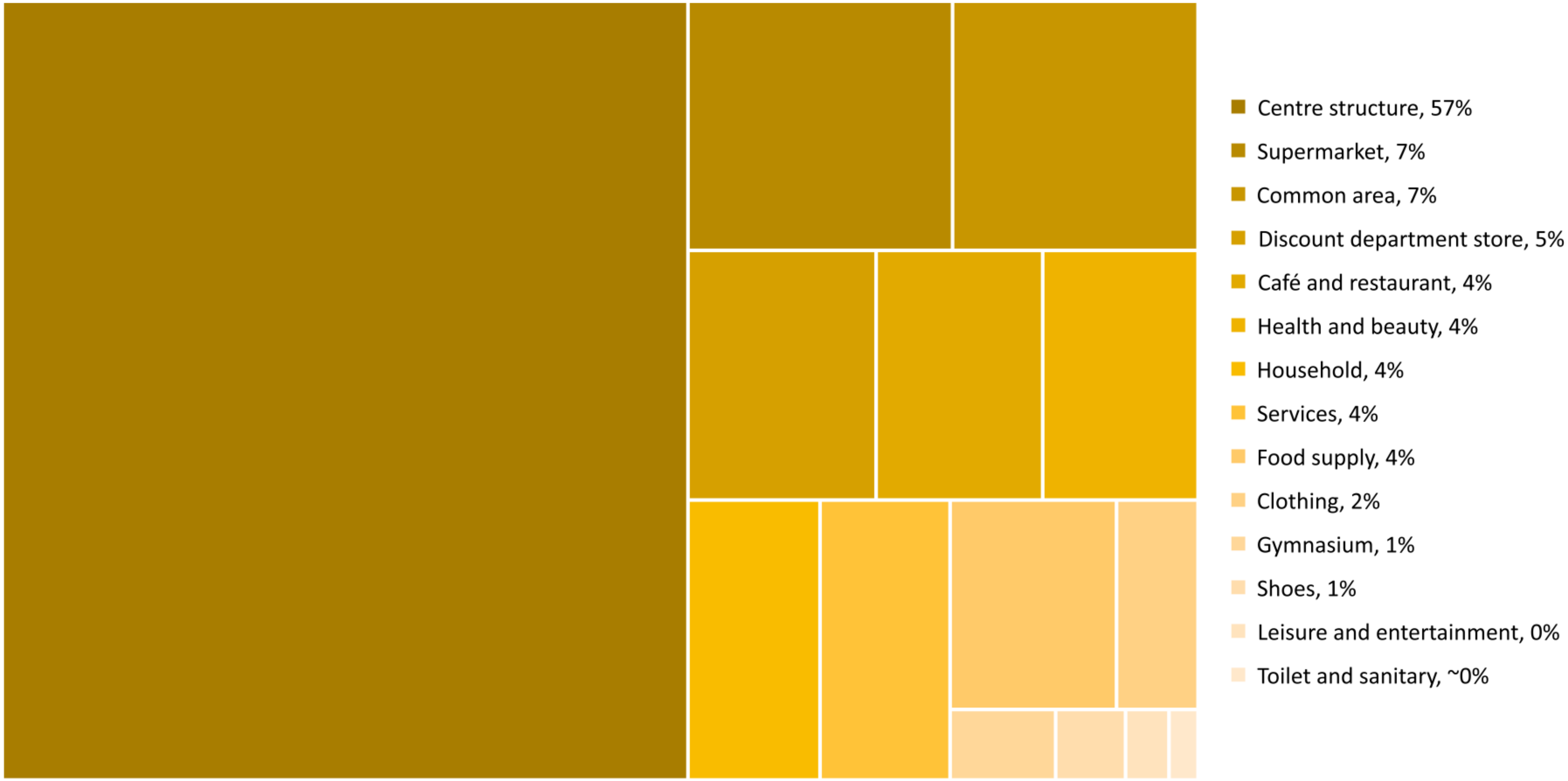


Figure 7.29: Life cycle material cost distribution across different shop types in the shopping centre business as usual scenario

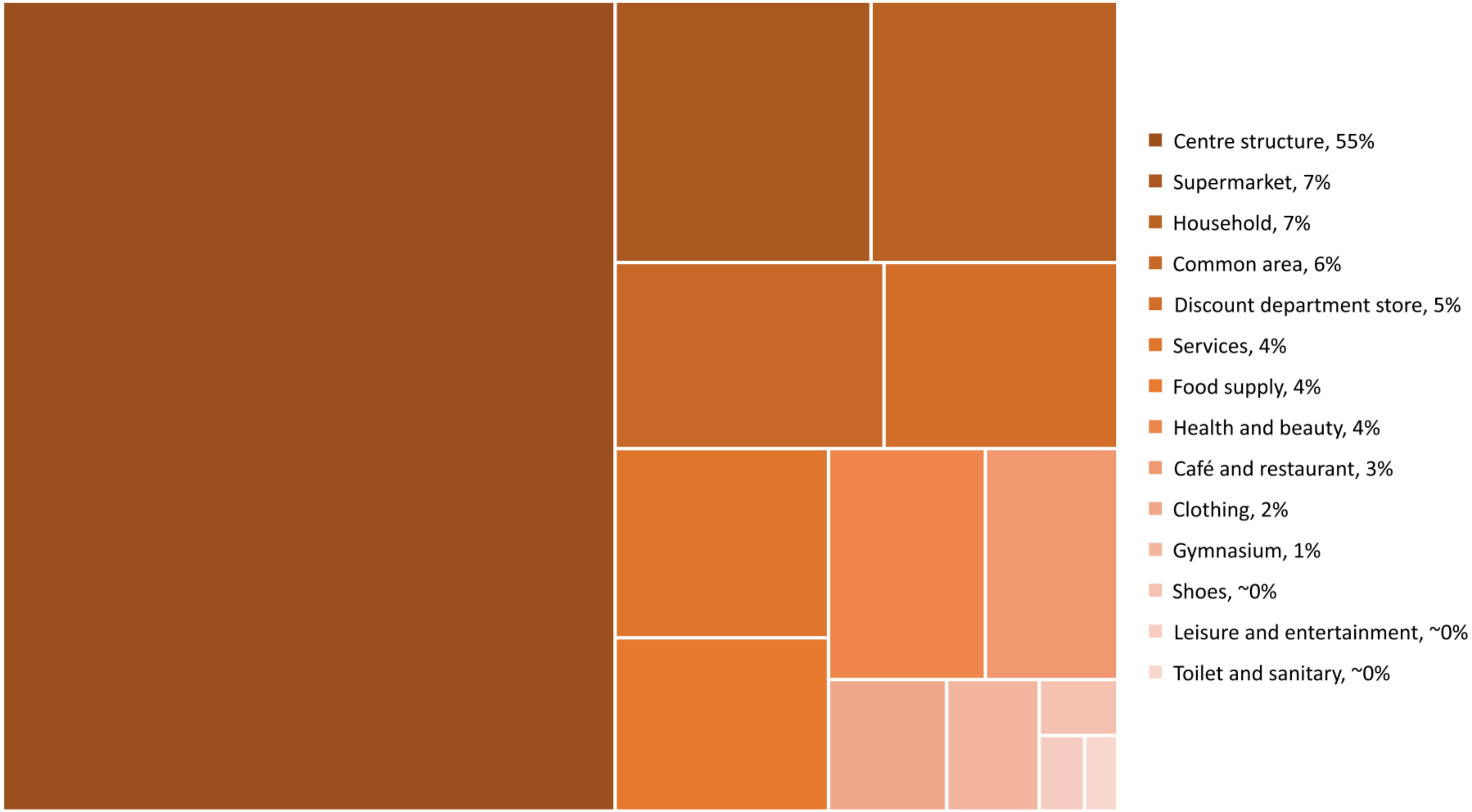


Figure 7.30: Life cycle material cost with carbon tax distribution across different shop types in the shopping centre business as usual scenario

Table 7.11: Comparison of life cycle embodied energy, embodied greenhouse gas emission and material cost with and without carbon tax per unit area of different shop types in the shopping centre business as usual scenario

Shop type	LCEE (GJ/m^2)	LCMC (AU$/m^2)	LCEGHGE (tonne CO_2e/m^2)	LCMCWT (AU$/m^2)
Supermarket	7.11	510.26	0.42	998.98
Discount department store	4.10	357.26	0.24	638.96
Clothing	19.26	1,746.19	1.13	3,069.41
Food supplies	14.56	953.23	0.86	1,953.54
Household	22.51	653.14	1.32	2,199.65
Gymnasium	23.97	764.16	1.41	2,410.99
Leisure and entertainment	23.67	1,394.58	1.39	3,021.04
Health and beauty	19.10	1,629.47	1.12	2,941.68
Coffee and restaurant	10.94	1,784.10	0.64	2,535.85
Shoes	18.83	1,805.68	1.11	3,099.74
Services	22.40	1,347.80	1.32	2,887.02
Common area	5.59	664.02	0.33	1,048.27
Toilets and sanitary	10.83	545.77	0.64	1,289.92
Centre structure	11.26	974.04	0.66	1,747.99

LCEE: Life cycle embodied energy; LCMC: Life cycle material cost; LCEGHGE: Life cycle embodied greenhouse gas emission; LCMCWT: Life cycle material cost with carbon tax

Table 7.11 presents the LCEE and LCMC intensities of different shop types defined in the study. Accordingly, it can be observed that the *gymnasium (23.97 GJ/m^2)* has the highest LCEE intensity, followed by *leisure and entertainment (23.67 GJ/m^2), household (22.51 GJ/m^2), services (22.40 GJ/m^2)*, *clothing (19.26 GJ/m^2)* and others. The least effect is from *discount department stores (4.10 GJ/m^2), common areas (5.59 GJ/m^2),* and *supermarkets (7.11 GJ/m^2)*.

The highest LCMC intensities are from *shoes (AU$ 1,810.00 /m^2)*, followed by *café and restaurant (AU$ 1,780.00 /m^2)*, *clothing (AU$ 1,750.00 /m^2), health and beauty (AU$ 1,630.00 /m^2)*, and others. The least effects are from *discount department stores (AU$ 360.00 /m^2)* and *supermarkets (AU$ 510.00 /m^2)*. Figure 7.31 displays the LCEE and LCMC intensities of different shop types in the shopping centre graphically using a parallel coordinates diagram.

The analysis shows that the LCEGHGE intensity distribution follows the same hierarchy as LCEE distribution. However, the LCMCWT intensities have a different order from LCMC. According to Table 7.19, the shops with the highest LCMCWT intensities are *shoes (AU$ 3,100.00 /m^2), clothing (AU$ 3,070.00 /m^2)* and *leisure and entertainment (AU$ 3,020.00 /m^2)*. Nevertheless, the least is from the *discount department store (AU$ 640.00 /m^2)* and *supermarket (AU$ 1,000.00 /m^2)*, as LCMC distribution, yet with higher values.

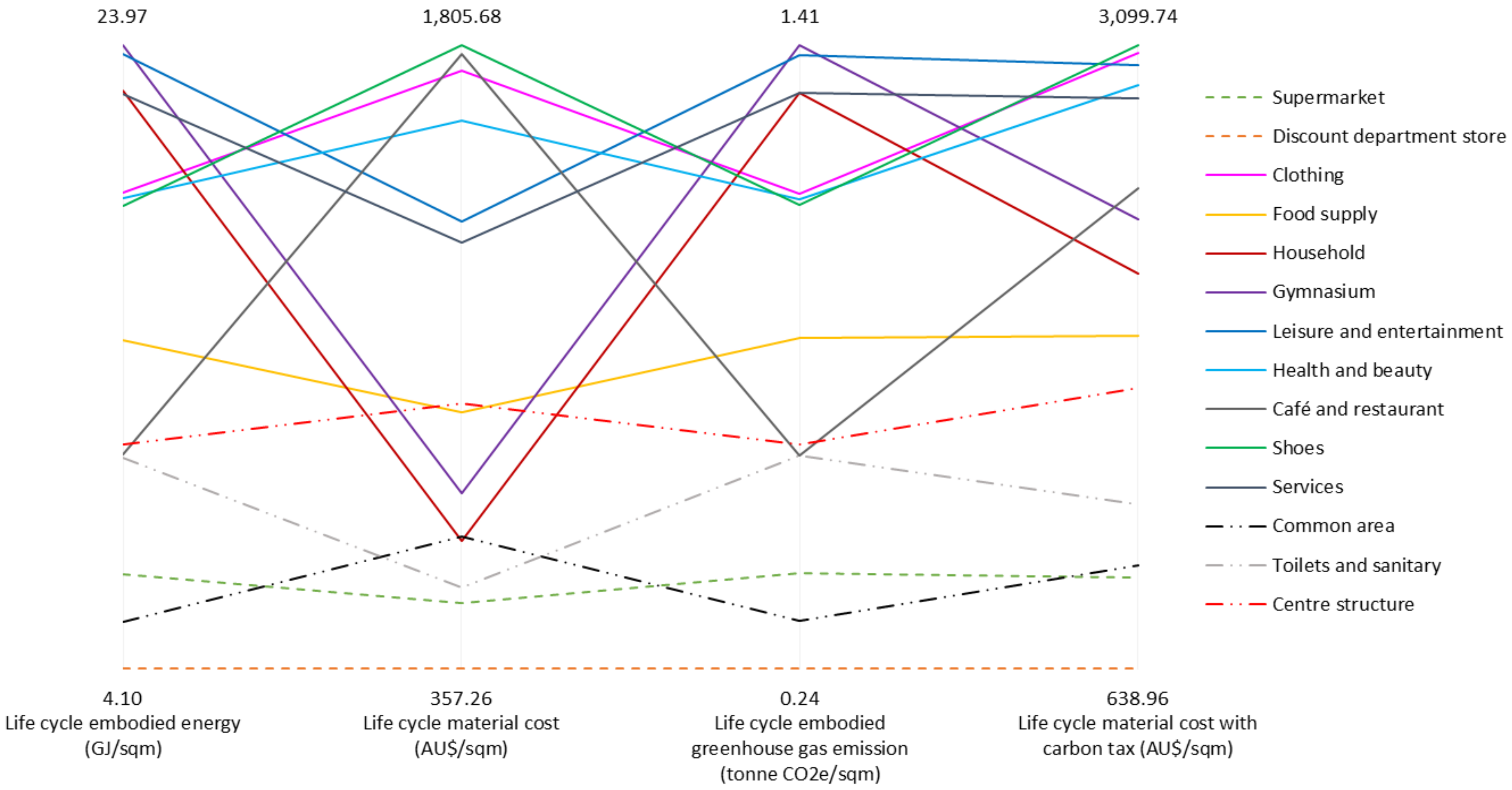


Figure 7.31: Life cycle embodied energy, embodied greenhouse gas emission and material cost with and without carbon tax per unit area of different shop types in the shopping centre business as usual scenario

7.8.2 Comparison of other scenarios

Through the understanding of the significance of LCEE in the *BAU* scenario, the model further identified the combinations of shops that can lead to embodied energy and material cost reductions at shopping centre level. Three scenarios of *minimum LCEE*, *minimum LCMC* and *optimal* are presented here in comparison to the *BAU* scenario, to analyse their similarities and differences.

Shopping centre scenario with the *minimum LCEE* is an aggregation of shop scenarios with *minimum LCEE*, as mentioned in Section 7.3. The LCEE of this scenario is 274,910.46 GJ, accounting for 12.22 GJ/m^2. This value is a very significant reduction of LCEE when compared with the *BAU* scenario leading to LCEE drop of 43%. The annual REE intensity of the shopping centre is 93.36 MJ/m^2/year, which is a 52% reduction from the *BAU* scenario. The *minimum LCEE* scenario results in AU$ 37.72 million of LCMC, which also reduces the LCMC of the *BAU* scenario by 1%. LCMC intensity of the shopping centre is estimated as AU$ 1,680.00 /m^2. Furthermore, LCEGHGE is quantified as 0.72 tonne CO_2e/m^2. As a result of the reduced GHG emissions, LCMCWT of this scenario is estimated as AU$ 2,500.00 /m^2, which is a 20% reduction from the *BAU* scenario. The findings reveal that the *minimum LCEE* scenario of the shopping centre can reduce both LCEE and LCMC effects; however, it is essential to maintain replacements with similarly lower embodied energy assemblies.

LCMC is minimised in the shopping centre by aggregating the shop type scenarios of *minimum LCMC.* The LCEE here accounts for 435,376.20 GJ, resulting in an intensity of 19.35 GJ/m^2. In comparison to the *BAU* scenario, 10% LCEE and LCEGHGE reductions can be achieved in this scenario. IEE and REE contributions are 59% and 41% respectively. The analysis shows that in the *minimum LCMC* scenario, the annual REE intensity is lowered by 18% when compared to the *BAU* scenario. The LCMC of this scenario is AU$ 1,410.00 /m^2, which is 17% lower than the *BAU* scenario. The most significant observation is that even when the model is geared towards minimising LCMC, embodied environmental effects are also reduced, resulting in 14% lower LCMCWT, 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 12.40 GJ/m^2. When compared to the *BAU* scenario, this is a significant reduction of 43%. The annual REE intensity of the shopping centre scenario is 96.66 MJ/m^2/year, which is a 50% reduction from the *BAU* scenario, yet 4% increase from the *minimum LCEE* scenario. Similarly, the LCMC of the scenario is valued as AU$ 1,570.00 /m^2, resulting in 7% cost-saving, in comparison to the *BAU* shopping centre. The LCEGHGE of the shopping centre is 0.73 tonne CO_2e/m^2 causing an LCMCWT of AU$ 2,400.00 /m^2. The LCMCWT reduction is 24% when compared to the *BAU* scenario.

After identifying the significance of each shopping centre scenario in terms of LCEE, LCMC, LCEGHGE and LCMCWT, it is vital to understand how each shop type contributes towards those variables across different scenarios. It is essential to recognise the most influential of the shop types, to reduce the life cycle effects. Figure 7.32 presents how LCEE is distributed through shop types across the scenarios. Accordingly, it can be observed that the *centre structure* is the most significant, accounting for more than 50% of LCEE across all scenarios. Among different shop types, it is apparent that *household (7% - 11%)*, *food supply (4% - 6%)* and *supermarket (4% - 8%)* shop types are larger embodied energy users over the service life of 50 years. Conversely, *toilets and sanitary (~0%), leisure and entertainment (~0%)* and *shoes (~0% - 1%)* are the least contributing shop types.

Similarly, Figure 7.33 and 7.34 present the distributions of LCMC and LCMCWT across shop types in different scenarios. In terms of LCMC contribution of different shop types, *common area (7% - 8%), supermarket (5% - 7%),* and *discount department store (4% - 5%)* are the most significant, which are different from LCEE contributions. However, the least influential shop types remain the same. The analysis of LCMCWT contributions shows that *household (6% - 7%)*, *common area (6% - 7%)* and *supermarket (5% - 7%)* have the highest effects, while the lowest shop types remain the same. However, it must be noted that the order of the lowest contributing shop types, is not the same across all scenarios.

Furthermore, the results can be presented identifying how much shopping centre LCEE reductions can be attained by replacing the *BAU* assembly combination of a shop type with its *minimum LCEE* assembly combination, one shop type at a time, as presented in Figure 7.35. Accordingly, it can be observed that the shift in the *centre structure* from *BAU* to the *minimum LCEE* assembly combination has the highest effect, which can lead to 18% reductions from the *BAU* scenario of the shopping centre. Among other shop types, *household (6%)* can lead to the largest LCEE reductions followed by *supermarket (5%)*, *services (4%)* and *health and beauty (3%).* Similarly, *shoes (0.14%), toilet and sanitary (0.2%)* and *leisure and entertainment (0.3%)* shops have the least effects of the replacements. Findings prioritise the order of shop types that need to be replaced with *minimum LCEE* assembly combinations to reduce LCEE of the shopping centre *BAU* scenario the most.

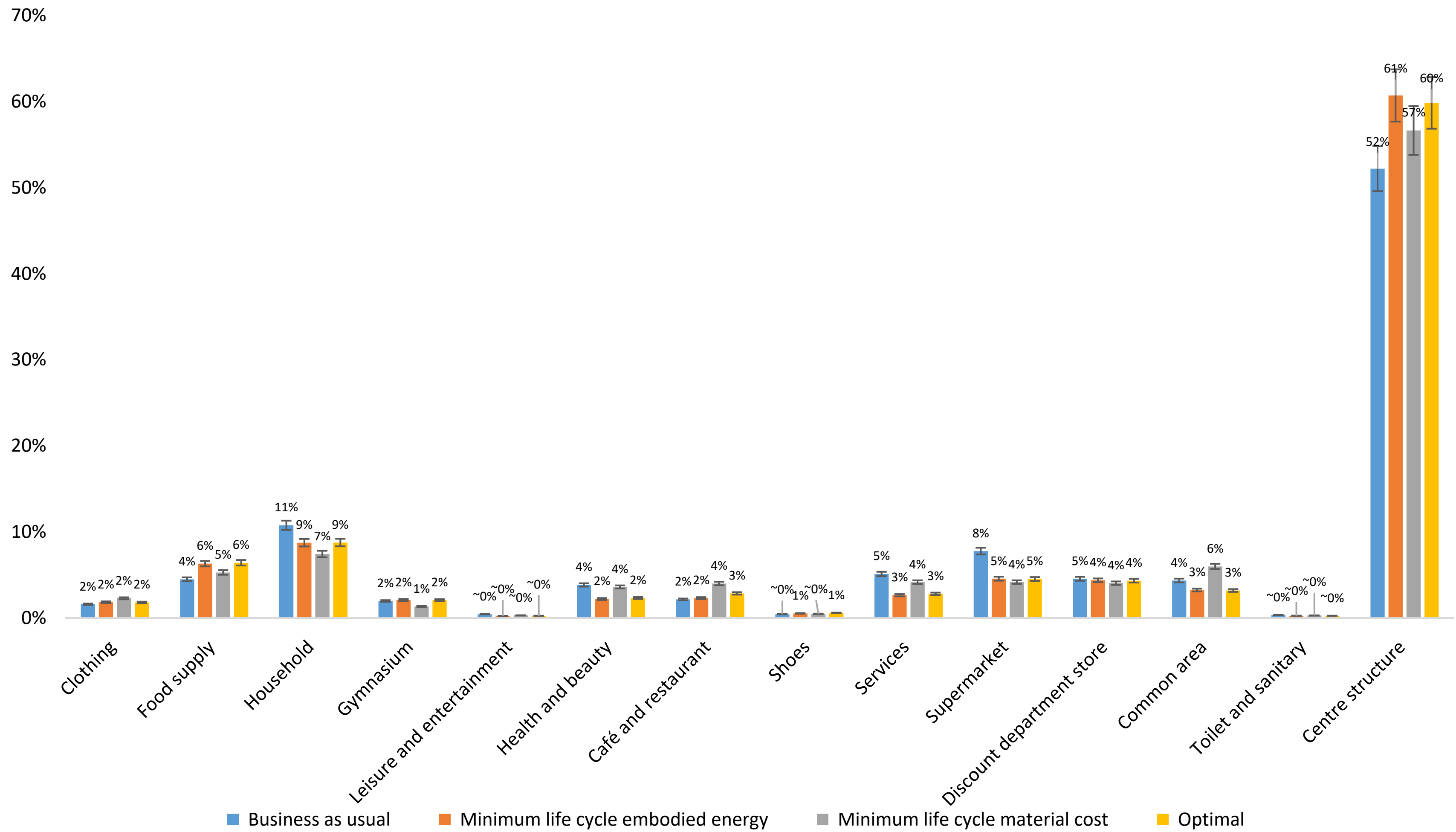


Figure 7.32: Life cycle embodied energy distribution across different shop types in the shopping centre across scenarios

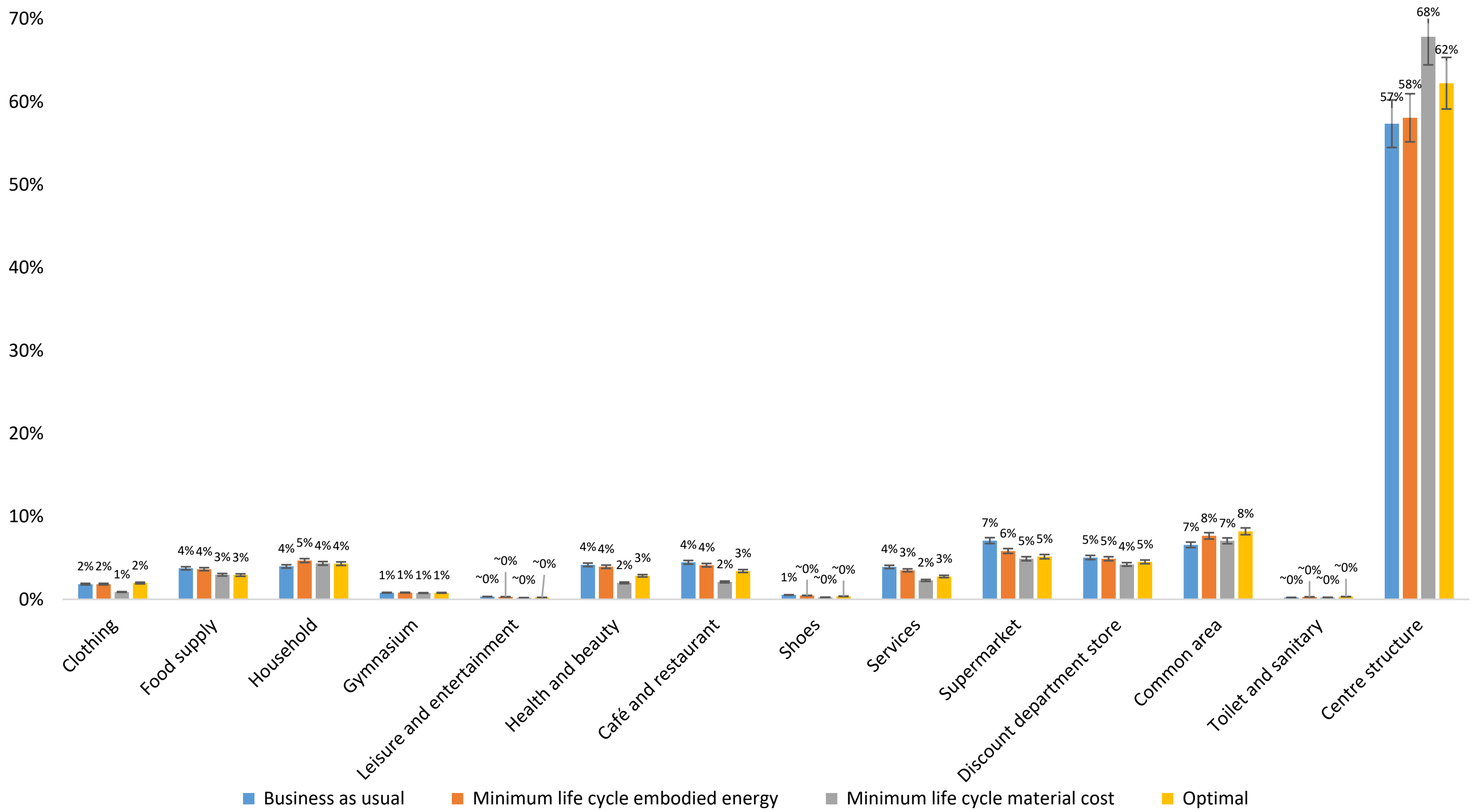


Figure 7.33:Life cycle material cost distribution across different shop types in the shopping centre across scenarios

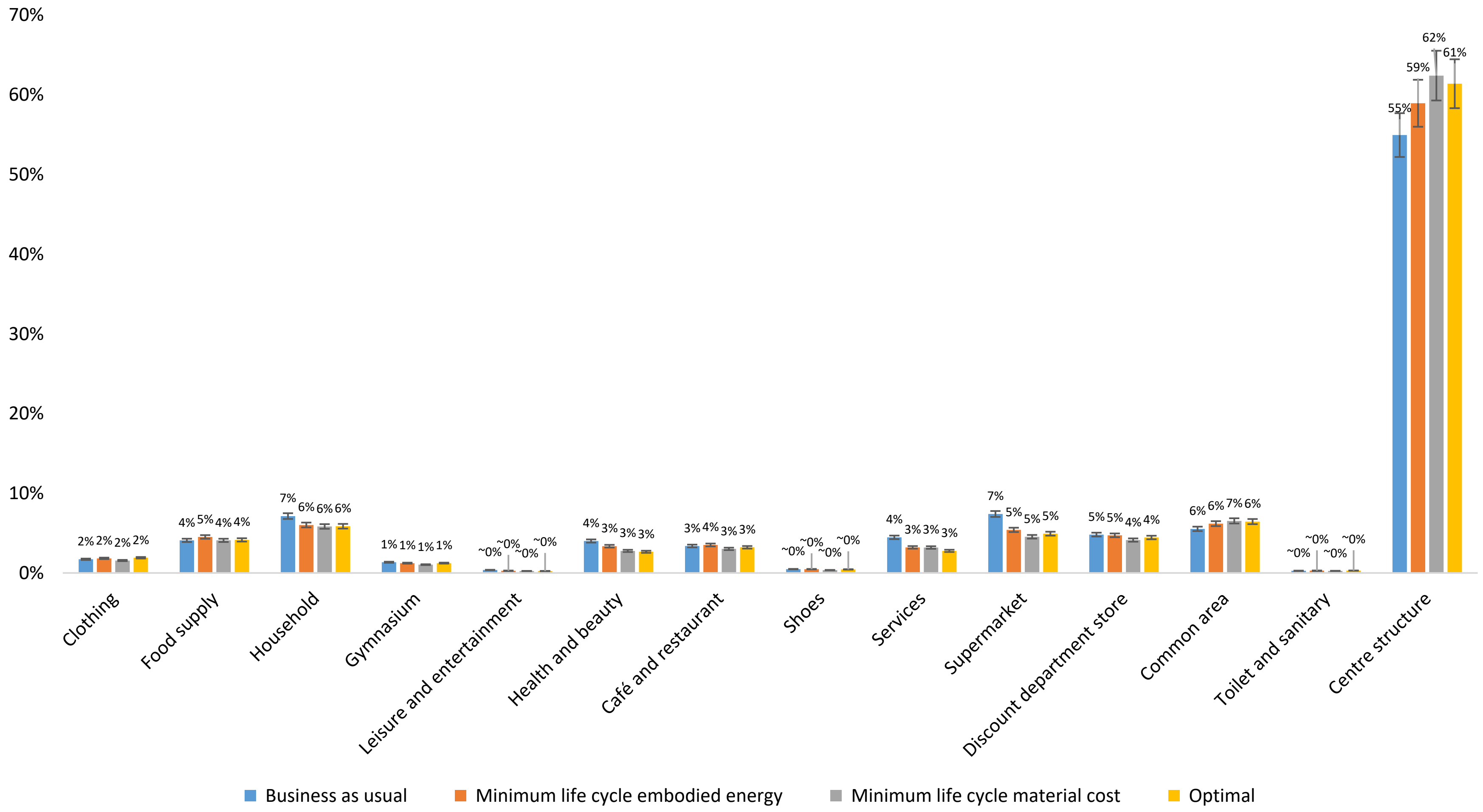


Figure 7.34: Life cycle material cost with carbon tax distribution across different shop types in the shopping centre across scenarios

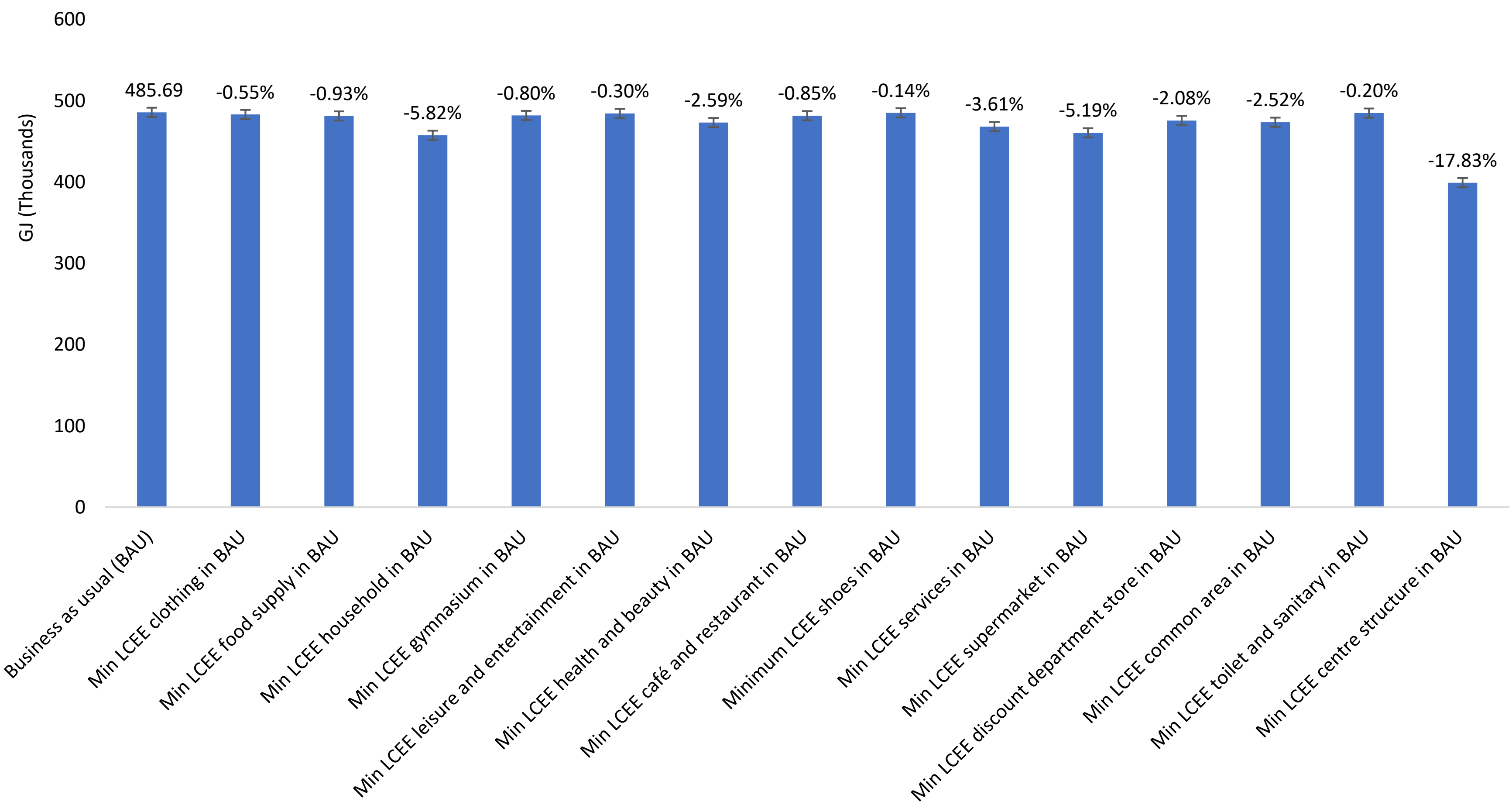


Figure 7.35: Comparison of life cycle embodied energy reductions of the shopping centre business as usual scenario when each shop type is replaced with its minimum life cycle embodied energy assembly combination, one shop type at a time

However, these comparisons of LCEE, LCMC and LCMCWT contributions of different shop types at the whole shopping centre level are affected by GLA of each shop type as discussed before. Therefore, variable intensities need to be compared to determine relative significance irrespective of GLA effects, as presented previously in Table 7.12. Data are graphically presented in a parallel coordinates diagram in Figure 7.36.

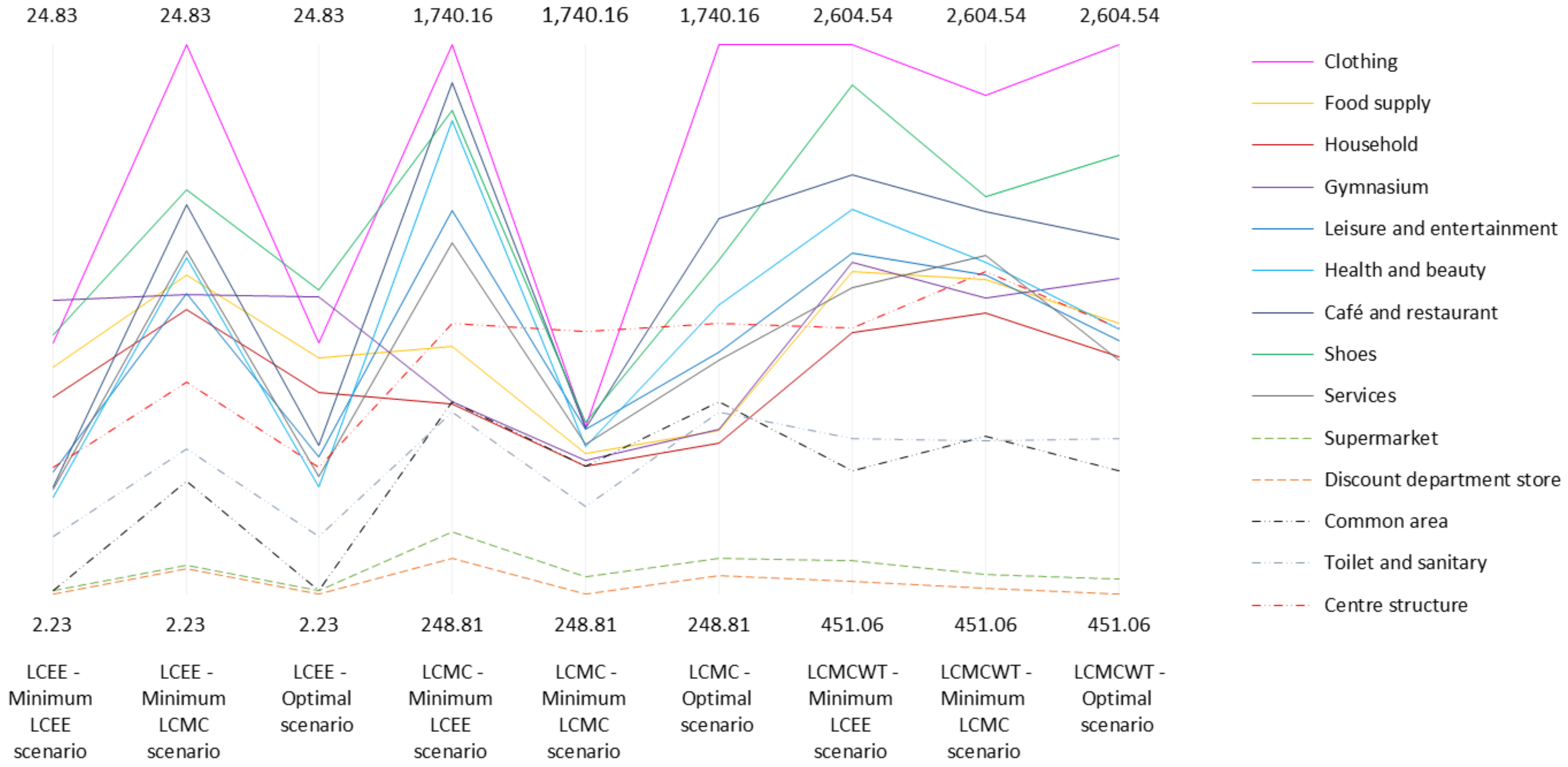
Accordingly, it can be observed that the *discount department store* has the least intensities in all variables across all scenarios. The *Supermarket* has the second least intensities except for LCEE in the *minimum LCEE* and the *optimal* scenarios, where its replaced by *common areas*. Nevertheless, due to their higher GLA, these shop types lead to higher LCEE, LCMC and LCMCWT contributions at the shopping centre level, when absolute values are compared. *Clothing* shop type has the highest intensities in LCEE, LCMC, and LCMCWT across almost all scenarios except for LCEE in the *minimum LCEE* and the *optimal* scenarios and LCMC in the *minimum LCMC* scenario. However, *clothing* shop type has lower effects towards the shopping centre when absolute values are considered due to its lower GLA proportion. In the *minimum LCEE* scenario, *gymnasium (14.29 GJ/m^2)* has the highest LCEE intensity and in the *optimal* scenario *shoes (14.76 GJ/m^2)* has the highest intensity. In the *minimum LCMC* scenario, the *centre structure (AU$ 980.00 /m^2)* has the highest LCMC intensity, which is the only occasion where the *centre structure* becomes the most significant in terms of intensities. Nevertheless, the *centre structure* is the most significant across all scenarios when absolute values are compared.

The scenario comparison of shopping centres presented above compares embodied energy and material cost of shopping centres identifying the effects of different shop types across all scenarios. This analysis provides knowledge on the shop types that are more significant in terms of LCEE and LCMC, variables which are highly influenced by the GLA proportions. Therefore, it is essential to evaluate both absolute and relative values of LCEE and LCMC to understand the behaviour of shop types better, to take appropriate actions to mitigate embodied environmental effects and reduce associated material costs.

The shopping centre analysis presented in this section is limited to the average shopping centre presented in Section 5.3. However, to develop more representative findings, the model assessed two other shopping centres with different GLA distributions and shop mixes, as outlined in the following section.

Table 7.12: Comparison of life cycle embodied energy and material cost with and without carbon tax intensities of different shop types across shopping centre scenarios

Shop type	Life cycle embodied energy (GJ/m²)			Life cycle material cost (AU$/m²)			Life cycle material cost with carbon tax (AU$/m²)		
	Minimum LCEE	Minimum LCMC	Optimal	Minimum LCEE	Minimum LCMC	Optimal	Minimum LCEE	Minimum LCMC	Optimal
Supermarket	2.37	3.42	2.38	418.09	293.93	344.66	580.59	528.90	508.11
Discount department store	2.23	3.26	2.24	345.40	248.81	297.24	498.60	472.93	451.06
Clothing	12.58	24.83	12.58	1,740.16	702.69	1,740.16	2,604.54	2,408.69	2,604.54
Food supplies	11.56	15.34	11.93	922.43	630.20	692.83	1,716.70	1,684.11	1,512.18
Household	10.34	13.93	10.52	765.80	594.85	657.47	1,476.44	1,551.88	1,379.95
Gymnasium	14.29	14.55	14.46	771.56	610.28	696.70	1,753.27	1,609.62	1,690.01
Leisure and entertainment	7.25	14.61	7.87	1,291.27	697.16	903.97	1,789.60	1,701.12	1,444.61
Health and beauty	6.21	16.08	6.62	1,533.06	648.80	1,033.79	1,959.51	1,753.66	1,488.47
Café and restaurant	6.63	18.24	8.33	1,638.50	698.87	1,268.37	2,094.12	1,952.26	1,840.60
Shoes	12.88	18.85	14.76	1,563.21	713.72	1,156.17	2,448.37	2,008.97	2,170.30
Services	6.56	16.37	7.06	1,201.73	655.97	883.76	1,652.26	1,780.46	1,369.03
Common area	2.36	6.89	2.36	770.71	594.57	770.71	932.57	1,068.00	932.57
Toilets and sanitary	4.61	8.21	4.61	741.32	486.51	741.32	1,058.23	1,050.68	1,058.23
Centre structure	7.42	10.96	7.42	982.18	960.39	982.18	1,491.67	1,713.14	1,491.67



LCEE: Life cycle embodied energy; LCMC: Life cycle material cost; LCMCWT: Life cycle material cost with carbon tax

Figure 7.36: Life cycle embodied energy and material cost with and without carbon tax intensities of shop types across minimum life cycle embodied energy, life cycle material cost and optimal shopping centre scenarios

7.9 COMPARISON OF SHOPPING CENTRES OF DIFFERENT GROSS LETTABLE AREA

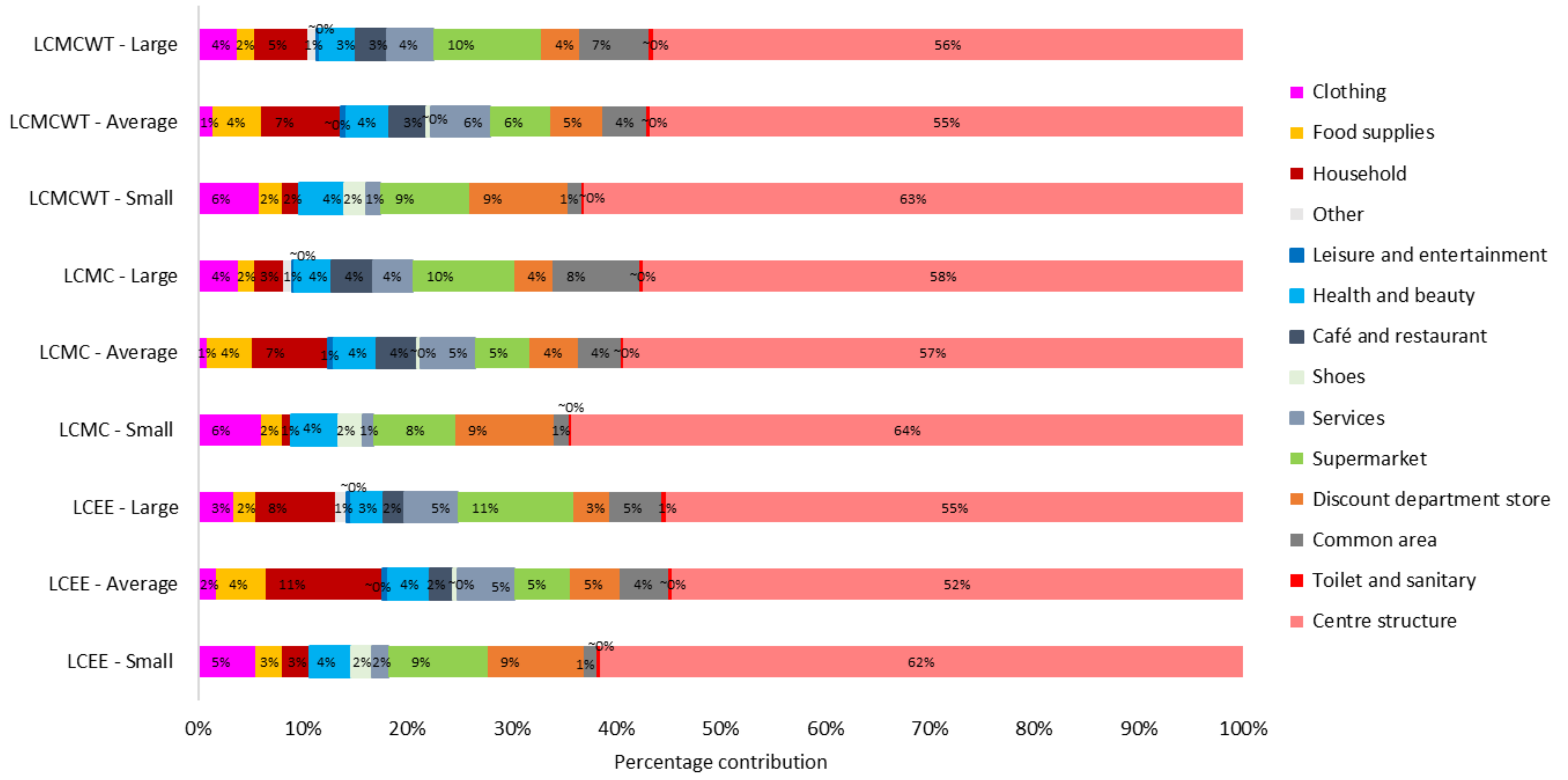
The analysis of the shopping centre level is carried out for the average shopping centre described in Section 5.3. However, the analysis was extended to include two other shopping centres with different GLA and shop compositions (one with larger GLA and one with smaller GLA as described in Chapter 5). The results can therefore be considered more representative since the analysis is not limited to a particular GLA but includes a smaller (noted as small), average (considered in Section 7.8) and larger (noted as large). The following section provides a detailed analysis of these two additional shopping centres.

7.9.1 Analysis of shopping centres with different gross lettable areas

The *small* shopping centre has a GLA of 11,427 m^2, and the distribution of GLA is based on the case study 2 shopping centre presented in Section 5.4. For modelling purposes, it consists of 20 *specialty shops*, 2 *anchor shops*, *common area, toilets and sanitary* area and the *centre structure*. The LCEE of the *BAU* scenario of the shopping centre is 244,432.83 GJ, resulting in an LCEE intensity of 21.39 GJ/m^2. This value is slightly lower than the *average* LCEE intensity (-1%). The annual REE intensity is estimated as 157.53 MJ/m^2/year, which results in 18% reductions in comparison to the *BAU* scenario of the *average* shopping centre. However, the LCMC of the shopping centre is AU$ 1,810.00 /m^2, which is 7% higher than the *average BAU* scenario. LCEGHGE of the shopping centre is quantified as 1.26 tonne CO_2e/m^2, which is just 1% lower than the *average BAU* scenario. Even though LCMC has indicated a noticeable rise when compared to the *average BAU* shopping centre, the LCMC with the carbon tax is valued at AU$ 3,250.00 /m^2 resulting in only a 3% increase.

In comparison, the *large* shopping centre has a GLA of 30,058 m^2, as described in Section 5.5. For modelling purposes, the shopping centre consists of 61 *specialty shops*, five *anchor shops*, *common area, toilets and sanitary* area and the *centre structure.* The LCEE of the *BAU* scenario of this shopping centre is 636,256.88 GJ resulting in an intensity of 21.59 GJ/m^2. The annual REE intensity is estimated as 176.18 MJ/m^2/year, which results in a 9% reduction in comparison to the *BAU* scenario of the *average* shopping centre. The LCMC is estimated as AU$ 51.6 million, accounting for AU$ 1,720.00 /m^2. The LCEE is reduced by 2% when compared to the *average BAU* scenario, but the LCMC is increased by 2%. The LCEGHGE of the shopping centre is 1.24 tonne CO_2e /m^2 resulting in an LCMCWT value of AU$ 3,140.00 /m^2. LCMCWT value increase is 0.02% when intensities are compared.

The distribution of LCEE, LCMC and LCMCWT of the *small, average* and *large* shopping centres' *BAU* scenarios across shop types is presented in Figure 7.37.



LCEE: Life cycle embodied energy; LCMC: Life cycle material cost; LCMCWT: Life cycle material cost with carbon tax

Figure 7.37: Life cycle embodied energy and material cost with and without carbon tax contribution across different shop types in the small, average and large shopping centres – Business as usual scenario (Percentages might not add to 100 due to rounding up to whole numbers)

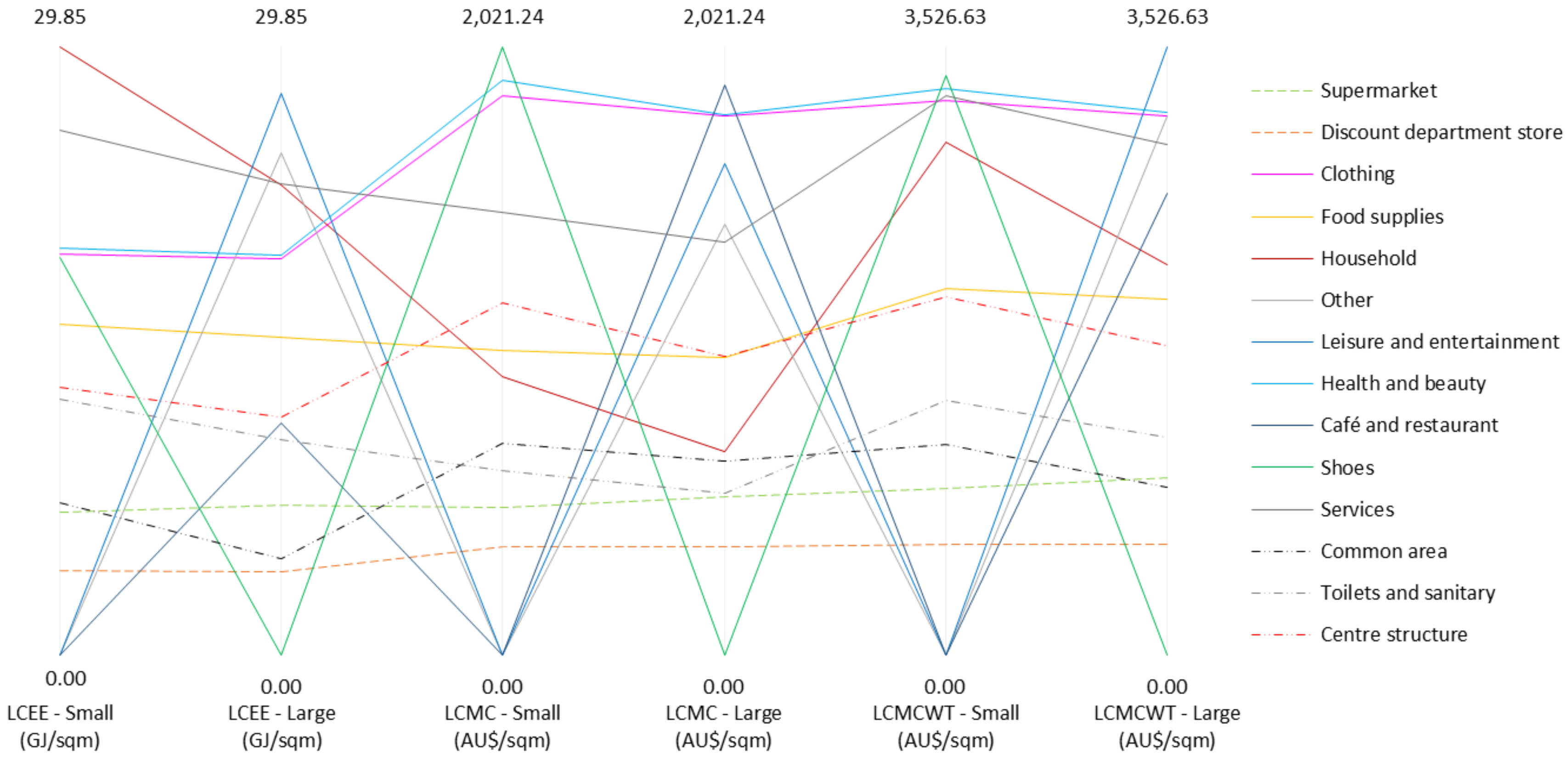
The distribution identifies the significance of the *centre structure*, across all variable distributions in both shopping centres. However, it can be observed that the percentage contributions are more significant for the *small* shopping centre. The difference in percentage contributions of the *centre structure* in *small* and *large* shopping centres indicate that when the GLA becomes smaller, the effect of the *centre structure* becomes much more significant. However, when the *centre structure* percentages are compared with the *average (LCEE contribution: 52%)* shopping centre *BAU* scenario, it can be observed that the values are lower than both *small (LCEE contribution: 62%)* and *large* centres, but closer to *large (LCEE contribution: 55%)* centre values.

Among other shop types, in the *small* shopping centre, *discount department store, supermarket* and *clothing* shops are the most significant across all variables. In the large shopping centre, *supermarket, common area* and *household* become more significant. *Toilets and sanitary* areas are the least significant in both shopping centres. In the small shopping centre, when the carbon tax is aggregated into the LCMC, the only percentage difference occurred is in *household (+1%)*, *supermarket (+1%)*, and the *centre structure (-1%)*. However, in the large shopping centre, several changes can be observed in shop types as, *household (+2%)*, *health and beauty (-1%) café and restaurant (-1%)*, *common area (-1%)*, and *centre structure (-2%)*. Nevertheless, it must be noted that these contributions can be profoundly affected by the GLA proportions of the shop types in shopping centres. Therefore, the relative values are compared to identify the most influential shops in the shopping centres' *BAU* scenarios using Table 7.13.

Table 7.13: Comparison of life cycle embodied energy and material cost with and without carbon tax intensities of shop types in the small and large shopping centres – Business as usual scenario

Shop type	**LCEE (GJ/m²)**		**LCMC (AU$/m²)**		**LCMCWT (AU$/m²)**	
	Small	**Large**	**Small**	**Large**	**Small**	**Large**
Supermarket	6.98	7.34	489.21	526.35	968.46	1,030.53
Discount department store	4.12	4.11	360.78	359.07	644.07	641.59
Clothing	19.72	19.45	1,859.64	1,792.47	3,214.25	3,128.50
Food supplies	16.22	15.58	1,014.59	990.90	2,129.32	2,061.47
Household	29.85	23.11	923.79	675.43	2,974.95	2,263.49
Other	-	24.69	-	1,432.25	-	3,128.94
Leisure and entertainment	-	27.56	-	1,632.89	-	3,526.63
Health and beauty	20.01	19.64	1,909.84	1,796.45	3,284.58	3,145.90
Café and restaurant	-	11.38	-	1,894.18	-	2,676.39
Shoes	19.53	-	2,021.24	-	3,363.38	-
Services	25.79	23.14	1,472.61	1,374.81	3,244.54	2,964.40
Common area	7.49	4.75	705.66	645.50	1,220.60	971.65
Toilets and sanitary	12.58	10.60	612.34	536.81	1,476.46	1,264.80
Centre structure	13.16	11.69	1,171.24	993.81	2,075.58	1,796.82

LCEE: Life cycle embodied energy; LCMC: Life cycle material cost; LCMCWT: Life cycle material cost with carbon tax



LCEE: Life cycle embodied energy; LCMC: Life cycle material cost; LCMCWT: Life cycle material cost with carbon tax

Figure 7.38: Comparison of life cycle embodied energy and material cost with and without carbon tax intensities of different shop types in the small and large shopping centres– Business as usual scenarios

Graphical representation of the relative values of LCEE, LCMC and LCMCWT are presented in Figure 7.38. Accordingly, it can be identified that in the *small* shopping centre, *household (29.85 GJ/m^2)* has the highest LCEE intensity followed by *services (25.79 GJ/m^2)*, and *health and beauty (20.01 GJ/m^2)* shops. As with the *average BAU* centre, *discount department stores (4.12 GJ/m^2)* and *supermarket (6.98 GJ/m^2)* are responsible for the lowest LCEE intensities. Nonetheless, in the *large* shopping centre, *leisure and entertainment (27.56 GJ/m^2)*, *other (24.69 GJ/m^2)* and *services (23.14 GJ/m^2)* shops have the highest intensities, while *discount department stores (4.11 GJ/m^2)* are followed by *common areas (4.75 GJ/m^2)* in the lowest intensities.

When LCMC intensities are compared, *shoes (AU$ 2,020.00 /m^2)* take the lead in the *small* centre, while *café and restaurants (AU$ 1,890.00 /m^2)* dominate in the *large* centre. As always, *discount department stores* and *supermarkets* have the lowest intensities in both shopping centres. However, the analysis of the LCMCWT values shows that in *small* centre *shoes (AU$ 3,360.00 /m^2)* still take the lead, but in *large* centre *café and restaurants* is replaced by *leisure and entertainment (AU$ 3,530.00 /m^2).* Shop types with the lowest LCMCWT intensities are the same as with LCEE intensities for both *small* and *large* shopping centres.

Results demonstrate that when shopping centre GLA is increased, the LCEE, LCMC and LCMCWT intensities of shop types tend to decrease. Hence, it is important to investigate the relationship between the shopping centre GLA and the total LCEE and LCMC to better understand their dynamics.

The analyses of average, small and large shopping centres provide detailed investigations on LCEE, LCMC and LCMCWT of the *BAU* scenarios, identifying the significance of shop types at shopping centre level comparing both absolute values and intensities. The following section presents the comparisons graphically to identify the relationship between the three shopping centres.

7.9.2 Analysis of trends between life cycle embodied energy, material cost with and without carbon tax along with gross lettable areas of shopping centres

This section identifies trends and relationships between embodied energy and material cost values with the GLA of a shopping centre. Figure 7.39 presents the absolute values of LCEE, LCMC and LCMCWT of the shopping centres along their GLA.

Accordingly, it can be observed that all variables have a strong positive linear relationship (Pearson's correlation coefficient more than 0.99 across all variables) with the GLA of the shopping centre when absolute values are compared. The LCEE, LCMC and LCMCWT regression lines predict that if shopping centre GLA is increased by 1 m^2, the LCEE, LCMC and LCMCWT will be increased by 21.09 GJ, AU$ 1,660.00, and AU$ 3,110.00, respectively.

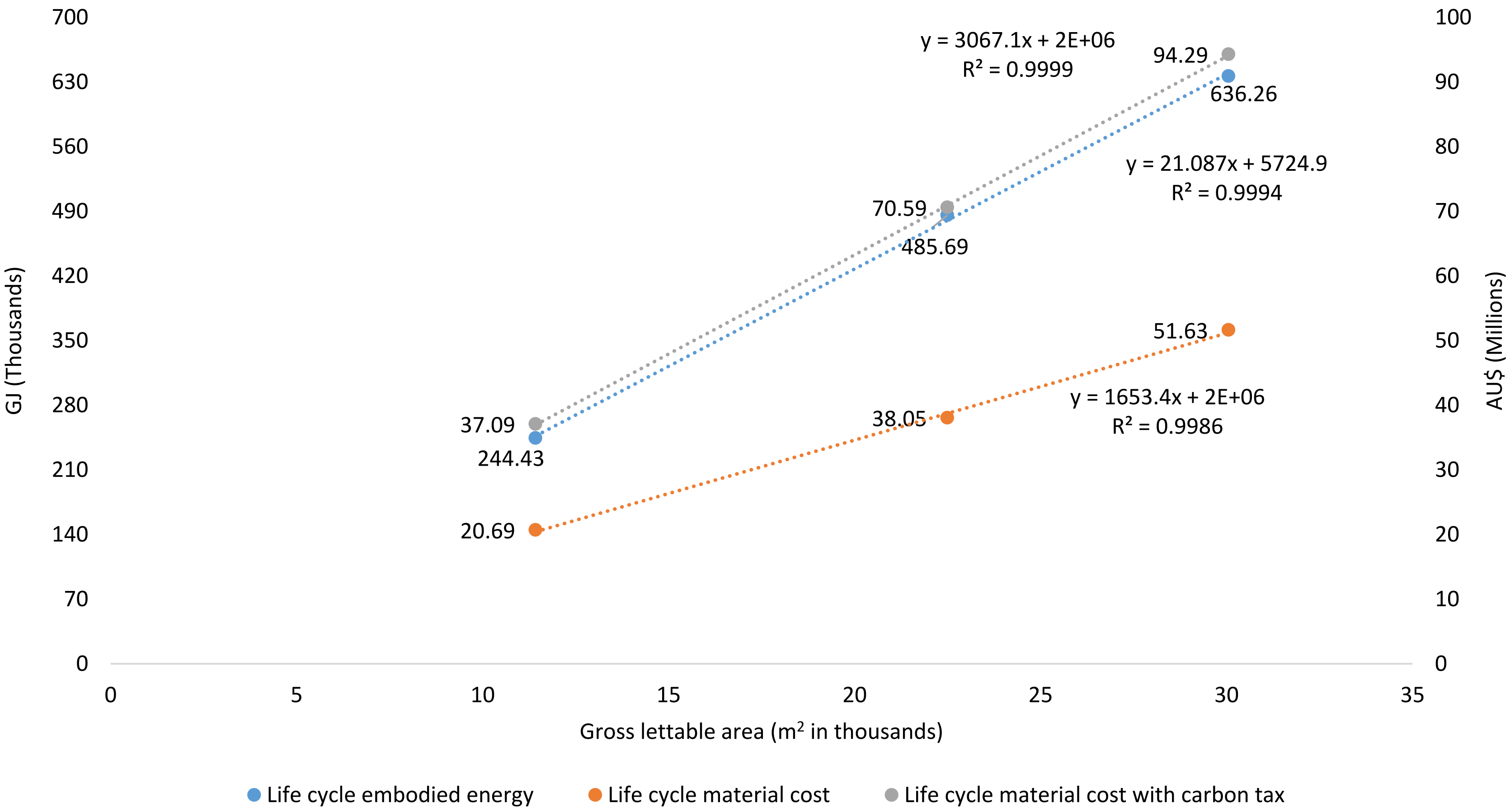


Figure 7.39: Relationships between life cycle embodied energy and material cost with and without carbon tax, and the gross lettable areas of shopping centres (Comparison of absolute values)

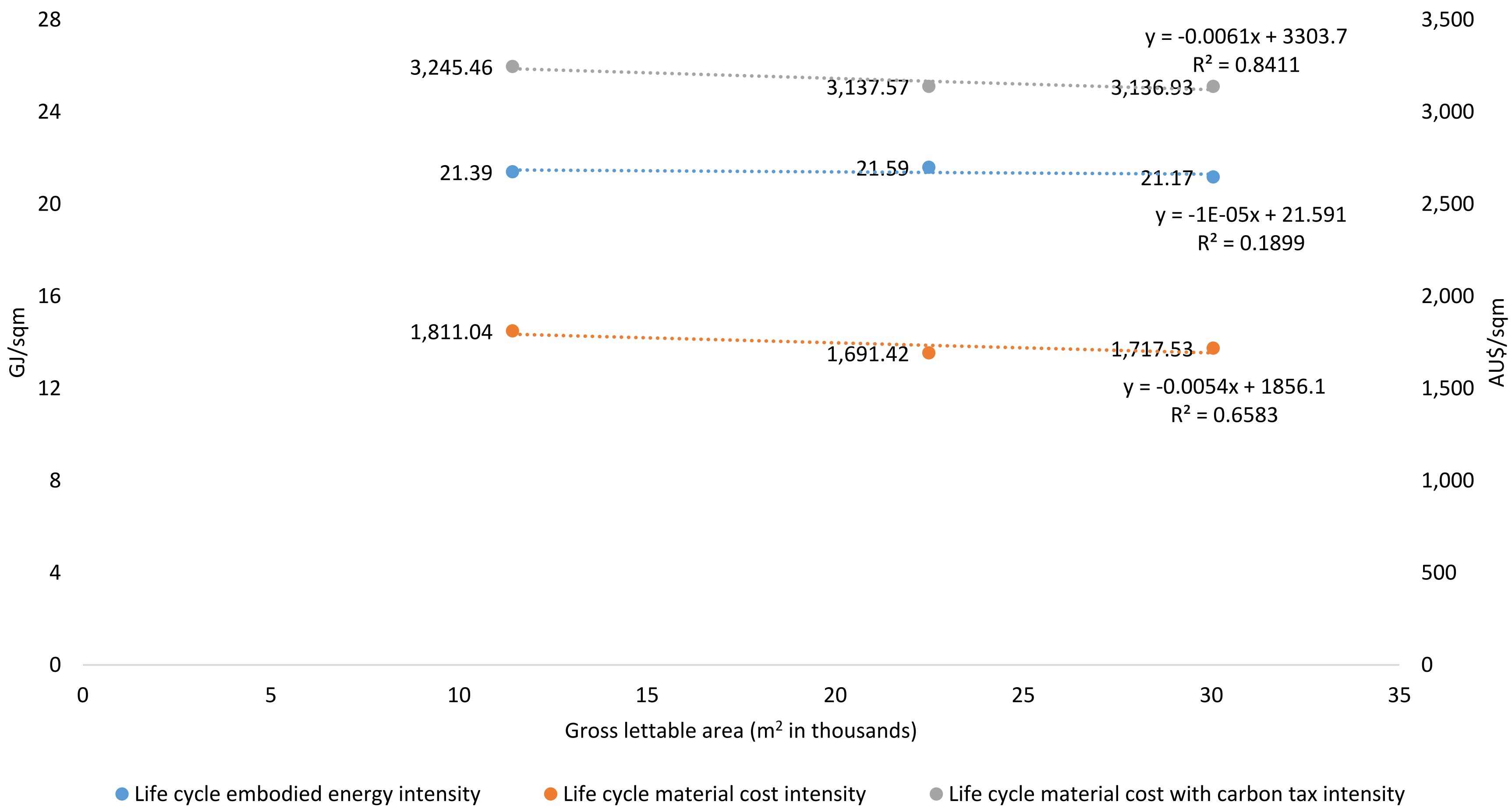


Figure 7.40: Relationships between life cycle embodied energy and material cost with and without carbon tax, and the gross lettable areas of shopping centres (Comparison of intensities)

On the contrary, the analysis of intensities across GLA of shopping centres indicates opposite associations between variable values, as presented in Figure 7.40. The regression line of LCEE intensities indicates a moderately strong negative linear relationship (PCC: -0.44) with the GLA. Although the trend is negative, the slope is almost flat. So, there is a small decrease in intensity as the GLA increases. Furthermore, LCMC (PCC: -0.80) and LCMCWT (PCC: -0.91) display strong negative linear relationships with the GLA.

The analysis of trends between LCEE, LCMC and LCMCWT presents that when GLA is increased, absolute values tend to rise while intensities have a propensity to decrease. Therefore, it is essential to assess LCEE and LCMC in terms of both absolute values and intensities to determine the most appropriate shopping centre GLA to mitigate adverse embodied environmental effects. A more comprehensive analysis similar to this approach can be used to evaluate different shopping centre scenarios with varying GLA to identify LCEE, LCMC and LCMCWT implications at the initial design stages and to determine the optimal GLA for the shopping centres.

7.10 SENSITIVITY ANALYSIS

This study carried out sensitivity analysis for refurbishment frequency at shop level and for carbon tax at shopping centre level. Conducting sensitivity analysis for refurbishment frequency at shopping centre level is unmanageable because base values of refurbishment frequencies are different from shop types. Hence shop level analysis was carried out to evaluate the sensitivity of refurbishment frequency data.

An analysis was carried out for a speciality shop (services) and the results are presented in Table 7.14. BAU refurbishment frequency was set at 5 years and sensitivity was analysed for different refurbishment frequency values of one year (1), three years (3), seven years (7) and ten years (10).

Table 7.14: Effect of refurbishment frequency on life cycle embodied energy and material cost with and without carbon tax for speciality shop

	Variable	RF	LCEE	LCMC	LCMCWT
	BAU	5.00	5,671.26	348,069.55	728,787.70
Scenario analysis	*Input Value*	1.00	28,356.32	1,690,648.59	3,594,239.35
	Relative difference with BAU	-80%	400%	386%	393%
	Input Value	3.00	9,641.15	579,762.42	1,226,983.28
	Relative difference with BAU	-40%	70%	67%	68%
	Input Value	7.00	4,537.01	272,474.99	577,049.52
	Relative difference with BAU	40%	-20%	-22%	-21%
	Input Value	10.00	2,835.63	183,745.15	374,104.23
	Relative difference with BAU	100%	-50%	-47%	-49%

BAU: Business as usual scenario, RF: Refurbishment frequency, LCEE: Life cycle embodied energy, LCMC: Life cycle material cost, LCMCWT: Life cycle material cost with tax

The greatest reductions in both energy and cost are visible when refurbishment frequency is increased by 100%. However, it is visible that the increase in energy and cost is far greater (up to 400%) for lower refurbishment frequencies (-80%) that the reductions achieved (up to -50%) for higher refurbishment frequencies. It is logical that an increased refurbishment frequency will imply less premature material replacements and hence a lower embodied energy and material cost. Following figure illustrates the sensitivity of LCEE to different refurbishment frequency values of services shop. Similar patterns are identified for LCMC and LCMCWT.

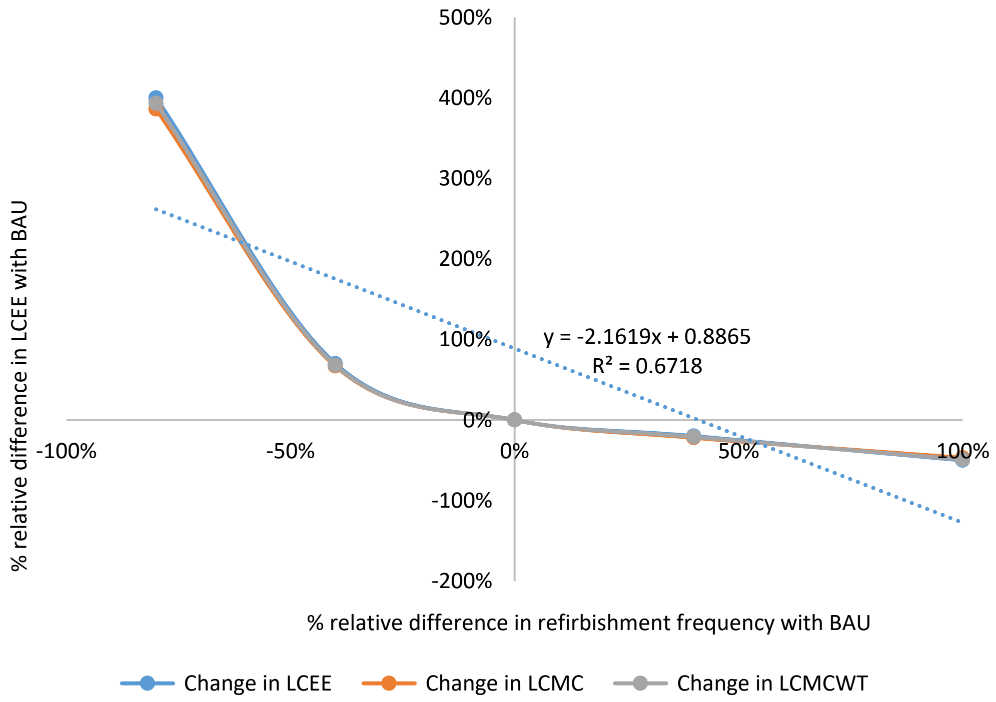


Figure 7.41: Sensitivity analysis of life cycle embodied energy and material cost with and without carbon tax and refurbishment frequency of services shop

LCEE: Life cycle embodied energy, LCMC: Life cycle material cost, LCMCWT: Life cycle material cost with carbon tax, BAU: Business as usual scenario

Sensitivity analysis for carbon tax was carried out at shopping centre level and the results revealed that carbon tax and LCMCWT has a linear straight-line relationship. An increase in carbon tax by 1% will result in an increase in LCMCWT by 0.463%. Following Figure shows the sensitivity between carbon tax and LCMCWT of the shopping centre.

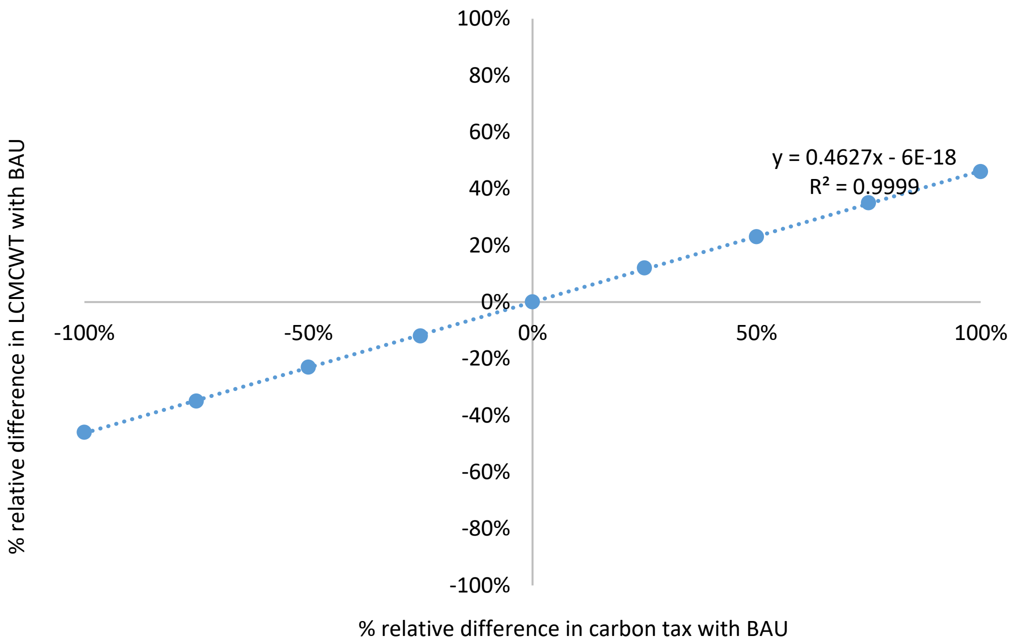


Figure 7.42: Sensitivity analysis of life cycle material cost with carbon tax and carbon tax of the shopping centre

LCMCWT: Life cycle material cost with carbon tax, BAU: Business as usual scenario

Results generated from sensitivity analysis can be used to evaluate how the changes in refurbishment frequency and carbon cost affect the outcomes of the model. Those results can be used to make more reliable and robust predictions on the outcome.

The next section summarises the results chapter identifying key findings and introducing the discussion chapter.

7.11 SUMMARY

This chapter presented the analysis of the results generated by the model at the assembly, shop and shopping centre levels of case studies based on the average shopping centre. Different GLA and shop combinations are also analysed and explained.

Results reveal that the *BAU* scenario of the shopping centres in Australia accounts for a significant amount of annual REE (193.15 MJ/m^2/year) when compared to other property types due to the frequent refurbishments and poor choices of building materials and assemblies. The results generated from the model identified building materials and assembly combinations that can lead to reduced LCEE and LCMC with and without a carbon tax. Furthermore, the analysis identified that the *centre structure* is typically responsible for the largest share of LCEE and LCMC in the shopping centre level. Results also revealed the types of shops that have the highest LCEE and LCMC intensities regardless of their GLA proportions.

Additionally, the results compared the effect of GLA on LCEE and LCMC of shopping centres in Australia to understand the trends and relationships to assist in future embodied energy assessments of shopping centres.

The findings and how they relate to the established research questions and the aim are interpreted in the subsequent chapter. It demonstrates the extended discussion that involves a sound basis for environmentally friendly, economical building design solutions for shopping centres in Australia. Furthermore, the discussion creates a platform for the improvement of policies on building planning and design in the retail property sector, achieving sustainability goals.

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8 DISCUSSION

8.1 INTRODUCTION

The results presented in Chapter 7 clearly establish the significance of embodied environmental effects associated with Australian shopping centres. It further demonstrates that recurrent embodied energy (REE) of shopping centres is as important as the initial embodied energy (IEE). The results also reveal that it is possible to achieve life cycle embodied energy (LCEE) and material cost (LCMC) reductions through informed material and assembly selection. The detailed analysis of different types of shops identified their effects on LCEE and LCMC independently and at the shopping centre level. In speciality shops with a refurbishment frequency of five years over 50 year life span REE is around 90% of LCEE, while in anchor shops it is estimated to be below 70%. Conversely, the *centre structure* analysis indicated that the IEE (90% - 95% of LCEE) is the most significant of its total embodied energy use over the life cycle. The implications of enforcing a carbon tax were also analysed by identifying indirect effects on the choice of materials and assemblies. The *centre structure* is recognised as the most critical component in terms of reducing LCEE, life cycle embodied GHG emissions (LCEGHGE), and LCMC of the shopping centre with (LCMCWT) and without the carbon tax. Furthermore, the relationship between the LCEE, LCMC, LCMCWT and the gross lettable area (GLA) of a shopping centre is evaluated. The results of the model have successfully answered the research questions outlined in Section 3.9.

The aim of this chapter is to discuss the implications of the results generated by the model, presented in Chapter 7. The results are interpreted in light of the analysis of the literature in Chapters 2 and 3. The discussion begins with the significance of LCEE of Australian shopping centres and comparing the findings against the prevailing literature. Then it summarises the shopping centre level findings on the benchmarks of LCEE, LCEGHGE, LCMC and LCMCWT intensities for different types of shops. These intensities can be used to assess embodied environmental effects and material costs of shops and shopping centres in Australia, at the initial design stage. A summarised demonstration of the combinations of building materials and assemblies that have the potential to reduce LCEE and LCMC of services shops is presented. Due to brevity other assembly combinations are attached as Appendix 15. Then the assembly solutions uncovered in Chapter 7 are further analysed identifying the limits of the adoption of the results in the industry along with the reasons as to why several assembly solutions are not as widely used despite their cost-efficiency with lower embodied energy.

This chapter then discusses how the results can be used by different stakeholders (policy enablers, developers, retailers) to improve embodied energy efficiency within shopping centre design and development so as to achieve sustainable development goals with minimal cost increments. The implications of a carbon tax are reviewed, identifying its effectiveness in directing the industry towards embodied energy efficient designs are then discussed. Finally, the limitations and potential improvements of the model and the results generated are discussed in detail, identifying how to address those limitations in future research. The final chapter will present the conclusions of the research.

8.2 SIGNIFICANCE OF LIFE CYCLE EMBODIED ENERGY OF SHOPPING CENTRES

The analysis presented in Chapter 7 assessed three different shopping centre cases in Australia to identify the significance of their embodied environmental effects. Results revealed that the construction of a typical shopping centre using steel and concrete requires 485.69 TJ of embodied energy and 28,548.72 tonnes CO_2e of embodied GHG emissions over a lifespan of 50 years. An important finding is that the REE of shopping centres is as significant as the IEE, resulting in an almost 1:1 ratio as demonstrated in Figure 8.1.

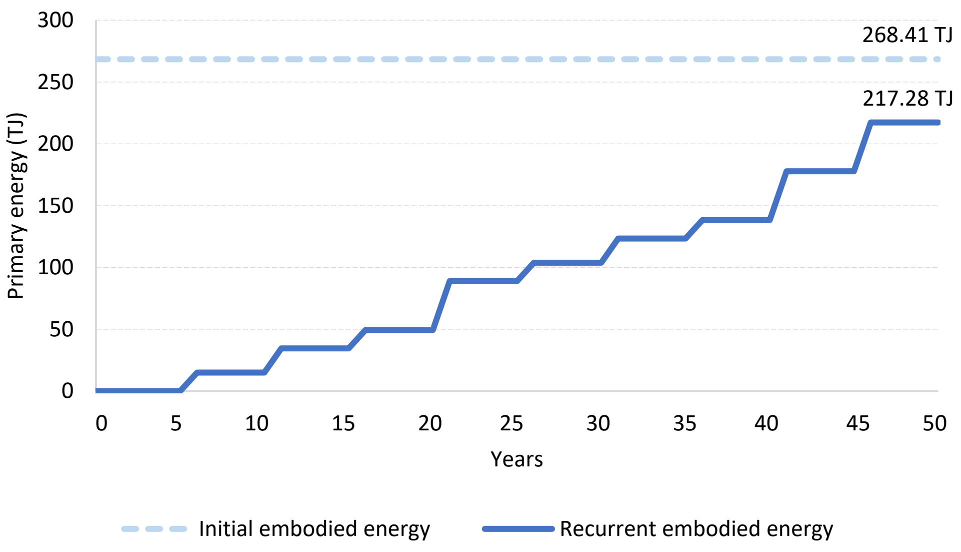

Figure 8.1: Recurrent embodied energy of the average shopping centre business as usual scenario over the 50 years in TJ

Yet current research on retail centres tend to focus mainly on IEE (Van Ooteghem & Xu, 2012). The percentage IEE of the *centre structure* solely, excluding initial inputs of the internal fit-outs, is responsible for more than 48% of the LCEE of the shopping centre. As REE of the centre structure is around 2% of the shopping centres LCEE, the remaining 50% is caused by the total LCEE of the internal shop fit-outs. This demonstrates the significance of the REE of shopping centres in Australia.

Using relative intensities, the average LCEE of a single-storey subregional shopping centre is 21.59 GJ/m^2, and the LCEGHGE intensity is 1.25 tonnes CO_2e /m^2 in the business as usual (BAU) scenario (where construction is dominated by steel and concrete). These values may appear high but this is most likely a result of the use of input-output based hybrid embodied energy coefficients (EEC) by Treloar and Crawford (2010), which are more comprehensive and complete compared to other life cycle inventory analysis methods. Using input-output based hybrid coefficients on a commercial building Crawford and Treloar (2005) identified that the LCEE was around 25.8 GJ/m^2, and that these decreased by around 31% (to 17.8 GJ/m^2) when process-based hybrid values are used. Dixit (2017a) also found that the assessments based on hybrid input-output based values are more than double in comparison to conventional input-output based coefficients. Therefore, it must be noted that the results are not comparable with other studies which follow different LCI analysis methods.

Despite the use of similar hybrid coefficients, the annual REE intensities are however, significantly higher when compared to assessments of other building assets. In the BAU scenario, the annual REE intensity of the shopping centre is 193.15 MJ/m^2/year. Studies by Rauf and Crawford (2013) and Stephan and Stephan (2014) found that annual REE intensities of houses are 160 MJ/m^2/year and 168.6 MJ/m^2/year respectively using the same coefficients. These values are around 15% lower than the annual REE intensity of the shopping centre, identifying that the embodied environmental effects of this building asset over the life span are more important than other building assets.

The annual REE of the *BAU* centre is almost 20% of the annual operational energy intensity of an enclosed shopping centre (including tenancies), estimated at around 984.25 MJ/m^2/year (ICSC, 2016). This demonstrates the effect of continuous replacement of building materials and assemblies are highly significant in shopping centres. Furthermore, with the use of more environmentally sensitive energy sources for operation, the importance of embodied effects is rapidly increasing. When LCEE is presented in terms of annual total embodied energy, it accounts for 431.8 MJ/m^2/year. This value indicates that if LCEE is equally distributed across the 50-year life span, embodied energy represents 30% of the annual total energy use of the shopping centre. Therefore, Australian shopping centres have a significant effect on embodied energy use and emissions generation in the built environment over the service life.

However, shopping centre stakeholders are currently more focused on operational energy and emissions reductions which can lead to monetary savings while achieving sustainability ratings of Green Star and NABERS (Buxton et al., 2016; GBCA, 2020b; SCCA, 2019). Despite the growing number of sustainable shopping centres in Australia, as discussed in Section 2.6, there is little concern for embodied environmental effects. The absence of evidence is one of the main reasons for this lack of concern. Nonetheless, 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 GHG emissions (GBCA, 2017). The findings of this study address the current knowledge gap and provide evidence on both environmentally responsible and cost-effective building materials available in the current market. As noted 'Australia has a real opportunity to become the world leader in shopping centre sustainability' (NABERS, 2019, p. 2) and with this research as a base can now focus on embodied environmental efficiency as well as operational efficiency.

8.3 EVALUATING LIFE CYCLE EMBODIED ENERGY, EMBODIED GREENHOUSE GAS EMISSIONS AND MATERIAL COST OF SHOPPING CENTRES

Chapter 7 quantified the LCEE, LCEGHGE and LCMC intensities to develop benchmarks that can be applied in future construction projects. Such benchmarks can be used to conduct life cycle environmental impact assessments of various material selection options for shops in shopping centres during initial design stages. Figures 8.2, 8.3 and 8.4 depict how LCEE, LCEGHGE, LCMC and LCMCWT intensities of different shops can fluctuate with the selection of different assembly combinations identified in Chapter 7. These benchmark values of different shops are demonstrated further in Appendix 16, providing the findings of lower and upper boundary values along with the averages, for all shop types.

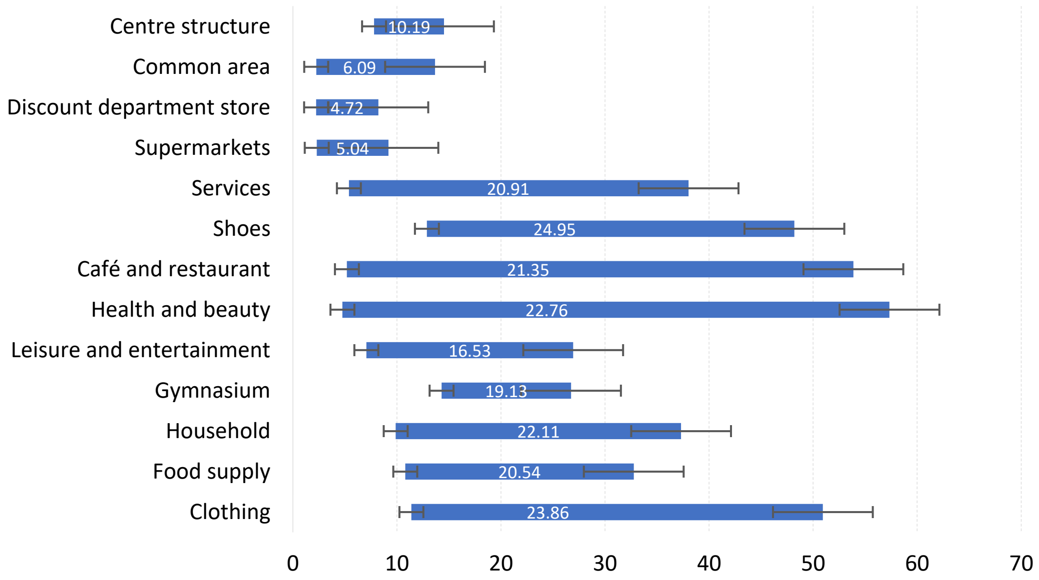

Figure 8.2: Ranges of life cycle embodied energy intensities of different shop types in GJ/sqm

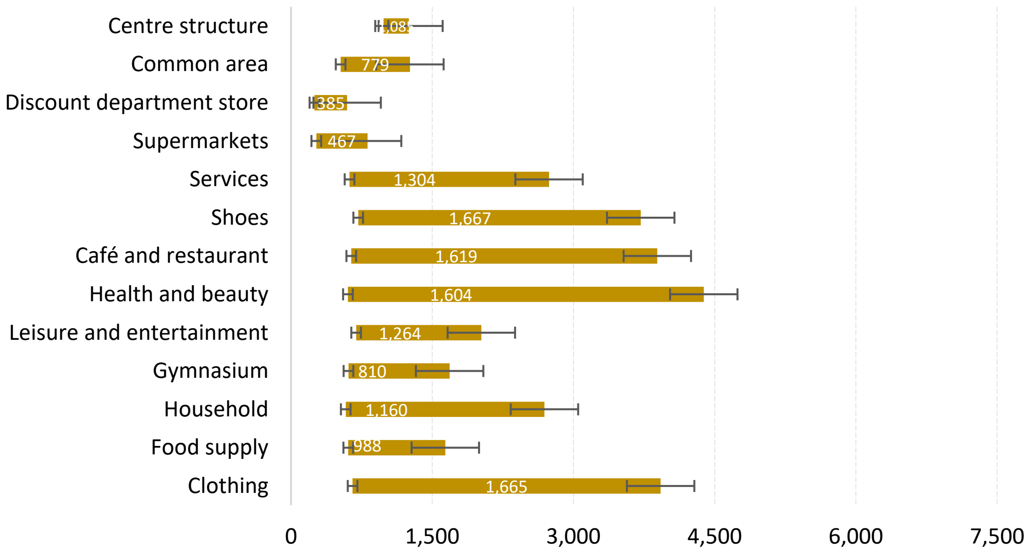

Figure 8.3: Ranges of life cycle material cost intensities of different shop types in AU$/sqm

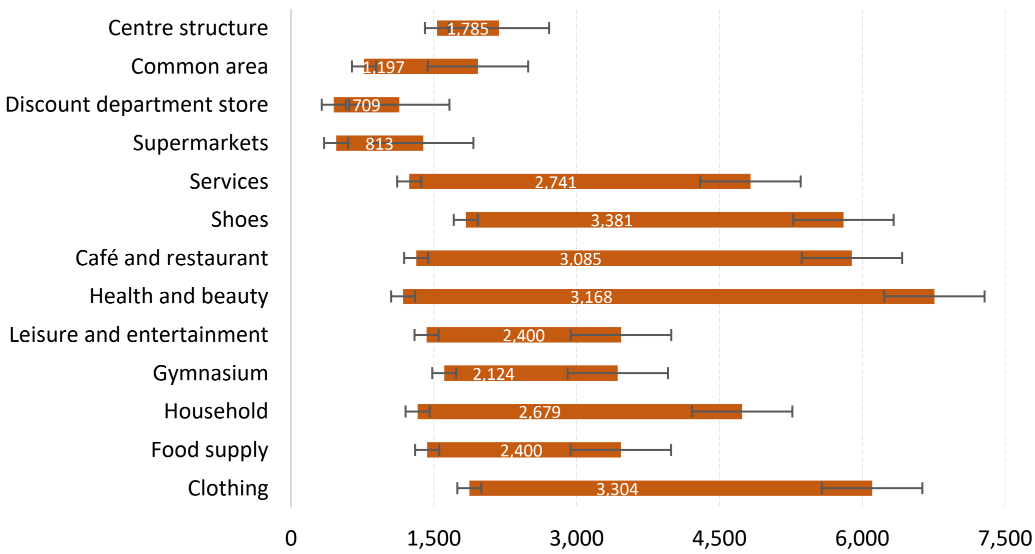

Figure 8.4: Ranges of life cycle material cost with carbon tax intensities of different shop types in AU$/sqm

Accordingly, it can be observed that *health and beauty*, *café and restaurant, clothing* and *shoes* shop types have the highest range of intensities in all comparisons. This considerable variance is identified as a result of the high levels of aesthetic sophistication required in these shops to attract customers. Typically, these shop types are very much attentive to the aesthetics of the shop, to increase the foot traffic and sales (Crewe, 2016). Making the shops more pleasing and aesthetically approachable is one of the key functions of these shop designs to create customer behavioural changes (Anderson & Mesher, 2019). To achieve this aim, these shop designs tend to utilise a vast array of building materials and assemblies, leading to significant variances in embodied energy and material cost variances (4,244 out of 8,820 assembly combinations assessed and compared in the model are for *health and beauty*, *café and restaurant, clothing* and *shoes* shops). These assemblies include lower embodied energy options of polished mortar screed wall finishes, terrazzo flooring and cork-based products as well as lower cost yet high energy options of vinyl tiles, nylon carpets and sheet metal products.

Conversely, *centre structure*, *discount department store* and *supermarket* have the lowest variances in embodied energy and material cost. These shop types have comparatively lower numbers of assembly combinations with a limited number of assemblies for selection (538 out of 8,820 assembly combinations assessed and compared in the model). The reduction of possible assembly combinations is due to the fact that these shops are typically much less concerned with aesthetics, in comparison to speciality shops that use additional efforts to attract customers via sophisticated marketing techniques. *Supermarkets* and *discount department stores* have a different business profile than the specialty retailers where customer attractions are typically increased through product price reductions (Gilbert & Jackaria, 2002; Ohta & Higuchi, 2013). They market essentials that are consumed more frequently on a daily basis, as such the customers are engaged more through cost savings rather than attractiveness or luxuriousness of the shop. The choices of assemblies thus include lower cost options porcelain and ceramic tiles, rubber carpets and water-based or oil-based paints.

This outcome is significant as it establishes how great the extent of embodied energy variations in shop fit-outs are, which is currently not considered. However, it must be noted that the results are subject to limitations due to the assumptions made throughout the modelling process as discussed in Section 8.6. 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 over the life cycle. The average values provide an approximate estimation of how intensive the shops are in terms of embodied energy, which is highly beneficial to evaluate and compare the effects of current and future projects. The lower boundary values deliver the potential maximum reductions that can be achieved with informed use of existing building materials and assemblies that are considered in the study, while the upper boundary denotes the highest values of embodied energy and material cost a shop could reach within the given assembly combinations.

Demonstration of ranges of embodied energy and material cost rather than exact values facilitates a more solid basis for comparisons of future projects in Australia.

8.4 Selection of Building Materials and Assemblies to Reduce Life Cycle Embodied Energy and Material Cost of Shopping Centres in Australia

Chapter 7 demonstrated that several building assembly solutions that lead to reduced LCEE can also result in LCMC reductions as well. The choice of assembly solutions for the *centre structure*, *anchor shops* and *specialty shops* have different levels of effects on LCEE and LCMC of the shopping centre. The assembly combinations identified can be used as a basis for material selection decision making for different types of shops in future shopping centre projects, thus addressing the key research question *"How can building material and assembly selection reduce life cycle embodied energy and material cost of shopping centres in Australia?"* (Refer to Section 3.9) to achieve the aim. This section discusses how embodied environmental performances of different shop types can be improved, utilising the results presented and analysed in the previous chapter.

8.4.1 Improving the life cycle performances of the centre structure

The results demonstrate that the *centre structure* has the most significant contribution to the LCEE and LCMC of a shopping centre. This outcome is important as there is not any evidence of its significance in terms of embodied energy, in prior research. Across all shopping centre scenarios presented in Section 7.8, it is evident that the *centre structure* is responsible for more than 50% of the total LCEE and LCMC of the shopping centre. Hence, the selection of materials and assemblies for the *centre structure* is a crucial decision that can lead to a significant reduction of both LCEE and LCMC. Architects, structural engineers and developers are the responsible project participants for material selection decisions for the *centre structure*. Hence, the knowledge of building materials and assembly solutions with lower embodied energy and material costs are vital if they are to select more sustainable choices.

8.4.1.1 Material and assembly selection for the centre structure

The analysis carried out in Chapter 7 identified that the use of *slab-on-grade foundation with 40% fly ash cement*, *steel columns, timber roof structure with Colourbond roof sheets* and *insulated sandwich panel walls* is the *optimal* scenario for the *centre structure,* minimising both LCEE and LCMC. This assembly combination could lead to around 34% LCEE reduction with just a 1% increase in the LCMC when compared to the typical assembly combinations of *slab-on-grade foundation with general purpose Portland cement, steel columns, steel roof structure with Colourbond roof sheets* and *precast concrete panel walls*. The *BAU* construction method is dominated by concrete and steel (refer Section 5.2) where the *optimal* scenarios identify the use of *engineered timber* and *fly ash cement in concrete* (Forest and Wood Products Australia, 2019; Standards Australia, 2016).

The use of *fly ash cement in concrete* production is promoted in Australia due to both the cost and environmental benefits (Neupane, 2016). The environmental benefits of *fly ash* are due to a waste management practice and carbon emission sequestration (Dananjayan, Kandasamy, & Andimuthu, 2016; Ukwattage, Ranjith, Yellishetty, Bui, & Xu, 2015). In addition, it has improved mechanical qualities (superior workability and durability) and reduced heat of hydration and thermal cracking (Şahmaran & Li, 2009). This makes it a much more sustainable alternative to *general purpose Portland cement*. Nonetheless, the use of *fly ash cement* has yet not reached the maximum of its potential in the cement and concrete industry. Currently, fly ash is used to replace only a limited percentage of cement in concrete (typically only up to 35% or 40% of cement used in concrete) (Hemalatha & Ramaswamy, 2017). Research is being conducted to improve the cement blend in concrete to achieve near 100% fly ash utilisation (Hashmi, Shariq, Baqi, & Haq, 2020). Recently, the use of supplementary cementitious materials (SCM) such as fly ash, slag cement, and silica fume in Australia has been promoted and it was found that 90% of concrete production cases utilising at least one of the SCM products. Among these materials, fly ash is the most widely used, following the specification and supply of concrete carried out in accordance with AS3582.1: Supplementary Cementitious Materials for use with Portland and Blended Cement, Part 1 – Fly Ash, and AS3972, Portland and Blended Cements (Standards Australia, 2016). Therefore, the use of *concrete with fly ash cement* is currently considered as the most appropriate alternative to construct foundation systems in shopping centres in Australia, which differs from current practice.

The results identified the use of *insulated sandwich panels* as a better option to the commonly used *precast concrete panels* for the wall construction of the *centre structure*. The primary reason behind this selection is the lower cost and the EEC of the assembly. Although precast concrete walls are regarded as a functional and an effective solution, it must be noted that the use of engineered timber structural components is considered more environmentally responsive since it is renewable (Forest and Wood Products Australia, 2019; Quesada-Pineda et al., 2018). A precast wall may be regarded by developers as providing an increased hindrance to public misuse (e.g. attempted theft, nuisance damage etc.) so it may take further research to promote the increased use of the insulated sandwich panels, in such a public place as a shopping centre. In that case the use of cross-laminated timber would be the most viable solution achieving environmental sustainability even with a slight increase in material costs.

The *engineered timber roof structure* and *glue-laminated timber columns* are proposed in the *optimal* combination. However, the use of structural timber has not been popular in Australian shopping centre construction to date for several reasons. Firstly, lack of information to support the use of structural timber has made shopping centre developers reluctant to consider its use (Gosselin et al., 2017). Secondly, while timber is widely identified as a residential construction material this is not the case within commercial or retail buildings (Ramage et al., 2017; Tam et al., 2017; Thomas & Ding, 2018). Thirdly there is a belief that higher costs and increased construction time have limited its use in shopping centre structure construction (Achenbach et al., 2018; Quesada-Pineda et al., 2018; Tam et al., 2017). Fourthly, a belief that timber has poorer performance than steel and this has limited its use (Bayne & Taylor, 2006). Finally, it was only recently the Building Codes of Australia approved the use of structural timber in Class 6 building types, such as shops or shopping centres (Forest and Wood Products Australia, 2019).

Recent studies have identified the usefulness of timber as a structural material for non-residential construction (Stocchero, Seadon, Falshaw, & Edwards, 2017; Tam et al., 2017). Newer forms of timber structural elements such as *cross-laminated timber* and *glue-laminated timber* are proving to be more promising options in non-residential construction with examples of its use in high-rise commercial buildings (Kremer & Symmons, 2015; Quesada-Pineda et al., 2018; Zeitz, Griffin, & Dusicka, 2019). The findings of the model proposes the use of timber structures, over both concrete and steel and its use does not affect building costs as much as developers may fear (Kremer & Symmons, 2015). Smith, Fragiacomo, Pampanin, and Buchanan (2009) found that cost of timber alternatives was only around 6% more than steel or concrete designs of an office building in New Zealand. This study found that when GLT is used as an alternative to steel column it is possible to achieve almost 45% material cost savings. This might change when labour cost components are included which is discussed in Section 8.6.2. Therefore, with its inclusion in Class 6 building types and superior sustainability properties for the shopping *centre structure,* developers should consider the use of timber as a structural building solution over concrete and steel.

While the model identified the use of engineered timber structures to achieve both reduced LCEE and LCMC for the *centre structure*, it must be noted that the cost component compared in the model involves only the life cycle costs of the materials used in the assemblies. It excludes labour costs, plant and equipment costs and any other miscellaneous costs. The effect of exclusion of labour costs on the results are discussed in Section 8.6.2. The analysis is carried out within these limits, to assess LCEE in shopping centres and evaluate the impacts of the choice of materials on embodied energy and cost, rather than to have a broader scope of life cycle assessment.

This section discussed the importance of selecting materials for the *centre structure* to achieve lower LCEE and LCMC. While the results found the use of *engineered timber structures* and *fly ash cement in concrete* as a better solution from a sustainability perspective it should be noted that for several assembly types, the use of concrete is still proposed to achieve cost savings. The real challenge is, therefore, to address material selection with developers who currently do not consider these assembly solutions as they deliver better sustainability at a negligible cost increment. The retail industry should focus on sustainability as a responsibility, rather than considering just cost or aesthetics. Sustainable designs need to be valued more, establishing a new norm in the retail property industry.

8.4.1.2 Relationship between shopping centre size and life cycle embodied energy and material cost

The analysis in Section 7.9.2 examined the relationship between the GLA of a shopping centre and its LCEE, LCMC and LCMCWT. This was further extended to identify trends between different GLAs using two additional case studies of *small* and *large* shopping centres, as described in Sections 5.4 and 5.5. Findings revealed that LCEE, LCMC and LCMCAT have a strong positive linear relationship with the GLA of the shopping centre when absolute values are compared. The increase in LCEE in the *small* and the *large* centres is +160% compared to +163% in GLA in *BAU* scenario. This indicates that LCEE tends to be almost linearly correlated with the shopping centres size. The increase in LCMC, however, is +150% whereas LCMCAT is +154% for an increase of +160% in GLA. This demonstrates that LCEE becomes more significant as shopping centres size increase in comparison to LCMC.

On the contrary, the comparison of embodied energy and material cost intensities indicate negative relationships with the GLA. The LCEE shows a minimal negative relationship with the GLA, where the decrease of LCEE intensity (-1%) is smaller than the LCMC decrease (-5%) in the *BAU* scenario. These trends indicate that bigger shopping centres are less energy and cost intensive on per sqm basis. However, it must be noted that using special functional units can hinder the actual representation of energy and cost requirements and tend to favour larger floor areas. A similar observation was made by Stephan and Crawford (2016), where they analysed the effect of house size on the life cycle energy demand.

The trend analysis of absolute values and intensities identified that the size of the shopping centre has strong relationships with its LCEE, LCMC and LCMCAT, either positive or negative. Therefore, the size of the shopping centre is a crucial factor in terms of embodied environmental effect reduction. It is important to trade-off the absolute values and intensities to identify the optimal size to reduce embodied energy, embodied GHG emissions and material usage in the shopping centre industry.

8.4.2 Improving life cycle performances of shop fit-outs

The interview findings identified that shop owners, inhouse facility managers, and small contractors typically involve in the design of fit-outs of different retail shops in shopping centres. Therefore, it is important to make them aware of the impacts of material selection on the LCEE and LCMC for different shop types. The primary function of a shop is the most influential factor in the choice of building materials and assemblies for the retail fit-outs. As described in Chapter 7, shop types have a different range of building materials based on owners preferences, that suit both their target customer profile, and the general design requirements of the shopping centre.

8.4.2.1 Material and assembly selection for shop fit-outs

Typically, *clothing* and *shoes* shops focus more on the aesthetics to tempt and lure customers, whereas *café and restaurants* are more attentive to provide a comfortable environment where people feel welcome and relaxed to sit and dine (Anderson & Mesher, 2019). Among *clothing* shops, high-end boutiques are concerned more with the aesthetics and level of luxuriousness of the shops to maintain customer interests (Crewe, 2016). However, these high-end luxury shops are typically not a feature in subregional shopping centres so the analysis does not incorporate material selection for them.

The types of assemblies that lead to both LCEE and LCMC reductions in *clothing* shops in shopping centres involve *metal framed ceilings with plasterboard* or *vinyl tiles* with *laminated timber* or *vinyl plank flooring* and *water or oil-based paint on mortar screed with putty* and *timber board cladding* as wall finishes. It should be noted that even though timber cladding is identified as a sustainable lower-cost solution to reduce embodied environmental impacts of the shops in shopping centres, currently the use of this product is under review due the fire risks they pose (Allen & Iano, 2019; Chen, Yuen, Yeoh, Yang, & Chan, 2019). The suitability and applicability of this product are discussed in Section 8.4.2.2.

The solutions identified are the most embodied energy saving and cost efficient for *clothing* shops while maintaining the aesthetic considerations important in this shop type. These assembly solutions can lead up to 21% LCEE reduction and LCMC saving up to 43% in comparison to the *BAU* scenario. However, it must be stated that the choice of materials is profoundly affected by the decision maker's mindset and preferences (Dangana, 2013; Sinha, 2011; Yudelson, 2009). Therefore, actions may be needed to guide the preferences of the decision-makers' to deliver a more sustainable shop design at a lower cost as identified in Section 8.6.6.

On the other hand, *services* and *household* shops are not as concerned with aesthetics since they are retailing essentials, which do not necessarily require additional components to increase customer attraction (Dangana, 2013; Woitenko & Clark, 2007). The choice of materials resulting in lower LCEE and LCMC for *services* shops involve *metal framed ceilings with plasterboard or vinyl tiles* along with *corkboard*, *ceramic tile* or *terrazzo flooring* and *mortar screed with white putty* that can result in up to 72% LCEE reduction and 33% LCMC savings in comparison to *BAU* scenario. These choices do not have the same aesthetic qualities as the assembly choices of *clothing* shops, but they fulfil the requirements of these retailers. Similarly, in *supermarkets* and *discount department stores*, shops need to be maintained nice and clean standard, but it is not necessary to install any extravagant finishing (Petermans & Kent, 2016; Reimers & Clulow, 2004). They typically use the internal fittings and furniture arrangement to make the shops attractive to the customers (Anderson & Mesher, 2019). These shops can have significant reductions in LCEE, reaching up to 50% difference in savings, in comparison with the shops such as *clothing*. Nonetheless, when optimal LCMC is considered, the savings are higher in *clothing* and *shoes* type shops (up to 57%), while for *services* like shops it is less (around 30%).

Therefore, it is important to note that different shop types within shopping centres behave differently, and this needs to be accounted for when sustainable materials are selected. In reality, the selection decisions are highly dominated by the preferences of the shop owners' and based on their business profiles (Anderson & Mesher, 2019; Kent, 2007; Petermans & Kent, 2016). So even with the knowledge and awareness of reduced embodied energy and lower material cost solutions available owners might still be reluctant to use them. If sustainability is to be taken seriously, it is essential to monitor the use of materials by different shop owners. The development, implementation and regulation of building materials policies are required to better manage embodied environmental effects. These need to consider the unique features of shopping centres uncovered by this research.

The centre management does, however, typically influence the choice of materials for *common areas*. *Common areas* represent the image of the shopping centre as a whole and a standard profile is often adopted if it is part of a shopping centre chain. Unfortunately, when a standard profile has to be adopted that ignores sustainability, the material selection can be significantly constrained for *common areas,* and their effects will be broader than one single shopping centre. The model advises the use of *wood plank ceilings on timber frame* along with several flooring options. These include *terrazzo flooring with infill slab* or *ceramic tiled flooring* and *water-based paint on mortar screed* or *timber board cladding* or *vinyl tiles*. Overall, this reduces the embodied energy (up to 38%) and material cost (up to 11%) in comparison to the *BAU* scenario. Centre management policies could be used to encourage better choices.

Therefore, it is apparent that the type of shops plays a vital role in the choice of materials. When understood by shopping centre management and shop owners more fully, building material choice can reduce both the LCEE and LCMC implications in these subregional shopping centres.

8.4.2.2 Use of timber cladding as a sustainable alternative

The following section discusses the suitability of *timber board cladding* as a sustainable building solution in Australia, considering both fire safety issues and environmental concerns.

Timber cladding is one of the most used building cladding products in Australia across many building types (Forest and Wood Products Australia, 2019). It is identified as the most versatile cladding solution that can adapt to and sustain the extreme weather conditions in Australia (Allen & Iano, 2019; Forest and Wood Products Australia, 2019; Silva, de Brito, & Gaspar, 2016a). Furthermore, timber is proven to have more fire-retardant qualities than steel (Allen & Iano, 2019). The Australian construction industry is evaluating the suitability of timber cladding in the built environment due to the uncertainty of fire resistance of several timber cladding products (ABCB, 2019; Chen, Yuen, et al., 2019). A legal case between a builder and the NSW Civil and Administrative Tribunal is currently awaiting a ruling on a composite timber cladding product in Class 2 (apartment) buildings, which is not in accordance with the fire rating requirements of the Building Codes Australia (BCA) and Standards Australia (ABCB, 2019). Therefore, in the future, timber cladding products may require assessments for combustibility even when they are used as an attachment in the façade of a building (Forest and Wood Products Australia, 2019; Webb & White, 2020). The Australian Building Codes Board has confirmed that the use of timber cladding is acceptable for all classes of buildings, except for Class 2 and Class 3 (residential buildings other than houses and apartments) low-rise buildings, if they comply with the 'Deemed-to-Satisfy' provisions of the National Construction Code.

Therefore, material selection must consider the fire safety requirements of the BCA (non-combustibility testing in accordance with AS 1530.1) and Standards Australia and comply with the standards when using combustible timber cladding. Even though the limitations do not apply to Class 6 single-storey shopping centres, it is better to assess the fire safety of the materials and use non-combustible timber cladding to prevent any undue fire risks (Chen et al., 2019).

8.4.2.3 Significance of shop type on improving life cycle performance of shopping centres

The analysis in Chapter 7 on suitable building materials and assemblies for different shop types revealed that the existing solutions could be appropriately used to attain embodied energy reductions with minimal material cost increments. The analysis demonstrated that even when the same assembly is used in different shop types, where refurbishment frequencies are different, the impacts of LCEE and LCMC with and without carbon tax were different. So, when adopting the materials and assemblies identified in the study it is crucial to consider their suitability (based on service life values of materials and assemblies and refurbishment frequency of the shop) to avoid any premature replacements that can cause unnecessary embodied energy and material cost increments (Hausladen & Tichelmann, 2010).

The LCEE distributions across different shop types in shopping centres (presented in Sections 7.8 and 7.9) demonstrate that they have different levels of contributions depending on their GLA proportions and the preferences of building materials and assemblies. In the average shopping centre, *anchor shops (13%)*, *common areas (4%)*, and the *specialty* shops of *household (11%), services (5%)* and *food supplies (4%)* account for more substantial shares of the total LCEE. However, these contributions are significantly affected by the GLA distribution. Therefore, if the shopping centres are to be made more sustainable in terms of the design, the responsibility relies mostly on the *anchor tenancies*, *common areas* managed by the centre management, and the *specialty shops* responsible for significant GLA proportions.

Nevertheless, it must be stated that the impacts of LCEE by shop types, can be represented differently when embodied energy intensities per unit area are considered. The use of relative values provides a more solid basis for comparison (Stephan & Crawford, 2016). Accordingly, in the *BAU* scenario of an average shopping centre, the most embodied energy intensive shop type is the *gymnasium*, followed by *leisure and entertainment* and *household*. Therefore, it will be beneficial to compare these intensities when the tenant mix is formulated in shopping centres, along with other market forces (Carter & Allen, 2012), to reduce the implications of high energy intensity shop types and to achieve sustainability in design.

A significant finding is that in a shopping centre redesign, aiming to reduce LCEE and LCMC, the shop types with higher embodied energy intensities do not necessarily become the most crucial due to the impacts of GLA. Retailers need to be more aware of the environmental impacts caused by the shops and have a social responsibility to engage more sustainable building solutions into fit-out designs. Furthermore, the materials need to be selected considering the refurbishment frequencies of the shop types since the use of a sustainable material with a higher service life to be replaced in a few years, only increases the resource waste (Rauf & Crawford, 2013). It is better to either use materials with smaller service life values to fulfil the needs or design for disassembly (Crowther, 1999; WGBC, 2018), allowing for more flexible shop fit-outs. The current shopping centre retailers should, therefore, emphasis on the selection of building materials and assemblies considering the behaviour of the shop fit-out over its life cycle. Nonetheless, in a circular economy where reuse and recycling are promising, the paradigm can be shifted to focus more on the EEC and material unit price for the selection, despite the refurbishment frequency or the service life (Di Maria et al., 2018).

The next section provides details on the impact of the results of the study on the policy development and implementation on sustainable shopping centre development in Australia.

8.4.3 Implications on policies

The previous section discussed the implications of the results and how the involvement of developers in material selection could reduce LCEE and LCMC of shopping centres. Nonetheless, in order to have significant embodied energy reductions in shopping centres, an integrated sustainable design policy is essential. Even though there are several sustainable building design regulations in Australia related to residential and commercial building construction (i.e. the '*environmentally sustainable design (ESD) in planning policy, liveable housing design guidelines, Parliament of Australia's Sustainable buildings mandatory construction standards* and *building codes Australia (BCA) standards*'(Collia & March, 2012; Department of Industry Innovation and Science, 2016; Summerville, Adkins, & Kendall, 2008), currently none exist for retail property or shopping centre design (Ferreira, Pinheiro, de Brito, & Mateus, 2020). However, the Green Building Council of Australia (GBCA) 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 become the guideline to achieve sustainability in design and construction of retail centres and has made a considerable impact on the retail sector (GBCA, 2017). The *Green star - retail centre design* tool addresses the significance of life cycle assessment of materials to evaluate the sustainability of building design. However, this tool does not differentiate different retail spaces, nor it is a mandatory requirement nor a policy that would create a substantial change in the sustainability of retail shopping centre design and construction (Mitchell, 2010). This study is beneficial in many ways to resolve this matter by providing a solid base for embodied energy and emissions assessments of future projects as well as with the identification of better assembly combinations that can lead to embodied emissions reductions with minimum material cost increments.

Therefore, it is essential that a guideline or policy to assess the use of building materials and assemblies in shopping centres to reduce their embodied energy throughout the building life is developed. The results in Section 7.8 demonstrated that the *centre structure* is the most significant in terms of LCEE reduction. Thus, government and other policy makers could use the findings of this study (building materials and assemblies) to promote increased consideration of sustainability in shopping *centre structure* design and construction. Since the engineered timber structures and fly ash cement in concrete may slightly increase in the cost of these materials (Forest and Wood Products Australia, 2019; Quesada-Pineda et al., 2018; Tam et al., 2017), an incentivised approach to encourage stakeholders to adopt those sustainable solutions should be considered.

Shopping centres which use building materials and assemblies with lower embodied energy could be awarded a rebate from the project cost or tax incentive by assessing the embodied energy savings and the *BAU* scenario of shopping centres which is currently dominated by steel and concrete. The benchmarks developed in the study become extremely useful in accessing the environmental performances of the shopping centres (refer to Section 8.3). Similar regulations to these are currently widely practiced in the residential building sector in Australia (Sustainability Victoria, 2020) so it's extension to the retail sector, using the findings of this study, may find some traction. Using a policy agenda, shopping centre development could therefore be regulated in a similar manner to improve sustainability.

Similarly, guidelines should also be established to promote sustainable development of retail shop fit-outs in shopping centres. Typically, shop fit-outs include *internal walls, wall finish, ceiling finish* and *floor finish (Petermans & Kent, 2016)*. Primarily, the level of aesthetic sophistication required for a shop governs the selection of building materials and assemblies for these elements (Anderson & Mesher, 2019; Hausladen & Tichelmann, 2010). The findings of this study revealed different combinations of building assemblies that can be used in different shop types in a shopping centre (refer Section 7.3). Guidelines on sustainable retail fit-out design could be developed utilising these findings on combinations of assemblies and their impacts on LCEE and LCMC. Shop types with varying lease periods and refurbishment frequencies should be treated differently as they have distinctive design solutions that can lead to LCEE reductions with almost zero cost increments. Refurbishment frequency is a significant factor that affects material selection in retail shops as assemblies tend to have different LCEE and LCMC depending on the nature of the shop (refer Section 7.7).

Another critical finding is the significance of *anchor tenancies*, *common areas* (maintained by shopping centre management), and *specialty retailers* in terms of LCEE reduction. When LCEE intensities are compared, *anchor tenancies* and *common areas* have much smaller values in comparison to other shop types. The higher embodied energy shares (in absolute values) are predominantly obtained in shops with comparatively larger GLA. Therefore, the attention needs to focus more on shop types with higher LCEE intensities as well as more substantial GLA proportions. It is important to encourage the retail shop owners and franchises to adopt more embodied energy-efficient building solutions through a variety of policy avenues as these more sustainable solutions do not necessarily lead to increased material cost. As well as government regulation and incentivisation, centre's themselves as well as shop franchises could develop internal company policies. As significant LCEE contributors, these *anchor tenancies* and *specialty shops* need to be prioritised in the policy guidelines to address the sustainability issues in a more substantial scale (Ferreira et al., 2020; Ramanan & Ramanakumar, 2014).

Therefore, both national and local level policy should be used to leverage change in this area so as to encourage and promote the use of sustainable building materials and assemblies in shopping centre design and construction in Australia.

8.5 IMPLICATIONS OF A CARBON TAX SCHEME

Apart from LCEE and LCMC assessments for building material selection, implications of the carbon tax on LCEGHGE were also investigated in the model. Embodied GHG emission is the combination of emissions resulting from embodied energy use and chemical reactions of building materials and assemblies (Engin & Frances, 2009; Hammond & Jones, 2008). Therefore, LCEGHGE can be identified as the sum of all emissions associated with building materials and assemblies that are used throughout the analysis of the building.

The embodied GHG emission is a significant measure of global warming, representing the climate change, which is the most severe sustainability issue globally (IEA, 2019; IPCC, 2019; NASA, 2020). Conventionally, embodied GHG emissions are considered optional in life cycle assessments given that they are of small magnitudes when compared with operational GHG emissions (Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2013). However, with the advancement of building materials and technologies, more energy-efficient building solutions have been developed which can reduce operational GHG emissions of a building (Fumo, Mago, & Chamra, 2009; Ibn-Mohammed et al., 2013; Mills, 2011). Therefore, over the past few decades, the relative significance of embodied GHG emissions has increased (Akbarnezhad & Xiao, 2017; Gan, Cheng, & Lo, 2019; Pomponi & Moncaster, 2018). Consequently, at present, embodied GHG emission assessment of buildings regards to building architecture and design solutions has become prominent (WGBC, 2019a).

The results demonstrated that the enforcement of a carbon tax could lead to substantial reductions in embodied GHG emissions while encouraging the use of building materials and assemblies with lower embodied energy. The analysis showed that the introduction of a carbon tax into material costs creates a shift in materials in comparison to the minimum LCMC solutions. More importantly, it was noted that the optimal assembly combinations minimising both LCEE and LCMC are identical to the assembly combination with minimum LCMCWT. This outcome is a key contribution of the study. It demonstrates that the introduction of a carbon tax could indirectly lead the stakeholders to select the optimal solutions. Additionally, it was observed that when carbon tax is increased, the selection leans more towards materials with lower embodied energy. Therefore, carbon tax needs to be optimised to achieve sustainability while managing both environmental and economic aspects.

However, imposing a carbon tax is a crucial decision in terms of economic implications. In most countries where carbon tax schemes are imposed, they are more of an economy-wide tax (Carbon Pricing Leadership Coalition & International Finance Corporation, 2019). Yet, a more suitable approach could be to develop a construction industry-based tax scheme for assessing the emissions of building materials and assemblies (Carattini, Carvalho, & Fankhauser, 2018; Laes et al., 2018; Metcalf, 2018). Research shows that the carbon tax has a direct and a significant impact on carbon emissions reduction in a short period (Andersson, 2019; Metcalf, 2018; Murray & Rivers, 2015). However, it is imperative to analyse its implications on the economy before enforcing (Carbon Pricing Leadership Coalition & International Finance Corporation, 2019). Addition of a cost component for GHG emissions can lead to increased building materials prices due to the cost increments along the supply chain (Sathre & Gustavsson, 2007; Wong et al., 2014). Nonetheless, it is possible to mitigate this economic stress through a tax swap or a tax release scheme (Metcalf, 2018; Wong, Ng, et al., 2013). Many economists believe that carbon taxes are the most efficient and effective way to mitigate GHG emissions with minimum adverse consequences on the economy (Comstock & Boedecker, 2011; Shi et al., 2019; Zhang, Wang, Liang, & Chen, 2016; Zuo et al., 2012).

As discussed in Section 3.6.2, in Australia, the carbon tax mechanism was implemented for two years, from 2012 to 2014 (Burke, 2016). When it was enacted, emissions from the construction industry showed significant reductions as illustrated below (Department of Agriculture Water and the Environment, 2019).

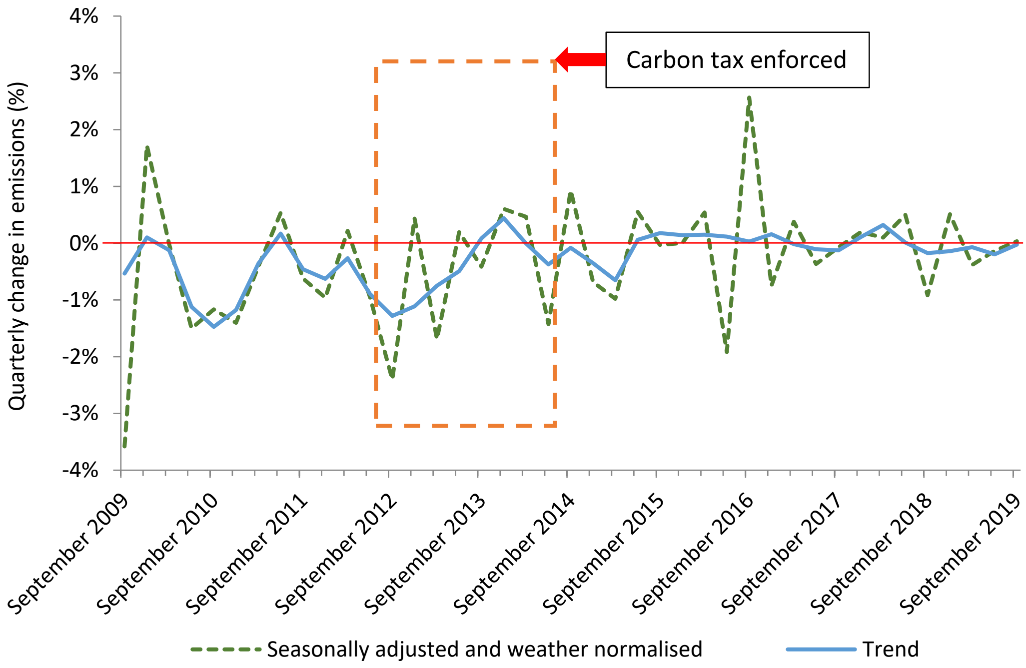

Figure 8.5: Emissions growth rates, by quarter, September 2009 to September 2019

Source: Department of the Environment and Energy (2020)

Figure 8.5 above depicts the quarterly trends of emissions from 2009 to 2019, identifying the fluctuations across the years. It is visible in the figure that after the carbon tax enforcement, the quarterly change in emissions was mostly below zero, indicating emissions reductions from 2012 to 2014. Since the beginning of 2014, quarterly change has again become positive signifying increased emissions. Even afterwards, in some quarters' negative changes are visible (March 2015, June 2016, September 2018) yet not as significant as before.

Therefore, it is important to take necessary actions on evaluating the introduction of the carbon tax scheme at the earliest possible to navigate shopping centre stakeholders towards sustainable and low embodied energy designs in Australia.

8.6 LIMITATIONS OF THE STUDY AND POTENTIAL FUTURE USES OF THE MODEL

This study developed a mathematical model to generate combinations of building materials and assemblies with lower LCEE and LCMC for shopping centre design in Australia. However, the developed model and the results generated contain several limitations. This section attempts to discuss these limitations in detail with means to address them and propose potential improvements for future uses of the model. At the outset, aspects concerning embodied energy, material cost, embodied GHG emission, carbon tax, refurbishment frequency, and designs of the shops and shopping centres are presented. Subsequently, the relevance of the selected case study shopping centres is analysed, identifying means to generalise the findings to a broader spectrum of retail shopping centres. Finally, potential future uses and improvements to the model are discussed.

8.6.1 Embodied energy quantification approach

The model carries out embodied energy calculations at different levels, namely; assembly, shop and shopping centre. These calculations endure several limitations ranging from appropriateness and reliability of data to quantification algorithms used in the model.

The most significant limitation in embodied energy quantification is the use of input-output based hybrid embodied energy intensities. The embodied energy intensities carry the complexity and time limitations of path exchange hybrid life cycle inventory analysis method (Treloar, 1997) as described in Section 3.5.1.3. Yet, concerning that they were the most recent and most comprehensive data available for Australia, at the time of the study, these coefficients were used. However, a more comprehensive and updated dataset was released at the end of 2019 (EPiC database) using the same LCI approach (Crawford et al., 2019). These data were not used for this thesis due to time constraints, but a comparative analysis of the two datasets will be presented in an academic research publication. Also, if a researcher needs to compare the LCEE values applying any other embodied energy intensities that are compiled using different LCI methods, it can be performed by updating the relevant EEC of materials in the *Materials* database.

Furthermore, the study does not incorporate the input-output remainder for the analysis of different shopping centre scenarios. The underlying reason is that it would not impact the solution as the remainder component affects equally in all scenarios. However, the remainder does affect the absolute value of LCEE of a shopping centre and the benchmark values per unit area by up to 20%. Inclusion of this remainder would enable a more holistic and comprehensive understanding of the impacts at the building level.

REE calculations in the model rely directly on the replacement rate of the assemblies in a shop. The number of replacements of an assembly in a shop is determined based on this replacement rate. The calculation of replacement rate of an assembly in a shop uses assembly service life, refurbishment frequency of the shop and the period of analysis of the shopping centre as described in Section 4.7.3.2. Accordingly, the study relies on a simple method to determine the replacement rate based on the assumption that assemblies installed in a shop are replaced at the end of its service life only if the shop is not refurbished prior to that. The service life values are mainly adopted from the literature (Rauf & Crawford, 2015) and for materials where service life values are not available in the existing literature, proxy values are allocated based on the values of materials with similar properties (Silva, de Brito, & Gaspar, 2016b). However, these service life values can vary extensively, given that the materials and assemblies could be replaced at any other rate due to several factors. This limitation can be addressed using the ‘factor method’ calculation of the material service life values based on the International Standards 15686: Building and constructed assets – Service life planning (International Organization for Standardization, 2017). This method uses the average material service life value to determine the service life of a particular material or assembly in a building based on seven factors as; 1) material quality, 2) design level, 3) the skill of construction workers, 4) indoor environment, 5) outdoor environment, 6) in-use conditions, and 7) maintenance levels. In a perfect scenario, all seven factors need to be considered to deliver the most reliable service life figure. By using this method, the life cycle forecasting of building materials and assemblies can be improved to befit the requirements of the building elements in which they are adopted.

Additionally, the refurbishment frequency data used in the model also has limitations regarding their applicability in the real-world context, which might affect the results of REE. The refurbishment frequency figures for the *centre structure*, *specialty shops* and *anchor shops* are obtained from the interview findings and literature (Fieldson & Rai, 2009; Hausladen & Tichelmann, 2010; Holtzhausen, 2007). However, the realistic practice suggests that the refurbishments of all speciality shops might not occur every five years as anticipated in the model, because, in reality, several tenants might renew their leases and remain for another lease period. This limitation can hinder the findings of the study to a greater extent. However, it should be stated that the study attempts to deliver a close representation of the LCEE and LCMC of shopping centres (not exact) and to identify assembly solutions leading to improved environmental performance. Therefore, the implications of the refurbishment frequencies on the findings of assembly combinations can be considered limited.

To address this limitation in future research, it is vital to carry out a study on the refurbishments of retail shops in a shopping centre over its life cycle and to develop a more extensive database. This database then can be used to identify trends and patterns in refurbishments occurring in different shop types in shopping centres and do forecasting for future shopping centre scenarios. These predictions on refurbishment frequencies can then be used to determine the replacement rates and to deliver more reliable REE figures for shopping centres.

Embodied energy quantification during the use phase of the building carries another limitation regarding the choice of replacement materials. The model quantifies REE based upon the fact that at each replacement, the building assemblies are replaced with the same materials and assemblies throughout the 50 years. However, in reality, this can be different due to a variety of reasons such as, client preferences, emergence of new materials, changes in shop fit-out, etc. Nevertheless, the model is currently unable to quantify all possible scenarios of assembly changes over the life cycle to deliver a more realistic outcome. Yet, the assembly changes at each refurbishment could be addressed at a single shop level with a limited number of assembly combinations. Therefore, future research could focus on REE more profoundly for a single retail shop type in a shopping centre in order to address the issue.

The LCEE quantifications in the model do not integrate the potential end of life energy impacts through reuse, recycling or incineration, as mentioned in Section 4.7.3. These actions can lead to recovery of energy from several building materials and assemblies, which can affect the total LCEE (Colling et al., 2016; Tam & Lu, 2016). However, the implications of end of life scenarios can be appropriately assessed through a study on the current construction and demolition waste management practices of the Australian shopping centres. Data on the quantity of building materials and assemblies that are reused, recycled and incinerated at any refurbishment of any shop can then be integrated into the LCEE quantification to deliver more realistic estimations.

To summarise, the embodied energy quantification process in the model suffers from a series of limitations. The main limitations include the use of input-output based path exchange hybrid EEC which are not the most recent, excluding the input-output remainder in comparison scenarios, using a simplified algorithm to define the replacement rate, the selection of building materials and assemblies at replacements, and exclusion of end of life potential energy recovery. Nevertheless, it is fair to conclude that this study provides a broad evaluation of embodied energy of the shopping centres and based on the implications offers a rational basis for the selection of materials and assemblies with improved environmental performances.

8.6.2 Material cost quantification approach

Material unit prices are predominantly used to quantify the material cost of the shops and shopping centres in the model. Similar to the embodied energy quantification, this approach also suffers from several limitations such as the reliability of material unit prices, the material replacement approach and the exclusion of potential end of life material cost savings. This section presents such limitations and possible means to address them in future research.

The major limitation is the reliability of material cost data used. The assembly unit cost calculation in the model is carried out using the material cost figures obtained from a series of sources. These 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 energy quantification also only material inputs are considered). However, this can hinder the results of the study. The inclusion of labour and equipment cost component would not influence the assembly solutions with minimising embodied energy but could affect the assembly solutions minimising cost and the optimal solutions minimising both energy and cost.

The implications of this limitation can be addressed by incorporating labour and equipment cost to the process of assembly unit price quantification. The following table presents how the labour cost onsite affects the unit rates of *internal_wall* and *wall_finish* assemblies. These assemblies are the most labour-intensive building elements. This analysis is only a first screening labour intensities using quantitative data published in Rawlinson's construction cost guide (2019).

Table 8.1: Ranking of assemblies with and without labour costs onsite

Assembly name	Unit	Material cost	Material cost - Rank	Labour cost	Labour cost - Rank	Total cost	Total - Rank
Internal walls							
Brick wall	m^2	41.82	4	34.22	4	76.03	4
Block wall	m^2	53.88	5	44.08	5	97.96	5
Gypsum block wall	m^2	4.76	1	3.89	1	8.65	1
Steel stud wall	m^2	28.11	2	17.49	2	45.61	2
Calcium Silicate brick wall	m^2	73.93	6	60.49	6	134.41	6
Timber stud wall	m^2	36.18	3	33.29	3	69.47	3
Wall finishes							
Sheet metal cladding	m^2	60.17	9	12.25	3	72.41	8
Water-based paint on mortar	m^2	11.63	4	21.07	6	32.70	4
Mortar screed with white putty	m^2	7.70	1	6.12	1	13.82	1
Oil-based paint on mortar	m^2	11.24	3	19.59	5	30.83	3
Terrazzo tiles on cement mortar	m^2	51.76	7	57.40	9	109.17	9
Water-based paint on plasterboard	m^2	9.28	2	19.13	4	28.41	2
Timber board cladding	m^2	64.35	10	73.29	10	137.64	10
Ceramic tiling on cement mortar	m^2	30.65	5	30.50	7	61.15	5
Bamboo panels on timber frame	m^2	96.20	11	110.36	11	206.56	11
Vinyl tiled walls	m^2	33.90	6	36.61	8	70.52	7
Compressed fibre cement panel	m^2	53.88	8	9.88	2	63.76	6

This comparison demonstrates that when labour cost onsite 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. For wall finishes, top five least expensive assemblies are the same 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 onsite will not affect the results obtained from the model at assembly level.

The analysis carried out is only a primary level assessment based on trade rations (Rawlinsons, 2019). It is important to perceive that labour costs vary from site to site based on geographic locations and thus using trade ratios will not provide a comprehensive understanding of the matter. Therefore, further studies are a must to understand how labour cost onsite can affect material selection decisions.

The cost-in-use quantification in the model uses the replacement rate figure which is calculated based on the service life of the assemblies and refurbishment frequency of the shops as described in Section 4.7.4.2. Therefore, this process suffers from the limitations associated with the service life and refurbishment frequency figures and the choice of building materials and assemblies at replacements, as discussed in Section 8.6.1. This can be addressed using the approaches mentioned previously. Furthermore, CIU quantifications have additional limitations in the model regarding the conversion of future financial flows of building materials and assemblies to present value. The algorithms used incorporates a discount rate and a real price escalation rate to account for the time value of money of assembly solutions over the life cycle. The real price escalation rate of 1.9% is used to address the increasing unit prices of the materials over the years (refer Section 4.7.4.2). However, this figure is only a representation of the forecasted growth based on past financial data. Nevertheless, the model uses a single growth rate for all building materials which does not represent the reality. This limitation can be addressed by developing a database of price fluctuations of different building materials over the past 50 years or so to deliver predictions based on machine learning or any forecasting algorithm to develop real price escalation rates for different assembly categories. This could deliver a more realistic representation of future financial flows of building assembly solutions.

The end of life cost impacts of building materials and assemblies are also not addressed in the model. The implications of potential costs of deconstruction and savings from reuse or recycling can affect LCMC values. Even though the scope of this study is limited to exclude end of life cost implications, it is essential to provide a measure to address the limitation in any future research. Since deconstruction costs are not material-related and only labour-related, the study neglects the deconstruction costs, but these could be incorporated into an analysis of life cycle costs of the building materials and assemblies focusing on labour costs as well. However, the potential cost savings of building assembly solutions from reuse and recycling are material related costs. These cost savings can be incorporated into the assembly unit price as the recycling potential (Nautiyal, Shree, Khurana, Kumar, & Varun, 2015; Thormark, 2006) at each replacement for retail shop fit-outs and at the end of 50 years for the *centre structure*. The implications of cost savings from reuse or recycling can be significant, given that in a majority of retail shops, replacements occur between every 5 to 10 years. The amount of building material waste generated because of these replacements is substantial. However, literature findings of the study illustrate that in terms of mass, many construction and demolition waste are currently sent to landfill in Australia, and only a small amount is reused or sent to recycling plants (Department of Agriculture Water and the Environment, 2019; Shooshtarian, Maqsood, Khalfan, Wong, & Yang, 2019).

Therefore, in the *BAU* scenario, the implications of potential cost savings would not be that significant, with minor effects on LCMC values. Nevertheless, it is better to incorporate the end of life material cost savings to obtain a more holistic representation of material costs.

Finally, it must be noted that material cost data are presented in the nearest 5 dollars in when reporting cost intensities in shop and shopping centre analysis in Chapter 7, for improved readability. However, the precise data are exhibited in the tables and figures as a mean of transparency and accuracy.

To conclude, the quantification of material costs in the model endures several limitations including reliability of material cost data, exclusion of labour and equipment costs, determination of replacement rate and growth rate, and finally exclusion of end of life cost savings. This section provided details of these limitations along with possible means to address them in future research. The next section discusses the limitations associated with the LCEGHGE quantification approach.

8.6.3 Life cycle embodied greenhouse gas emission quantification approach

The model quantifies LCEGHGE of the shop scenarios using the LCEE values and a conversion factor (refer Section 4.7.5). This approach is considered realistic since LCEGHGE is a direct representation of the LCEE of a building (Biswas, 2014). However, the conversion factor approach does not deliver a detailed analysis of the embodied GHG emissions at the assembly level and is limited to the whole life cycle level of shops and shopping centres only. This limitation can be addressed by using the embodied carbon coefficients of the building materials (Crawford et al., 2019) to generate assembly-level assessments using a similar approach as embodied energy calculation (as used in a study by Kumanayake, Luo, and Paulusz (2018)). As a result, it will provide a more realistic and detailed analysis of the LCEGHGE of shopping centres in Australia from the assembly level.

The limitations associated with LCMCWT quantification process are presented in the subsequent section.

8.6.4 Life cycle material cost with a carbon tax quantification approach

The assessment of LCMCWT follows a simple approach LCEGHGE and the theoretical carbon tax value for Australia (refer Section 4.7.6). Since LCEGHGE is the core value for the calculation, this approach also suffers from the limitations of the LCEGHGE quantification approach. Besides, the carbon tax value used is a theoretical figure based on the values in 2014, and the algorithm involves a real price escalation rate for carbon pricing, to accommodate for increasing prices over the next 50 years. Furthermore, the LCMCWT values were also discounted to present values using the same net present value method, as discussed in Section 4.7.4.2. The limitations associated with present value calculations are already identified in Section 8.6.2, along with possible approaches to address them in future research.

The next section discusses the limitations related to the designs of shops and shopping centres used in the model.

8.6.5 Shop and shopping centre design

The shopping centre designs used in the model are based on actual case study shopping centres in Australia, as described in Chapter 5. However, these cases are only representations, in terms of the use of building materials, tenant mixes and shop layouts. 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 (refer Sections 6.3.2.4 and 6.10.3). This simplification of the building morphology could affect the material cost and embodied energy results.

This study itself attempted to address this limitation to a certain extent by maintaining the GLA of all the shops and shopping centres in the case study buildings in the simplified designs as well. They followed the same tenant mix of the actual case studies to improve the reliability of data and findings of the study. However, due to the simplification of shop designs, the quantities are affected as follows.

For instance, consider an actual shop in Case study 1 presented in Figure 8.4 (a) and its simplified design in 8.6 (b).

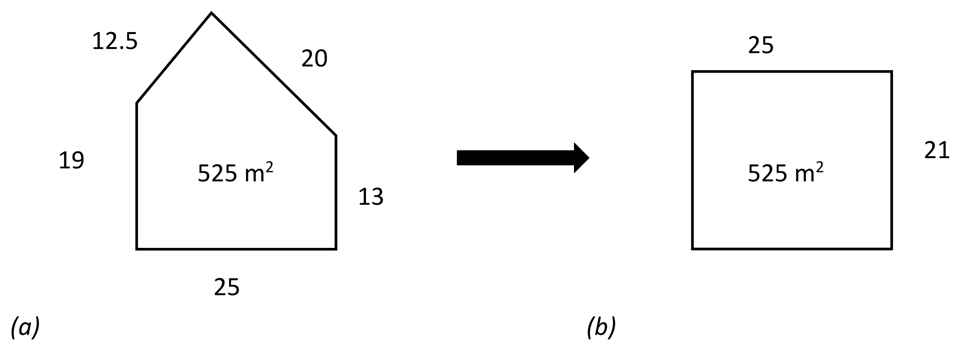

Figure 8.6: Simplification of the shop design

Building element	Functional unit	Actual design (a)	Simplified design (b)	Variance
Gross lettable area	m^2	525.00	525.00	0%
Internal wall	m^2	395.00	407.50	+3%

The difference in the internal wall area of the simplified design (b) is increased by +3% in comparison to the actual shop design (a). Similarly, it could affect the quantity of wall finishes. However, the design change does not affect the quantities of ceiling and floor finishes as the GLA remains the same in both designs.

However, this limitation can be remedied by adjusting the height of each shop individually to maintain actual quantities and minimise the effects of design simplification on the results.

The following section delivers the limitations associated with the choice of building materials and assemblies and possible means to address them in future research.

8.6.6 Choice of building materials and assemblies

The databases of building materials and assemblies created in the study involved the most common and embodied energy-efficient building materials and assemblies available for shopping centre construction in Australia (refer Sections 6.3.2.1 and 6.3.2.2). Several innovative materials and assemblies were also incorporated to make the industry more aware of the environmental benefits of those materials and to encourage their use in shopping centres. However, databases do not include potential future building materials and assemblies that might have better environmental and cost performances. Nevertheless, this can be immediately addressed 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.

Furthermore, the choice of building materials and assemblies for different types of shops is incorporated as a constraint in the model. The model runs scenarios for all possible combinations of building materials and assemblies for all shop types, in order to identify the optimal scenarios with minimum LCEE and LCMC. However, the process of sorting the best combinations is solely dependent upon the embodied energy and material cost. This simple process of selection, therefore, overshadows the reality of material and assembly selection. It is a rigorous process, based on a series of factors such as cost, durability, workability, physical properties of the material, availability, aesthetics, ease of maintenance and several others (Ogunkah & Yang, 2012). In the past decade, several researchers have developed multiple tools to assist this multi-criteria decision-making process (Castro-Lacouture et al., 2009; Ogunkah & Yang, 2012; Rahman et al., 2008; Wastiels & Wouters, 2009). These tools typically create weighted systems to prioritise the factors affecting the selection (Akadiri et al., 2013; Chen, Martínez, et al., 2019; Govindan et al., 2016). The variables are ranked in various manners in several research studies depending on the researchers' preferences.

Although the factors can be ranked differently based on the project participants' perspectives, cost has been identified as one of the most significant factors (Akadiri, 2015; Ogunkah & Yang, 2013), which is prioritised in this study. However, in addition, when client perspectives are considered, aesthetics become a significant factor (Chen, Martínez, et al., 2019; Ogunkah & Yang, 2012). Retail shop owners regard aesthetics as an extremely significant factor when selecting materials since it influences the shop foot traffic and the competition (Anderson & Mesher, 2019). Therefore, aesthetics needs to be incorporated into the model if the findings need to be more realistic, representing the clients' requirements on the selection. An investigation could be carried out to address this limitation by identifying the most preferred assembly solutions based on the clients' perspectives for different shop types in the shopping centres. Then weights could be assigned to those assemblies based on the preferences, and the model could be adjusted to prioritise the combinations by embodied energy, material cost and the aesthetic preferences. This approach could also be used in future research as an extension of this study.

The next limitation associated with the selection of building materials and assemblies is that the shops typically have more than one finish type for floor, ceiling and wall. However, in the model, these assemblies are limited to have only one finish at a time, for ease of the quantification process. For instance, a *clothing* shop could have three types of *floor finishes* at the entrance, in the sales area and at the rear in the stores. However, in the model, it only uses a single *floor finish*. This limitation is set to reduce the number of possible combinations generated. If it is not limited, the number of scenarios to model could increase beyond control. Nonetheless, in any future research, this limitation could be addressed by approaching a simple solution where the types of assemblies are increased in the databases to incorporate a range of assemblies for the same type. For instance, other than having a single assembly type as a *floor finish*, the database could have several, as *floor finish_1, floor finish_2, floor finish_3,.., floor finish_n*. However, it should be stated that this adjustment could make the model more complex and might affect the run time. Therefore, it is suggested that the solution be carried out for individual shop scenarios to investigate the implications.

As discussed in Section 5.3.2, assemblies used in shopping centres are of different sizes at different locations to meet structural requirements. For instance, the ground slab of Case 1 shopping centre had four different thicknesses in various locations in the shopping centre such as, 120 mm in some specialty areas, 150 mm in some supermarket areas, 180 mm in storage rooms and 200 mm in some loading zones. The selection of assemblies for foundation systems (ground slab and footings) is influenced by the soil conditions of the site and other structural requirements. But for simplification purposes a best represented size was selected based on the average volumes of the assembly and a similar process was carried out with other assemblies as well. An in-depth analysis of a single shopping centre could be carried out to address this limitation and investigate the most realistic effects.

The final limitation of the study is the negligence of the impact of material selection on operational energy use of shopping centres. Several researchers have examined how material selection affects the operational energy use of different building assets around the globe (Dodoo et al., 2014; Huberman & Pearlmutter, 2008; Shoubi, Shoubi, Bagchi, & Barough, 2015; Thormark, 2006; Zhu, Hurt, Correia, & Boehm, 2009). Findings reveal that material selection has a direct effect on the thermal operational energy use of the building due to different thermal masses of materials and assemblies. Results further demonstrate that the use of some low embodied energy materials could increase operational energy use (Shoubi et al., 2015). However, with the growing use of renewable energy sources in the future, operational energy would have minimum adverse effects on the environment (D'Agostino & Mazzarella, 2019; Laes et al., 2018; White, 2016). Thus, the use of low embodied energy materials is sensible, albeit the slight increase in operational energy use. Nevertheless, this effect on operational energy is not assessed in the model. If required, this limitation could be addressed by involving operational energy as a variable and as a constraint in the model while demoting the combinations that exceed the maximum limit. However, this is a rigorous process requiring complex calculations and analysis to assess the operational energy effects due to changing materials and assemblies. This could be investigated as an individual research.

The choice of building materials and assemblies in this study has several limitations which can hinder the results. The study attempted to minimise the implications of the limitations using possible approaches. Results are then justified within the set boundaries. The following section discusses the limitations related to uncertainty and variability assessment of the study.

8.6.7 Uncertainty and variability

The mathematical model relies heavily on data inputs from different databases to quantify the LCEE and LCMC of shopping centres. The uncertainty and variability of these data sets were asserted using the interval analysis approach, as described in Section 4.7.7.5. However, this approach presents some limitations that need to be discussed and to identify possible means to address them in any future research. This discussion is based on the publication by Stephan (2013).

Interval analysis in simple terms is a method that delivers an interval of values with boundaries (upper and lower) for a variable instead of a single fixed value. The mathematical representation is; all possible values for $f(x)$ for all $x \in [a, b]$, where a and b are the lower and upper boundaries (Moore, 1966). The study uses this method to analyse the uncertainty and variability of the results to understand their effects on the results better. This method is considered the most appropriate regarding the lack of data on the multitude of variables used in the quantification processes.

Nevertheless, this method does not indicate the likelihood of deviation of the variable, i.e. the probability of the variable value being closer to the upper boundary and the lower boundary is the same. This limitation can affect the interpretation of the results to a significant extent when the results show a minimal difference in nominal values of the embodied energy of shop or shopping centre solutions. It is possible to address this limitation by using more advanced methods such as probabilistic distributions of major parameters. Yet, the development of probabilistic distributions is data and resource intensive, and the results might not reach expected accuracy if the distributions of the parameters are not realistic. As indicated in Stephan (2013), a possible solution to overcome these limitations is to combine the use of interval analysis and probabilistic distributions. Since interval analysis resembles a flat probabilistic distribution, the model can incorporate known probabilistic distributions of certain parameters leading to a more accurate assessment of uncertainty and variability, and facilitating better decision making.

Therefore, it is essential to note that future research and investigations are necessary to improve the accuracy and reliability of the uncertainty and variability of the results through more advanced and data-intensive techniques.

8.6.8 Case studies

The case study shopping centres selected for the analysis were single-storey subregional shopping centres in Victoria, Australia (refer Chapter 5). These case studies represent the typical subregional shopping centre design and layout across Australia. Therefore, the results of this study could be generalised to other locations in Australia in a similar climate zone with proper adjustments. However, the profile of case studies can be expanded to multi-storey subregional and even to other categories of shopping centres, i.e. major regional, neighbourhood and others, to evaluate the impacts of LCEE and LCMC to assist in material selection decision making. It would be better to use more case studies to attain more realistic results. Furthermore, the use of different case studies across Australia would expand the *Materials* and *Assemblies* databases, increasing the usefulness of the model.

The model could further be extended by incorporating different shopping centre case studies across different climate zones and economies, globally. However, this relies heavily on the availability of data and resources.

To conclude, Section 8.6 discussed all the limitations associated with this study, namely regards to embodied energy, material cost with and without carbon tax, and embodied GHG emissions quantification processes, design of shops and shopping centres, choice of building materials, uncertainty and variability assessment and the case studies selection. Moreover, it reviewed the implications of those limitations on the findings of the study, identifying possible means to address them in future research. The following section attempts to further expand the research outcomes through potential improvements in the model.

8.7 POTENTIAL IMPROVEMENTS TO THE MODEL

Other than the embodied energy assessment, the model could be used to assess operational energy effects of Australian shopping centres. Except for energy, there are several other measures that are used to investigate the environmental impacts of building materials (embodied water content, recycling potential, global warming potential, etc.) (Bhochhibhoya et al., 2017; Crawford et al., 2019; Thormark, 2006). Those measures could be integrated into the model and develop a more comprehensive platform to assist material selection decision. Moreover, the model could be extended to evaluate the adverse environmental impacts of material selection of other building assets as well.

Therefore, this section examines the potential advancements to the model by incorporating other measures to broaden the investigation of the environmental impacts of building materials selection. Furthermore, it discusses the importance of evaluating the environmental impacts of material selection in other building assets and the possibility to adopt the model in those contexts.

8.7.1 Impact on the operational energy

Operational energy effects of materials could also be used as a measure to assess the severity of environmental impacts over the use phase. The operational energy use of a retail building can be provisioned for space heating, ventilation and air conditioning, lighting, water heating, refrigeration, electronics, cooking and others (Spyrou, Shanks, Cook, Pitcher, & Lee, 2014). Building based operational energy consists of thermal and lighting energy. Only this energy use is affected by the material selection decisions of the building. Thermal and lighting energy could be quantified in the model using the following approaches.

Thermal operational energy of the shopping centres could be modelled using thermal simulation software such as EnergyPlus, BLAST, Quick II, eQUEST, or any other suitable application (Amara & Agbossou, 2015; Crawley, Hand, Kummert, & Griffith, 2008; Kim, Jeong, Clayton, Haberl, & Yan, 2015). These software tools use the heat transfer characteristics and physical properties of the building envelope assemblies and nominal ventilation rates to quantify energy use for maintaining thermal comfort.

Operational energy use for lighting could be assessed using a specific lighting energy coefficient for retail shops and shopping centres, as used by Stephan (2013) for residential buildings. Quantification of the effect of different assembly combinations on the lighting energy use could be done using the rate of energy transfer of light bulbs (Watt) and the total quantity of visible light emitted from the lighting fittings (lumen) and the illumination requirements of the retail shops and the shopping centres (Scholand & Dillon, 2012).

Nonetheless, the assessment of the operational energy effects due to material changes is a complex, data and time intensive process, as discussed in Section 8.6.6. Despite the complexity, incorporating operational effects into the model would improve its comprehensiveness and provide a more holistic assessment of the building asset.

8.7.2 Life cycle embodied water requirement

The construction industry is a large consumer of water resources. The global construction industry water consumption is estimated at 20% of the total (NASA, 2020). Nonetheless, the development of building materials and assemblies with improved environmental performances has offered the potential to reduce this water consumption by almost 40% (Al-Qawasmi, Asif, El Fattah, & Babsail, 2019; Heravi & Abdolvand, 2019; Horne, 2019). The embodied water of building materials and assemblies could be identified as the total water requirement to produce and deliver materials at all production stages, directly and indirectly (Crawford & Treloar, 2005). Although water is considered a scarce resource, many research in the past have disregarded the impacts of embodied water in the built environment. However, recent studies have identified the significance of embodied water in building materials and assemblies and are researching possible means to reduce the impacts globally (Crawford & Treloar, 2005; McCormack, Treloar, Palmowski, & Crawford, 2007; Rahman, Rahman, Haque, & Rahman, 2019; Stephan & Athanassiadis, 2017; Webster-Mannison, 2017).

The model developed in this study could be used to assess the embodied water of different assembly scenarios across shops and shopping centres. This extension to the model could be carried out by developing embodied water quantification modules and functions similar to those for embodied energy. The embodied water quantification relies on the embodied water coefficients of building materials. The input-output based hybrid embodied water coefficients in EPiC database compiled by Crawford et al. (2019) could be used as they are the most comprehensive and the latest figures available for Australia.

The potential improvements to the model through implementing life cycle embodied water use demonstrates that the model is adaptable. More environmental impact measures such as global warming potential, resource depletion rate and waste generation rate could be implemented in the model. The model can, therefore, be improved into a comprehensive life cycle assessment tool, that can evaluate implications of building materials and assemblies used in shopping centres. Materials selection, being a multidisciplinary decision-making process, could consequently be improved by offering a comprehensive basis.

8.7.3 Application to other building assets

The model could expand its applicability from shopping centres to any other retail and building asset by carrying out required modifications to the databases and the mathematical model itself.

Potential expansions to other retail assets include different types of shopping centres (i.e. major regional, neighbourhood centres), retail chains (i.e. Optus, Flight centre, Subway) with different functions and aesthetic requirements, and overseas shopping centres.

In the context of other building assets, it is essential to identify the least researched building assets for assessing adverse environmental impacts of building materials selection to make the best use of the model expansion. An extensive amount of studies are available in the current academia on environmental impact assessment of materials on residential buildings (Monahan & Powell, 2011; Mpakati-Gama, Brown, & Sloan, 2016; Stephan, 2013; Stephan & Stephan, 2016; Treloar, 1998), followed by commercial office buildings (Crawford & Treloar, 2005; Junnila & Guggemos, 2006; Kneifel, 2010; Noller, 2005). A study by Stephan and Athanassiadis (2017) modelled and mapped the building stock in Melbourne in terms of environmental impacts, including different types of building assets. Therefore it is essential to shift the trend to other building assets such as hotels (Filimonau, Dickinson, Robbins, & Huijbregts, 2011; Rosselló-Batle, Moià, Cladera, & Martínez, 2010), industrial (Collinge, Landis, Jones, Schaefer, & Bilec, 2013; Lee, Trcka, & Hensen, 2011), educational (Alshamrani, Galal, & Alkass, 2014) and public buildings (Van Ooteghem & Xu, 2012) which only have a limited number of studies.

The adaption of the model to other building assets involves updating *Materials* and *Assemblies* databases including building materials and assemblies that are widely used in the respective building assets. Building designs and the layouts need to be incorporated in the respective databases of *Shop* and *ShoppingCentre,* and nomenclatures could be updated relatively. Some minor modifications to the model algorithms would also be required. However, it should be noted that the data collection process and selection of the most suitable case studies is resource consuming. The model could also be expanded to other geographies but require location-specific data on EEC and material prices. The robustness of the model, due to the use of object-oriented programming, provides potential for adaptations in the future to accommodate forthcoming requirements in the academia and the construction industry as well.

The following section summarises the areas discussed in this chapter leading to the conclusion of the thesis.

8.8 SUMMARY

This chapter discussed the implications of the results presented in Chapter 7, identifying the significance of LCEE in Australian shopping centres. The importance of material selection for the *centre structure* in terms of LCEE and LCMC reductions of shopping centres was also discussed. LCEE and LCMC intensities for different shop types were presented along with their possible variances from different assembly choices. The highest to the least embodied energy intensive specialty shops were ranked, and possible material choices to reduce the adverse environmental effects were discussed.

The effects of enforcing a carbon tax were also presented, identifying it as a powerful method to drive the construction industry to adopt more sustainable solutions. Furthermore, the relationship between the GLA with the LCEE and LCMC of the shopping centres was discussed identifying the necessity to optimise the building size to mitigate the associated embodied environmental impacts and material use. However, this proposal requires further interdisciplinary studies evaluating social, economic, cultural and sustainability feasibility.

The limitations associated with the model and results were then discussed. In particular, limitations regarding embodied energy, embodied GHG emissions and material cost with and without carbon tax quantification, shop and shopping centre designs, choice of building materials and assemblies were discussed identifying their impacts on results and possible means to address them in future research.

The final section discussed potential improvements to the model to develop a more comprehensive, robust life cycle assessment tool that could assist in material selection decision for shopping centres and possibly other building assets. This research has made an important contribution, but further work is needed to fully address sustainability within the retail sector both in Australia and overseas.

The next chapter provides the conclusion for the research, discussing how the aim and objectives of the research were fulfilled and possible future research in the area.

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9 CONCLUSIONS

9.1 INTRODUCTION

The adverse impacts of climate change are clearly visible throughout the world, as evidenced by changing ecosystems, increasing surface temperatures, melting ice caps and more frequent severe weather incidences (IPCC, 2019; Letcher, 2015; NASA, 2020). Increasing anthropogenic greenhouse gas (GHG) emissions are considered one of the most significant causes of global warming (Lashof & Ahuja, 1990; Meinshausen et al., 2009; Satterthwaite, 2008). As of 2019, Australia is one of the highest emitters of GHG per capita (Climateworks Australia, 2019; Department of Agriculture Water and the Environment, 2019). However, as operational GHG emissions decrease, the effect of embodied emissions and energy will become more important (De Wolf, Pomponi, & Moncaster, 2017; Kumanayake et al., 2018; Pomponi & Moncaster, 2018; Teh et al., 2019). The embodied emissions associated with building materials, assemblies and technologies contribute approximately 20% of all Australia's GHG emissions (Department of Agriculture Water and the Environment, 2019).

Due to the adverse effects of embodied GHG emissions and energy use, research within the Australian built environment has become increasingly active in developing empirical evidence to support change. However, this has mainly focused on either residential or commercial office buildings (Biswas, 2014; Crawford & Stephan, 2013; Rauf & Crawford, 2013; Stephan, 2013; Stephan & Athanassiadis, 2017; Treloar, Ilozor, & Crawford, 2002). Retail building assets have not been accorded similar attention nor that required to underpin serious sustainability discussions within this sector. Shopping centres are now a common urban feature in Australia since the 1950s, and due to their more frequent refurbishments, attract much higher levels of embodied energy in comparison to other building assets (Fieldson & Rai, 2009; Fridley et al., 2008; Van Ooteghem & Xu, 2012). The embodied environmental effects of Australian shopping centres have not been previously examined in a thorough and systematic manner.

The purpose of this research was to assess life cycle embodied energy (LCEE) and material cost (LCMC) of Australian shopping centres and to identify combinations of building materials and assemblies that optimised both embodied energy and building material cost. Subregional shopping centres are the fastest-growing and the largest planned retail floor space in Australia, and so were selected for investigation. Five research objectives were established, to identify typical shopping centre construction, assess and examine the relationship between embodied energy and material cost, to investigate the effect of a carbon tax enforcement and propose combinations of materials and assemblies.

One of the key approaches to reducing embodied energy is to use building materials and assemblies with lower embodied environmental effects (Dixit, 2017a; Pomponi & Moncaster, 2016; Zeitz et al., 2019) during construction and refurbishment of shops in shopping centres. Thus, material selection is a crucial decision in shopping centre design, construction, and refurbishments. Material selection is a multi-criteria decision-making process that factors in suitability, availability, cost and several other criteria, from which cost is typically dominant (Akadiri, 2015; Ogunkah & Yang, 2013). However, as these are commercial assets, shopping centre developers can be resistant to change and often use the justification of increased material cost as a reason for not achieving better and more sustainable outcomes (Akadiri, 2015; Yudelson, 2009). A review of building materials and their embodied energy and costs were, therefore, conducted to investigate their relationship.

The study used object-oriented programming (OOP) in Python to implement a mathematical model that simulates different scenarios of building materials and assemblies for shopping centres that optimise different objective functions. Both primary and secondary data collection methods (semi-structured interviews, document analysis, on-site observations) were used, with qualitative data converted to a quantitative format and used in the model. The business as usual (BAU) scenario in terms of building materials and assemblies of the largest sector of Australian shopping centre market was established. Alternative assembly scenarios that can be used to construct these shopping centres were also identified.

Three case studies of different gross lettable area (GLA) and tenant mix were selected representing 75% of subregional shopping centres to apply the established BAU scenario and alternative scenarios and to assess their LCEE and LCMC using the model. These values were then used to identify assembly combinations with minimum LCEE or LCMC which were considered as single objective minimisation problems. Minimising both LCEE and LCMC was then regarded. In this multi-objective optimisation, trade-offs between the objectives must be made, based on the decision criteria to attain preferable outcomes (Mattson et al., 2004; Messac & Mullur, 2007). In this study, the optimal solution was defined as the point at which both objectives were given equal priorities. Pareto frontier development, with weighted sum method was used to find the optimal solution (assembly combination) which equally minimises embodied energy and material cost.

The model assessed and analysed the embodied energy and material cost of different scenarios at the assembly, shop, and shopping centre levels. The application included the development of databases of input values and a computing core with automated quantification processes, which were implemented and verified. The following sections summarise how the findings of this study contributed to research and practice, along with recommendations for further research.

9.2 RESEARCH CONTRIBUTIONS

This research has made significant contributions to fulfil the gap in knowledge on LCEE and LCMC assessments of Australian shopping centres by identifying combinations of building materials and assemblies which minimise their environmental impacts. The findings contribute to the body of knowledge and practice and present cost-effective opportunities to achieve emissions reductions for this major built environment asset.

This study answered the main research question '*how can building material and assembly selection reduce life cycle embodied energy and material cost of shopping centres in Australia?*' through four sub research questions. Table 9.1 illustrates how these research questions were addressed along with the methods used and the outcomes made pertaining to each question.

The research aim was split into five research objectives, which were fulfilled using the object-oriented model applied to three case study shopping centres. These objectives are discussed in turn with concise explanations of research findings and how they contribute to each objective. Each of the following sub-sections, therefore, establishes the research contribution of this study.

9.2.1 Objective 1: To review typical and alternative building materials and assemblies used in shopping centres in Australia

This research reviewed the typical construction technologies, building materials and assemblies used in Australian shopping centres, revealing that the centre structures are dominated with steel and concrete building materials. Using primary and secondary data it was established the slab-on-grade with strip and pad footings foundation with general purpose Portland cement as the most frequently used foundation type along with precast concrete panel external walls mainly due to their cost effectiveness and structural adequacy. Typically, vertical and horizontal supports were structural steel (columns and roof frames) owing to their ease of construction, lower labour requirements and quicker erection times. Prior research (Allen & Iano, 2019; Heidrich, 2002; Hemalatha & Ramaswamy, 2017; Neupane, 2016; Quesada-Pineda et al., 2018) demonstrated that the use of fly ash cement in concrete and engineered timber structures (cross-laminated timber and glue-laminated timber) could be viable alternatives to reduce the embodied emissions shopping centres.

Primary and secondary data found that shop fit-outs typically use a vast range of material choices often depending on the functional requirements of the shop types, as well as the aesthetics provided by the materials. Typically, the inter tenancy walls which are developed with the shell are steel framed walls with unpainted and fire rated plasterboard. The fit-out internal walls developed by the tenants are usually steel or timber stud walls with either gypsum-bonded, wood-based or mineral bonded boards.

Table 9.1: Research questions and outcomes

Research question	Methods	Outcomes
How can building material and assembly selection reduce life cycle embodied energy and material cost of shopping centres in Australia?	Object-oriented modelling with case studies. Data collection using semi-structured interviews, document analysis, observations, and literature findings.	The object-oriented model can be used to assess the embodied energy and material cost to identify better assembly combinations for shopping centre construction in Australia. A scenario analysis of different assembly combinations identified a positive relationship between life cycle embodied energy and material cost at shops and shopping centre level when absolute values are considered. However, the analysis of per unit quantity values of LCEE and LCMC demonstrated negative relationships.
1. What building materials and assemblies reduce life cycle embodied energy the most, and at what financial cost?	Single objective optimisation using the object-oriented model.	The combinations of assemblies minimising life cycle embodied energy of the 16 different shop types were identified. These are presented in detail in Appendix 15. The use of fly ash cement in concrete and engineered timber structures led to significant reductions in embodied energy while delivering material cost savings. Additionally, the use of more natural, recycled and waste by-products such as cork, timber and terrazzo, for finishes also resulted in embodied energy savings with minimum material cost increments.
2. What are the optimal combinations of building materials and assemblies that reduce both life cycle embodied energy and material cost of shopping centres?	Multi objective optimisation using the object-oriented model. Weighted sum method was used to find the optimal Pareto solutions.	The optimal assembly combinations minimising both life cycle embodied energy and material cost for different shop scenarios are presented in Appendix 15. In several shop types the optimal assembly combinations were almost similar to the minimum LCEE combinations (i.e. centre structure). The use of fly ash cement in concrete and engineered timber structures were therefore identified as optimal alternatives in comparison to the use of general purpose Portland cement and structural steel in the BAU scenario. For shop fit-outs the use of gypsum blocks and calcium silicate bricks were identified as optimal alternatives on top of the typically used timber and steel stud walls. For finishes, using more natural, recycled and waste by-products such as cork, timber and terrazzo were recommended.
3. What mechanism can be used to encourage behavioural changes in material selection decision-makers' in shopping centres to achieve embodied energy reductions in Australia?	Single objective optimisation using the object-oriented model. Comparison of graphical representations of the results.	The scenario analysis of shops identified that the assembly combination minimising life cycle material cost with a carbon tax is identical to the optimal assembly combination. Therefore, a carbon tax is identified as significant and highly effective in driving shopping centre industry towards more environmentally responsive design and construction.
4. What is the impact of the refurbishment frequency on the selection of building materials and assemblies to reduce the life cycle embodied energy and material cost of different types of shops in shopping centres?	Optimisation and scenario analysis using the object-oriented model. Comparison of graphical representations of the results.	The model has the flexibility to be updated with new materials and also compare different scenarios of refurbishment frequencies for shops and shopping centres. The scenario analysis of two different refurbishment frequencies for various shop categories identified that the life cycle embodied energy and material cost has a negative relationship with the refurbishment frequencies. Results suggested that it is better to have a smaller number of refurbishments to reduce the adverse environmental implications of shops and shopping centres.

Finishes were found to vary widely depending on the shop types. Fashion and accessories related shops (i.e. clothing, shoes, health and beauty) tended to use luxurious finishes, such as vinyl tiles, laminated timber and nylon carpets, to enhance its aesthetic attractiveness and increase foot traffic. Material choices for the finishes in shops that market daily essentials (i.e. food supply, supermarket, discount department stores) and provide services (i.e. gym, services) were dominated by aesthetic concerns but rather the functionality of the finishes. For instance, terrazzo flooring and porcelain tiles and painted plaster boards were commonly used. Prevailing research established that the use of more natural products such as cork, timber boards and bamboo could lead to a substantial savings in embodied energy (Allen & Iano, 2019; Nolan, 2011; Richardson, 2013; Tam et al., 2017).

All the different materials and assemblies identified in the study that are used in Australian shopping centres were stored in the *Assemblies* database, which was then used in this study to compare and analyse the effects of different assembly combinations in different shop fit-outs in shopping centres. Until this study only very general information was available. No previous research distinguished the nature of different tenancy types and their building material choices, which is addressed in this study.

9.2.2 Objective 2: To assess life cycle embodied energy and material cost of shopping centres in Australia

This study assessed the LCEE and LCMC of Australian shopping centres using an object-oriented model applied to case studies of subregional shopping centres.

Results demonstrated that the mathematical model provides an objective approach to material selection for shopping centres such that the minimum LCEE and LCMC are achieved. This model incorporating unique characteristics of shopping centres inevitably delivers a good foundation for material selection with pre-determined objective functions of minimising embodied energy, cost, and emissions. The use of unique refurbishment frequencies for different shop types demonstrates a more realistic approach to model behaviour of shopping centres throughout the life cycle. These refurbishments are one of the critical factors causing the increased embodied energy, embodied GHG emissions and material costs in shopping centres. The inclusion of reliable data inputs for refurbishment frequency values enables the model to deliver more realistic results. The model uses input-output based hybrid embodied energy coefficients (EEC). The embodied energy values obtained with this technique tend to be much higher than using EEC compiled using other life cycle inventory methods, yet produce comprehensive and reliable results (Crawford et al., 2018; Dixit, 2017a; Lenzen & Crawford, 2009).

Prior to assessing the embodied energy and material cost of shops and shopping centres, the study quantified EEC and unit prices of the assemblies in the

Assemblies database. This knowledge is useful for initial assessments of embodied energy and material cost of future building projects which utilise such assemblies. These per unit intensities were then used in this study to assess the embodied energy and material cost of different scenarios of shops and shopping centres.

The assessment of embodied environmental effects illustrated that a typical single-storey subregional shopping centre, with a GLA of 22,500 m^2, constructed using mainly steel and concrete, requires 485.69 TJ (21.59 GJ/m^2) of embodied energy over 50 years and emits 28,548.72 tonnes CO_2e (1.25 tonne CO_2e/m^2) of embodied GHG. These values represent around 30% of the total life cycle energy (LCE) use of a typical Australian shopping centre. In comparison to other Australian commercial property assets, the LCEE contribution of life cycle energy (including operational energy) as a percentage is slightly closer to where similar hybrid EEC are used (Crawford & Treloar, 2005; Stephan, 2013). Yet, as operational emissions are decreasing with the use of energy efficient approaches and sustainable sources for energy production during the use phase, the percentage contribution of embodied energy could increase drastically by the next decade. Therefore, it is imperative to take the necessary actions to reduce embodied environmental effects.

Another significant revelation is that the initial and recurrent embodied energy (IEE and REE) contributions of shopping centres result in an almost 1:1 ratio. More importantly, IEE contribution of the *centre structure* accounted for more than 48% of total LCEE of the shopping centre, while LCEE of internal shop fit-outs accounted for almost 51%. These figures indicate that it is essential to focus on both initial and recurrent embodied environmental impact mitigation of Australian shopping centres since they both are equally significant. However, annual REE intensity of the shopping centre was estimated as 193.15 MJ/m^2/year, which is almost 18% higher than Australian residential houses (Rauf & Crawford, 2013; Stephan & Stephan, 2014). This figure shows that recurrent embodied environmental effects of shopping centres are crucial.

Results further established that the LCEE use per unit LCMC is 12 MJ/AU$ as of 2019. This figure is approximately 70% higher than the findings by Langston and Langston (2008), where the relationship between embodied energy and cost of 30 Australian buildings was investigated. However, it must be noted that Langston and Langston (2008) had considered IEE and capital cost (CC) only. It can be observed that in shopping centres, LCEE intensity per currency unit can be higher than other built assets due to their excessive use and premature replacements of materials and assemblies over the life cycle. Another reason could be the difference in the choice of materials to achieve aesthetic sophistication.

Shopping centre level analysis identified that the embodied energy and material cost have strong positive linear relationships with the GLA of the shopping centres. This positive correlation is inevitable since the amount of materials and assemblies used for construction and refurbishments is highly dependent on the GLA of the shopping centre. The interesting fact is that when the GLA was increased, the corresponding increase in LCEE was observed to be approximately 4% more than the LCMC increase. This outcome indicates that the escalation of embodied energy with the increasing GLA is more significant than the material cost. But embodied energy and material cost intensities per unit area indicated negative relationships with the GLA of shopping centres favouring larger GLA. These observations demonstrate that the size of the shopping centre is a crucial factor in terms of embodied environmental impact reduction, which needs to be optimised, to mitigate its adverse effects.

These findings address the knowledge gap of embodied energy and material cost assessments of Australian shopping centres, recognising their importance to achieve emissions reductions.

9.2.3 Objective 3: To examine the relationship between material selection, life cycle embodied energy and material cost of shopping centres in Australia

Prior research demonstrated a positive correlation between embodied energy and material cost of building materials or assemblies (Bansal et al., 2014; Copiello, 2016; Dixit, 2017b; Jiao et al., 2012). However, this relationship is found to be weakened when the analysis is carried to the product level. The assembly level analysis of this study identified that the relationship between embodied energy and material cost of assemblies depend on other factors. A key observation made was that the same assembly had different LCEE values based on the type of shop in which it was installed. However, the difference was not due to the type of shop but based on its refurbishment frequency and the service life of assembly itself. This finding is important as it demonstrates that the selection of building materials and assemblies for shopping centres requires more rigour, identifying its unique applications in different shop types.

The shop level analysis further demonstrated that the type of business conducted in a shop has a direct effect on the selection of building materials and assemblies, and by extension on the LCEE and LCMC. *Leisure and entertainment, household, health and beauty,* and *gymnasium* were identified as the most embodied energy intensive shop types when LCEE per unit area were considered. Similarly, *clothing, shoes, and café and restaurants* were identified as the most material cost intensive shop types. This finding is significant in terms of offering shop owners a different perspective concerning the adverse environmental effects caused by those shops. This knowledge is useful to encourage (perhaps through incentives) and inform shop owners regarding sustainable material selection at a single shop level rather than focusing on the entire shopping centre. The assessments of the embodied energy and GHG emissions of shop types also provide suggestions to select materials and assemblies that lead to better performance. Those suggestions can be implemented in future shop designs to mitigate the adverse effects of conventional materials and assemblies.

9.2.4 Objective 4: To investigate the impact of carbon tax enforcement on potential behavioural changes of material selection decisions of shopping centres in Australia

This research found that the assembly combinations that minimise LCMCWT are almost identical to the assembly combinations that minimise LCEE, LCMC and LCMCWT across all shops. This is a significant finding that demonstrates the potential effectiveness of enforcing a carbon tax in achieving embodied emissions reductions. Additionally, it was observed that with the increase in carbon tax, the selection leaned more towards materials with lower embodied energy but higher costs. Therefore, the carbon tax may need to be optimised to achieve better sustainability while managing both environmental and economic aspects. Results established that a carbon tax scheme should encourage the use of building materials and assemblies with lower embodied energy and embodied GHG and the government could potentially earn revenue when high embodied energy materials are used. However, unlike other sectors, the carbon pricing in shopping centres needs to incorporate frequent refurbishments to evaluate material and assembly options realistically. The findings of this study provide a solid base the policy makers could use to help establish a carbon pricing scheme. It could also help navigate shopping centre stakeholders towards sustainable and low embodied energy designs in Australia.

9.2.5 Objective 5: To propose combinations of materials and assemblies, with minimum life cycle embodied energy and material cost at varying replacement frequencies for different shops in shopping centres in Australia

The research conducted scenario analysis namely; *business as usual, minimum LCEE, minimum LCEGHGE, minimum LCMC, minimum LCMCWT* and the *optimal* scenario at the shop and shopping centre levels. It was observed that when shifting from the *BAU* scenario to "*minimum*" scenarios, building materials and assemblies change significantly. The combinations of assemblies that lead to *minimum LCEE* occasionally also lead to *minimum LCMC*. For instance, when structural assemblies of the shopping centre are selected, it is better to select the *slab on grade concrete with 40% fly ash cement* over the *general purpose Portland cement* option. There are other situations where the *minimum LCEE* solution is not concurrently the least cost solution. Such as for different shop options, it is usually better to use *corkboard ceiling* tiles to reduce embodied energy, and *plasterboard ceiling* to reduce cost. Nevertheless, the most critical finding is that for almost 90% of shops and shopping centres analysed in this study, the combinations of building materials and assemblies identified by the model lead to significant reductions of both LCEE and LCMC when compared to their *BAU* scenarios.

Another significant outcome is that by using the optimal combinations of assemblies, it is possible to reduce LCEE and LCMC by up to 40% and 10%, respectively, in comparison to the *BAU* scenario of the shopping centre. Therefore, it is evident that the informed use of existing building materials and assemblies has the potential to reduce adverse environmental effects without increasing material costs. Most of the structural assemblies that were proposed by the model as energy efficient are mainly produced from renewable resources such as timber, and innovative recycled or waste by-products. The use of structural timber applications in high rise and other large building projects is highly encouraged by the environmental organisations around the world. As of 2019, in Australia, the use of cross-laminated and glue-laminated timber products for Class 6 structural applications is approved and encouraged (ABCB, 2019) directing the shopping centres towards improved environmental performances.

The use of timber cladding is also acclaimed as a sustainable low embodied energy assembly solution for shop and shopping centre finishes. Despite being recognised as one of the most used and most versatile cladding solutions in Australia (Forest and Wood Products Australia, 2019), currently its suitability is being revaluated due to the uncertainty of fire resistance of several timber cladding products (ABCB, 2019; Chen, Yuen, et al., 2019). They are now required to comply with non-combustibility testing in accordance with AS 1530.1, and the safety provisions of the National Construction Code, even when they are used as an attachment in the façade of a building (Forest and Wood Products Australia, 2019; Webb & White, 2020).

9.2.6 Overall comment on objectives

While achieving the five objectives, this study made significant contributions to the current body of knowledge and practice. However, the application of these findings and implementation in the shopping centre industry needs to engage all stakeholders. Primarily, behavioural changes are required from the 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. Furthermore, the shopping centre management needs to be more involved in the design processes of individual shops and to monitor the shop owners' decision making on the selection of building materials and assemblies to guide them towards low embodied energy alternatives with lower costs. Green star retail interior fit-out rating tool could be used by the centre management as a guide to assess environmental sustainability of the shop fit-outs. 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 educate shop owners regarding the environmental implications of the shops and the necessity to mitigate them. The low embodied energy options identified by the model with low LCMC can then be appropriately engaged in the shopping centre construction process and throughout the life cycle.

Results are valuable to the policy enablers to develop specific policies and guidelines dedicated to shopping centres. The Green Building Council of Australia can integrate the proposed solutions as preferred materials and assemblies for shopping centres to achieve green star ratings leading to a low embodied energy material selection and environmental performance. The use of more environmentally responsive materials is already a criterion that is assessed to reward Green Star points in the rating system (GBCA, 2015). 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 environmental performances of Australian shopping centre designs and achieve sustainability goals as a nation.

However, it must be noted that results of this study suffer from certain limitations associated with model development, notably regarding data requirements and basic quantification algorithms (refer Section 8.6). The assessments of embodied energy, GHG emissions and material costs require significant databases which are complex to develop. Material selection based solely on embodied energy and material cost is also identified as a significant limitation in this study, which might produce results different from the actual practice. Still, the priority of this research was to reveal the significance of life cycle embodied environmental effects of shopping centres and to provide a solid basis for future comparative assessment of assembly choices, which it has achieved.

Despite these limitations, this study has significantly contributed to knowledge regarding both the life cycle embodied environmental impact and material cost assessments on material selection for shopping centres. It provides a solid base for future research.

9.3 RECOMMENDATIONS FOR FURTHER RESEARCH

The current study developed a mathematical model to optimise and identify the combinations of building materials and assemblies with the least LCEE, LCEGHGE and LCMC for shopping centre construction in Australia. This has made a significant contribution to the area, but there is still other research that needed to be addressed.

The next stage of this research would be to validate the findings through actual adoption and implementation by shopping centre developers and managers to ensure compliance and evaluate their applicability. Assembly combinations that were proposed by the model require validations and reasons for their limited use in shopping centres despite their potential for embodied energy reductions at lower costs. A better understanding of these assemblies from industry perspectives will deliver more rationalised outcomes that are ready to utilise in shopping centres. Any new building materials and assemblies can be added to the databases and execute the application to obtain updated results.

A further study is required to assess the effect of labour costs on material selection assessment. As these were excluded in this study, the suitability and cost effectiveness of the identified optimal assembly solutions may differ. It was assumed that labour costs would be the same for various scenarios. A useful addition to the research would be to now include labour inputs for various assemblies to see if this simplification was justified and if not, how does it affect material selection. This would deliver a more comprehensive consideration of building costs. In addition, there may be other costs from different erection methods, plant and equipment as well as from other industry standards and regulatory requirements (i.e. fire rating applications) which need to be included as project costs in a life cycle assessment.

The embodied energy quantification of the model uses coefficients based on path exchange hybrid life cycle inventory analysis approach by Treloar and Crawford (2010). Towards the very end of this research, a more comprehensive and consistent database of building material EEC (EPiC) was developed by Crawford et al. (2019). The *Materials* database in the model can be updated to accommodate these more recent values to compare how the estimated embodied energy and GHG emission values would change. As the database was released in November 2019, replacing all values and changing all results was considered outside the scope of this work. This work would be valuable in identifying what changes would occur through the adoption of a more comprehensive and consistent database with embodied energy intensities for a vast range of building materials and assemblies.

Using a similar modelling process, further research could explore other retail forms and building types, including those of different sizes and locations, that are understudied and have frequent refurbishments. For instance, large shopping malls and strip shops in different climatic conditions. Retail chains who refurbish a significant amount of their building asset annually and in a similar manner could more significantly reduce their environmental impact. Hotels as a building asset would also be a fruitful area for further work, as they also encounter more frequent refurbishments over their life cycle. The process would require the development of reliable databases for respective building assets and some modifications to the computing core. However, the use of OOP enables model implementation with a great extent of flexibility and the potential to expand. Other assets such as aeroplanes, theme parks or cruise ships which also have more frequent refurbishments are also worth examining.

While the developed model only assesses the environmental implications in terms of LCEE and LCEGHGE, the current work could be extended and incorporate other environmental assessment measures such as resource depletion, waste generation, recycling potential, and others. With extensions to the databases and computing core, the model can also be developed into a more comprehensive life cycle assessment tool for shopping centres.

This research was limited to the scope of initial and recurrent effects of building materials and assemblies for material selection decision making. However, as these retail fit-outs go through frequent refurbishments it would be worth examining how the demolition waste is managed and its effect on the environment. Also incorporating potential end of life energy savings of building materials and assemblies into the model would also deliver a more comprehensive life cycle assessment.

Currently, the tool includes only a Python-based computing core that uses inputs from databases to execute the commands. Further research could be conducted to develop it into a software tool that can be used to assist in the material selection for shopping centres. The development of a graphical user interface (or dashboard) connecting the computing core and databases would make this work more assessable and improve its adoption.

It must be noted that it is not realistic to achieve embodied emissions reductions by assuming material selection concerns embodied impacts and material costs alone. Prior research regarded material selection as a multi-criteria decision making process, and specifically in retail buildings (shopping centres and fit-outs) material selection is highly affected by the preferences of the shop owners (clients). Accordingly, further research should focus on incorporating required measures to input client preferences on material choices (i.e. based on a ranking system) into the model. Being better able to see the effect of their decisions may change behaviour and also help in development of new materials with improved sustainability.

Findings of this study regarding the selection of sustainable assembly solutions will assist in future material selection decisions of shopping centres. Currently, embodied emissions reduction is not considered by shopping centre developers. Given that material selection is a multi-criteria decision informed by several stakeholders, it is imperative to investigate the challenges and barriers to the adoption of sustainable solutions from developers and managers perspectives. Future research should emphasise ways to overcome the trade-offs between aesthetics and sustainability of shopping centres.

The transition towards carbon neutrality in the built environment requires immediate actions to attain greater awareness, innovation, advanced methods to quantify, trail and report embodied emissions, voluntary reduction goals from the industry itself and implementation of new legislation at national and regional levels (WGBC, 2019a). In the end, it will only be possible to achieve sustainability goals relating to the built assets by evaluating the environmental implications of every decision taken throughout their lives.

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APPENDICES

APPENDIX 1

Appendix 1 offers the input-output based hybrid embodied energy coefficients compiled by Treloar and Crawford (2010) used in the study. These coefficients were used in the model to quantify embodied energy at assembly, shop and shopping centre levels. Appendix 1 was referred in Sections 3.5.2, 4.7.2.1, 6.3.2.3, 6.6, 6.8, 6.10.3, 7.3, 7.6, 8.4 and 9.4.

Material	Unit	Embodied energy coefficient (GJ/unit)
Aluminium		
Virgin	t	252.600
Reflective foil	m^2	0.137
Asphalt	m^3	3.080
Bitumen	m^3	48.390
Carpet		
Wool	m^2	0.741
Nylon	m^2	0.683
Ceramics		
Clay bricks (110 mm)	m^2	0.560
Ceramic tiles	m^2	0.293
Terracotta roof tiles (20 mm)	m^2	0.986
Concrete		
5 MPa concrete	m^3	2.790
15 MPa concrete	m^3	4.030
20 MPa concrete	m^3	4.440
25 MPa concrete	m^3	5.010
30 MPa concrete	m^3	5.440
32 MPa concrete	m^3	5.810
40 MPa concrete	m^3	6.750
Aerated concrete (200 mm)	m^2	0.495
Cement	t	16.960
Concrete block, hollow (200 mm)	m^2	0.805
Concrete roof tile (20 mm)	m^2	0.251
Fibre cement sheet (4.5 mm)	m^2	0.235
Fibre cement sheet (6 mm)	m^2	0.288
Mortar	m^3	2.000
Precast	m^3	4.440
Glass		
Clear float glass (4 mm)	m^2	1.730
Glass fibre	m^3	432.100
Toughened glass (6 mm)	m^2	3.660
Toughened glass (12 mm)	m^2	7.310
Insulation		
Expanded polystyrene insulation (50 mm)	m^2	0.361
Fibreglass insulation (80 mm)	m^2	0.183

Fibreglass insulation (100 mm)	m^2	0.217
Fibreglass insulation (160 mm)	m^2	0.348
Paint		
Oil-based paint	m^2	0.101
Water-based paint	m^2	0.096
Plasterboard		
Plasterboard (10 mm)	m^2	0.207
Plasterboard (13 mm)	m^2	0.232
Plastics		
General (PVC)	t	156.900
Laminate (1 mm)	m^2	0.200
Plastic membrane (1 mm)	m^2	0.514
Polyester	t	156.900
Polystyrene	m^3	7.040
PVC water pipe (20 mm)	m	0.212
UPVC pipe 100	m	0.266
UPVC pipe 100 (slotted)	m	0.208
Vinyl flooring (2 mm)	m^2	0.661
Sand and stone		
Granite	t	0.087
Sand	m^3	0.617
Screenings	m^3	0.691
Steel		
Colourbond steel decking	m^2	0.933
Reinforcement	t	85.460
Stainless steel	t	445.200
Steel	t	85.460
Steel decking	m^2	0.796
Timber		
Hardwood	m^3	21.330
MDF/Particleboard	m^3	30.350
Softwood	m^3	10.930
Oil	m^3	34.000
Other metals		
Copper	t	378.900

Source: Treloar and Crawford (2010) & Stephan (2013)

APPENDIX 2

Appendix 2 - A provides the interview guidelines used to gather data via semi-structured interviews with shopping centre developers. It was referred in Section 4.5.1.

SEMI-STRUCTURED INTERVIEW GUIDELINE

(For sub regional shopping centre developers)

Research Topic **:** Assessment of life cycle embodied energy and material cost of Australian shopping centres: Implications for material selection

Researcher`s use only

Code :

Designation :

Date :

Duration :

Venue :

Thank you for your time today

- *Go through the purpose of the study*
- *Ensure participant has had the opportunity to read the Plan Language Statement*
- *Confirm participant's consent to interview being recorded*
- *Sign the consent form*

Identification of backaround information

1. Can you please indicate your current role in your organisation and the number of years of experience you have had in sub regional shopping centre management?
   Role: ____________________
   Experience: ____________________*years*
2. How many sub regional shopping centres have you completed as a developer? [Are all of them located in Victoria? If the answer is "No" please provide other locations][*]
   *Number:*____________________
   States:
   VIC ☐
   NSW ☐

[*] For interviews in Victoria only. This will help to determine if case studies are required to expanded to NSW and QLD also.

QLD ☐
WA ☐
SA ☐
NT ☐
TAS ☐

Sub regional shopping centre development

3. How would you describe the current and future demand for these shopping centre developments in Australia?
   Prompt: Increasing ☐ *Decreasing* ☐
   Please explain.
4. Are there any differences in these shopping centre developments in different Australian states with regard to construction techniques and use of materials?*
   Yes ☐ *No* ☐
   Please explain.

Material selection for sub regional shopping centre development

5. At what stage are material selection decisions made in these shopping centre developments?
6. Who are the key stakeholders responsible for material selection decision?
7. Are there any situations where the investor demands specific materials?
   Yes ☐ *No* ☐
   If "Yes" please explain.
8. What are the common materials used in shopping centres and within each assembly category listed below?
   - Structural
   - Envelope
   - Finishes
   - Systems
   - Other
9. What factors do you take into consideration when selecting materials and construction techniques for building these shopping centres?
   Prompt: Durability, cost, ease of maintenance, time for installation, availability, ease of transportation, physical qualities, etc.
10. Can you please rank these considerations when it comes to selecting materials?
    Prompt: Which is the most important?
    Which is the least important?

Now we are going to talk about importance of cost for material selection.

"Life cycle material cost is considered the combination of capital costs, replacement costs of materials and demolition and disposal costs of a material"

11. Do you consider life cycle material costs when selecting materials?

* For interviews in Victoria only. This will help to determine if case studies are required to expanded to NSW and QLD also.

Yes ☐ *No* ☐
Prompt? Capital cost only?
Please explain.

Now we are going to talk about importance of replacement frequency for material selection.

"The material replacement frequency in shopping centres is typically 2 to 10 years due to continuous refurbishments and tenant turnover".

12. How much do you agree with this statement?
    Agree ☐ *Disagree* ☐
    If "Disagree" what is it in your opinion?
13. When you are selecting a material, do you think about the replacement frequency of the assembly it goes in to?
    Yes ☐ *No* ☐
    If "Yes" for which assemblies?
    If "No" please explain your answer.

Now we are going to talk about importance of embodied energy for material selection.

"Embodied energy is defined as the energy used for raw material extraction, transport, material manufacturing and transport, construction, maintenance and finally demolition and disposal of building materials and assemblies (Stephan, 2013)".

14. In your opinion, do you think embodied energy is an important aspect of material selection?
    Yes ☐ *No* ☐
    Prompt? Initial embodied energy? Recurrent embodied energy?
    Please explain.
15. Do you use recycled materials for these shopping centre developments?
    Yes ☐ *No* ☐
    If "Yes", what are they? What are the motivations for using them?
    If "No" please explain.

Environmental performance of shopping centre development

16. How important is the environmental performance of these shopping centres for your organisation?
17. Are there any policies and guidelines for you to use regarding the environmental performance of shopping centres?
18. Do you think building material selection is important for the environmental performance of shopping centre development?
    Yes ☐ *No* ☐
    Why? Please explain:
19. Are there any strategies you have used or heard of which could increase the use of building materials with low embodied energy?
    Yes ☐ *No* ☐
    Suggestions:

Now that is the end of our formal interview, but would you like to comment on any aspects of the material selection and sustainable shopping centre development that we have not covered today that you regard as important?

Thank you for your time today!!!

APPENDIX 2

Appendix 2 - B provides the interview guidelines used to gather data via semi-structured interviews with shopping centre management bodies. It was referred in Section 4.5.1.

SEMI-STRUCTURED INTERVIEW GUIDELINE

(For sub regional shopping centre management)

Research Topic **:** Assessment of life cycle embodied energy and material cost of Australian shopping centres: Implications for material selection

Researcher`s use only

Code :

Designation :

Date :

Duration :

Venue :

Thank you for your time today.

- *Go through the purpose of the study*
- *Ensure participant has had the opportunity to read the Plan Language Statement*
- *Confirm participant's consent to interview being recorded*
- *Sign the consent form*

Identification of background information

1. Can you please indicate your current role in your organisation and the number of years of experience you have had in sub regional shopping centre management?
   Role: ____
   Experience: ____________________*years*
2. Can you tell me some key facts about this shopping centre?
   Prompt:
   Gross lettable floor area: ____________________*sqm*
   Year of construction: ____________________________________
   *Tenant mix:*____
   ____
   *Ratios of floor spaces:*____________________________________
   *Other:*____

Material replacements in sub regional shopping centres

"Material replacement frequency of shopping centres is typically 2 to 10 years due to continuous refurbishments and tenant turnover".

3. What is the refurbishment frequency of this shopping centre?
   *Frequency:*____
   Prompt: Does it differ by tenancy type, retail vs common areas, etc
   Yes ☐ *No* ☐
   If "Yes" please explain.
4. What are the typical lease periods for anchor tenants and small tenants?
   *Anchor tenants:*________________________*years*
   *Small tenants:*_______________________________*years*
5. What is the average tenant turnover of small tenants?
   ____*years*
   Prompt: Do they normally refurbish at that time?
   Yes ☐ *No* ☐
   Why? Please explain.
6. Who is responsible for the tenant replacements of small tenants?
7. What happens to the small tenant shops when tenants are replaced?
   Prompt: Is it same for anchor tenants?
   Yes ☐ *No* ☐
8. Are small shops redesigned to meet new tenant requirements at replacements?
   Yes ☐ *No* ☐
   Why? Please explain.
   Prompt: Is it same for anchor tenants?
   Yes ☐ *No* ☐
   Why? Please explain.
9. What happens to the materials replaced due to these refurbishments and tenant turnover?
   Prompt: Recycle/ reuse/ landfill?
10. Do you or your tenants consider using recycled materials when you are refurbishing?
    Yes ☐ *No* ☐
    Why? Please explain.
    Prompt: Is it same for anchor tenants?
    Yes ☐ *No* ☐
    Why? Please explain.

Sustainable shopping centre management

11. What is the current energy consumption of shopping centre?
12. Are there actions you take to reduce the use of energy?
13. Are there any strategies you have used or heard of which could improve the building material waste management during operational phase?
    Yes ☐ *No* ☐
    Suggestions:

Now that is the end of our formal interview, but would you like to comment on any aspects of the material replacements and sustainable shopping centre management that we have not covered today that you regard as important?

Thank you for your time today!!!

APPENDIX 2

Appendix 2 - C provides the interview guidelines used to gather data via semi-structured interviews with shopping centre owners. It was referred in Section 4.5.1.

SEMI-STRUCTURED INTERVIEW GUIDELINE

(For sub regional shopping centre owners)

Research Topic **:** Assessment of life cycle embodied energy and material cost of Australian shopping centres: Implications for material selection

Researcher`s use only

Code :

Designation :

Date :

Duration :

Venue :

Thank you for your time today

- *Go through the purpose of the study*
- *Ensure participant has had the opportunity to read the Plan Language Statement*
- *Confirm participant's consent to interview being recorded*
- *Sign the consent form*

Identification of background information

1. Can you please indicate your current role in your organisation and the number of years of experience you have had in sub regional shopping centres?
   Role: ______________________________
   Experience: ____________________ *years*

Sub regional shopping centre ownership

2. How many sub regional shopping centres does your organisation own? [Are all of them located in Victoria? If the answer is “No” please provide other locations]*
   *Number:*____________________

---

* For interviews in Victoria only. This will help to determine if case studies are required to expanded to NSW and QLD also.

States:

VIC ☐
NSW ☐
QLD ☐
WA ☐
SA ☐
NT ☐
TAS ☐

3. Are there any differences in this shopping centres in different Australian states regarding refurbishment frequencies, lease periods and tenant turnover? *
   Yes ☐ *No* ☐
   Please explain.

Material replacements in sub regional shopping centres

"Material replacement frequency of shopping centres is typically 2 to 10 years due to continuous refurbishments and tenant turnover".

4. What is the typical refurbishment frequency of sub regional shopping centres?
   *Frequency:*____
   Prompt: Does it differ by tenancy type, retail vs common areas, etc
   Yes ☐ *No* ☐
   If "Yes" please explain.
5. What are the typical lease periods for anchor tenants and small tenants?
   *Anchor tenants:*____________________________*years*
   *Small tenants:*___________________________________*years*
6. What is the average tenant turnover of small tenants?
   ____*years*
   Prompt: Do they normally refurbish at that time?
   Yes ☐ *No* ☐
   Why? Please explain.
7. Who is responsible for the tenant replacements of small tenants?
8. What happens to the small tenant shops when tenants are replaced?
   Prompt: Is it same for anchor tenants?
   Yes ☐ *No* ☐
9. Are small shops redesigned to meet new tenant requirements at replacements?
   Yes ☐ *No* ☐
   Why? Please explain.
   Prompt: Is it same for anchor tenants?
   Yes ☐ *No* ☐
   Why? Please explain.
10. What happens to the materials replaced due to these refurbishments and tenant turnover?
    Prompt: Recycle/ reuse/ landfill?
11. Do you or your tenants consider using recycled materials when you are refurbishing?
    Yes ☐ *No* ☐

* For interviews in Victoria only. This will help to determine if case studies are required to expanded to NSW and QLD also.

Why? Please explain.

Prompt: Is it same for anchor tenants?

Yes ☐ *No* ☐

Why? Please explain.

Environmentally sustainable shopping centres

12. What is the current trend in your organisation for environmental sustainability of shopping centres?
13. Are there any policies and guidelines you follow for the sustainable management of shopping centres?
14. Do you think building material use optimisation is important for environmentally sustainable shopping centres?

    Yes ☐ *No* ☐

    Why? Please explain:
15. Are there any strategies you have used or heard of which could improve the building material waste management during operational phase?

    Yes ☐ *No* ☐

    Suggestions:

Now that is the end of our formal interview, but would you like to comment on any aspects of the material replacements and sustainable shopping centre management that we have not covered today that you regard as important?

Thank you for your time today!!!

APPENDIX 3

Appendix 3 offers the database of Materials used in the model development. It was referred in Sections 4.5.1, 4.7.7.3, 5.2 and 6.3.2.1.

Material id	Material name	Material type	Material unit	Material embodied energy coefficient	Material unit price	Material lifespan	Wastage coefficient
M1	Bitumen	DPC (1 mm)	m^2	0.514	2.44	20	1.05
M2	Concrete	Polished exposed concrete 20 MPa (100 mm)	m^3	4.440	500.00	100	1.05
M3	Concrete	Hollow blocks (200 mm)	m^2	0.805	47.50	100	1.05
M4	Concrete	Mortar (10 mm)	m^3	2.000	748.00	100	1.03
M5	Insulation	Fibreglass (100 mm)	m^2	0.217	571.00	30	1.10
M6	Steel	Steel rebar (Virgin)	t	85.460	1,700.00	100	1.05
M7	Ceramics	Burnt clay bricks (110 mm)	m^2	0.560	32.86	50	1.05
M8	Concrete	Precast panel with SL92 (150 mm)	m^3	4.440	2,360.00	100	1.05
M9	Insulation	Extruded Polystyrene (XPS) Board (50 mm)	m^2	0.386	28.95	30	1.10
M10	Gypsum	Plasterboard (10 mm)	m^2	0.207	5.10	30	1.05
M11	Steel	Colourbond cladding	m^2	0.933	30.68	100	1.02
M12	Terracotta	Bricks	m^2	0.825	90.00	50	1.05
M13	Gypsum	Blocks	m^2	0.533	4.41	50	1.05
M14	Gypsum adhesive	Mortar	m^3	6.460	76.00	50	1.03
M15	Paint	Water based	m^2	0.096	1.35	10	1.05
M16	Glass	Toughened (12 mm)	m^2	7.310	115.00	80	1.03
M17	Concrete	32 MPa with nominal aggregate size 20 mm	m^3	5.810	354.20	100	1.10
M18	Sand	Fine	m^3	0.617	86.52	100	1.05
M19	Timber	Formwork	m^3	10.930	1,319.44	50	1.05
M20	EPS	EPS pods (1090 × 1090 × 300 mm)	m^2	0.593	4.63	100	1.10
M21	Timber	Structural	m^3	21.330	1,269.84	50	1.15
M22	Paint	Oil based	m^2	0.101	0.98	10	1.05
M23	Terrazzo	Tiles	m^2	0.007	41.96	75	1.05
M24	Vinyl	Tiles	m^2	0.661	24.95	10	1.05

M25	Ceramics	Tiles	m^2	0.293	19.95	50	1.15
M26	Cork	Tiles	m^2	0.025	24.19	25	1.05
M27	Linoleum	Sheets (2 mm)	m^2	0.337	30.00	20	1.05
M28	Rubber	Sheets (4 mm)	m^2	0.871	30.98	20	1.05
M29	Nylon	Carpet	m^2	0.683	68.31	10	1.05
M30	Wool	Carpet	m^2	0.741	122.95	20	1.05
M31	Polypropylene	Carpet (4 mm)	m^2	0.782	29.00	7	1.05
M32	Timber	Laminated sheets (18 mm)	m^2	0.036	59.67	25	1.05
M33	Bamboo	Planks	m^2	0.128	90.00	25	1.05
34	Void	Void	m	0.000	0.00	50	0.00
M35	Calcium Silicate	Bricks (230 × 110 × 76 mm)	m^2	0.499	68.65	50	1.05
M36	Steel	Structural steel galvanised	t	85.460	2,553.80	50	1.10
M37	Steel	Steel mesh SL92	t	85.460	1,550.00	100	1.05
M38	Plastic	Premium high-density polyurethane/ polyethylene plastic water barrier (1 mm)	m^2	0.514	3.83	10	1.15
M39	Plastic	Re-bonded Polyurethane Carpet underlay (10 mm)	m^2	0.444	8.42	30	1.15
M40	Timber	Carpet Edge Timber (W:33 H:10 L:1200 mm)	m	0.004	0.83	30	1.15
M41	Grout	Tile grout	kg	0.040	20.89	25	1.15
M42	Gypsum	Plasterboard (13 mm)	m^2	0.232	13.62	25	1.15
M43	Steel	Nails and other ironmongery	t	56.700	12,950.82	50	1.05
M44	Insulation	Glass wool R6.0 (W:430 H:1160 L:275 mm)	m^2	0.092	11.67	50	1.10
M45	Steel	Steel stud	t	56.700	4,529.10	100	1.05
M46	Engineered timber	Glue laminated timber (Glulam)	m^3	2.530	2,100.05	50	1.01
M47	Engineered timber	Cross laminated timber (CLT)	m^3	2.530	2,100.05	50	1.01
M48	Insulation	Wood fibre 140 × 375 × 1220 mm long, 1.83 m^2	m^2	0.692	26.57	50	1.10
M49	Concrete	Insulated precast sandwich wall panel (220 mm)	m^3	3.872	1,500.00	50	1.05
M50	Primer sealer undercoat	British Paints 1 L White 4 In 1 Prep Water Based Primer Sealer Undercoat	m^2	0.011	2.39	10	1.05
M51	Concrete	32 MPa with 40% fly ash nominal aggregate size 20 mm	m^3	4.067	309.93	100	1.10
M52	Compressed fibre cement (CFC)	Compressed Fibro Cement Sheet 3000 x 1200 x 6 mm factory finish applied	m^2	0.288	46.51	30	1.10

M53	Colourbond roofing	0.42 mm thick	m^2	0.933	29.85	50	1.15
M54	Wet area waterproofing	Dunlop Express Wet Area Waterproofing (1 mm)	m^2	0.261	26.35	10	1.05
M55	Porcelain	Tiles	m^2	0.354	53.82	50	1.15
M56	Metal	Tiles (610 × 610 × 19 mm)	t	85.460	12,105.08	25	1.05

APPENDIX 4

Appendix 4 presents the database of Assemblies used in the model development containing data on material inputs of assemblies. It was referred in Sections 4.5.1, 5.2, 6.3.2.2 and 7.2.1.

Assembly id	Assembly type	Assembly name	Assembly unit	Assembly lifespan	Material id0	Material quantity0	Material id1	Material quantity1	Material id2	Material quantity2	Material id3	Material quantity3	Material id4	Material quantity4	Material id5	Material quantity5
RS01	Roof structure	Roof structure with Steel beams 530UB92, Purlins C30024, bracings and steel truss and Colourbond sheets	m^2	50	M36	0.031	M6	0.030	M11	1.000	M15	1.000	M5	1.000	M53	0.004
RS02	Roof structure	Roof structure with Glue Laminated Timber beams 535 mm x 85 mm Beam 21 and Colourbond sheets	m^2	50	M46	0.042	M6	0.030	M11	1.000	M15	1.000	M5	1.000	M53	0.004
RS03	Roof structure	Void	m^2	50	M34	1.000										
CF01	Ceiling finish	Plasterboard lining with paint on timber frame	m^2	20	M21	0.011	M42	1.000	M15	1.000	M43	0.001	M44	0.800		
CF02	Ceiling finish	Wood planks with paint on timber frame	m^2	15	M21	0.011	M32	1.000	M43	0.001	M44	0.800				
CF03	Ceiling finish	Plasterboard lining with paint on metal frame	m^2	20	M45	0.003	M42	1.000	M15	1.000	M43	0.001	M44	0.800		
CF04	Ceiling finish	Metal frame ceiling with Metal tiles	m^2	20	M45	0.003	M56	0.003	M43	0.001	M44	0.800				
CF05	Ceiling finish	Metal frame ceiling with Cork tiles	m^2	20	M45	0.003	M26	1.000	M43	0.001	M44	0.800				
CF06	Ceiling finish	Metal frame ceiling with Vinyl tiles	m^2	10	M45	0.003	M24	1.000	M43	0.001	M44	0.800				
CF07	Ceiling finish	Void	m^2	50	M34	1.000										
CL01	Column	Glum Laminated Timber columns 150 mm × 150 mm	m	50	M46	0.023										
CL02	Column	Steel columns 150 mm × 150 mm × 8 mm SHS	m	50	M36	0.034										
CL03	Column	Void	m	50	M34	1.000										
EW01	Structural wall	150 mm thick precast panel SL92 central with 1N16 trimmer bar central each edge	m^2	50	M8	0.150	M9	1.000								

EW02	Structural wall	Insulated precast sandwich wall panels 220 mm thick (70 mm exterior, 50 mm insulation, 100 mm interior)	m^2	50	M49	0.220	M9	1.000								
EW03	Structural wall	Cross laminated timber 205 mm thick (5-layer panel), self-weight 1.2 kPa	m^2	50	M47	0.205	M48	1.000								
EW04	Structural wall	Void	m^2	50	M34	0.000										
FF01	Floor finish	Vinyl planks with water barrier underlay	m^2	10	M24	1.000	M38	1.000								
FF02	Floor finish	Cork boards with water barrier underlay	m^2	20	M26	1.000	M38	1.000								
FF03	Floor finish	Linoleum sheets with water barrier underlay	m^2	15	M27	1.000	M38	1.000								
FF04	Floor finish	Rubber carpet with double sided tape	m^2	25	M28	1.000										
FF05	Floor finish	Nylon carpet with underlay	m^2	7	M29	1.000	M39	1.000	M40	0.500						
FF06	Floor finish	Wool carpet with underlay	m^2	15	M30	1.000	M39	1.000	M40	0.500						
FF07	Floor finish	Polypropylene carpet with underlay	m^2	5	M31	1.000	M39	1.000	M40	0.500						
FF08	Floor finish	Ceramic tiling on 10 mm thick cement mortar screed	m^2	20	M25	1.000	M4	0.010	M41	0.081						
FF09	Floor finish	Terracotta tiles 10 mm thick cement mortar screed	m^2	35	M12	1.000	M4	0.010	M41	0.081						
FF10	Floor finish	Terrazzo with 100 mm infill slab 20 MPa	m^2	50	M23	1.000	M4	0.010								
FF11	Floor finish	Bamboo planks	m^2	30	M33	1.000	M38	1.000								
FF12	Floor finish	Laminated timber	m^2	15	M32	1.000	M38	1.000								
FF13	Floor finish	Polished exposed aggregate concrete - gloss with 100 mm infill slab 20 MPa	m^2	50	M2	0.100										
FF14	Floor finish	Porcelain tiles 800 mm × 800 mm	m^2	50	M55	1.000	M4	0.010	M41	0.081						
FF15	Floor finish	Void	m^2	50	M34	1.000										
FD01	Foundation	Concrete Foundation (Slab on grade) 150 mm thick provide SL92 fabric top, poured on PVC damp proof membrane lapped and tapped at joints on 50 mm bedding sand. Pad footings to be 2300 mm × 2300 mm × 500 mm with N16 - 250 mm each way. Strip footings to be 450 mm × 400 mm with 4L11-TM top and bottom, and R10-450 ties. Concrete grade: N32 (dense weight) To AS 3600Concrete grade: N32 with general purpose Portland cement	m^2	50	M17	0.186	M18	0.050	M37	0.005	M1	1.000	M6	0.002	M19	0.005

FD02	Foundation	Waffle raft slab 385 mm thick with N32 concrete, SL92 fabric top, poured on PVC damp proof membrane lapped and tapped at joints	m^2	50	M17	0.380	M1	1.000	M20	0.909	M37	0.004	M19	0.001	M6	0.004
FD03	Foundation	Concrete Foundation (Slab on grade) 150 mm thick provide SL92 fabric top, poured on PVC damp proof membrane lapped and tapped at joints on 50 mm bedding sand. Concrete grade: N32 with 40% fly ash cement	m^2	50	M51	0.186	M18	0.050	M37	0.005	M1	1.000	M6	0.003	M19	0.005
FD04	Foundation	Void	m^2	50	M34	0.000										
IW01	Internal wall	Brick walls (110 mm)	m^2	50	M7	0.854	M4	0.016								
IW02	Internal wall	Block walls (140 mm)	m^2	50	M3	0.931	M4	0.010								
IW03	Internal wall	Gypsum block wall (500 × 500 × 100 mm)	m^2	50	M13	0.960	M14	0.004								
IW04	Internal wall	Steel stud walls (welded)	m^2	20	M45	0.003	M44	1.000								
IW05	Internal wall	Calcium Silicate brickwork (110 mm)	m^2	50	M35	0.854	M4	0.016								
IW06	Internal wall	Timber stud walls (90 × 45 mm)	m^2	20	M21	0.011	M44	1.000	M43	0.001						
IW07	Internal wall	Void	m^2	50	M34	0.000										
LT01	Lintel	Steel lintel 2400 x 150 x 100 x 6mm Galvanised Angle Lintel	m	50	M6	0.011										
LT02	Lintel	Concrete lintel	m	50	M2	0.015	M6	0.003								
LT03	Lintel	Timber lintel	m	50	M48	0.015										
LT04	Lintel	Void	m	50	M34	0.000										
WF01	Wall finish	Sheet metal cladding on metal frame - external	m^2	30	M11	1.000	M45	0.003	M43	0.001						
WF02	Wall finish	Water based paint on 10 mm thick cement mortar screed with white putty	m^2	5	M15	1.000	M4	0.010	M50	1.000						
WF03	Wall finish	10 mm thick cement mortar screed with white putty	m^2	5	M4	0.010										
WF04	Wall finish	Oil based paint on 10 mm thick cement mortar screed with white putty	m^2	5	M22	1.000	M4	0.010	M50	1.000						
WF05	Wall finish	Terrazzo tiles on 10 mm thick cement mortar screed	m^2	50	M4	0.010	M23	1.000								
WF06	Wall finish	Water based paint on 10 mm plasterboard	m^2	20	M15	1.000	M50	1.000	M10	1.000						
WF07	Wall finish	Timber board cladding	m^2	15	M43	0.001	M32	1.000								
WF08	Wall finish	Ceramic tiling on 10 mm thick cement mortar screed	m^2	20	M25	1.000	M4	0.010								
WF09	Wall finish	Bamboo panels with panelling adhesives and finishing nails on timber frame	m^2	30	M33	1.000	M43	0.001								

WF10	Wall finish	Vinyl tiles	m^2	10	M24	1.000	M4	0.010
WF11	Wall finish	Compressed fibre cement (CFC) façade pane	m^2	15	M52	1.000	M43	0.001
WF12	Wall finish	Void	m^2	50	M34	0.000		
WD01	Window	Metal framed glass windows (2.4 m × 3.6 m)	m^2	40	M6	0.003	M16	0.950
WD02	Window	Timber framed glass windows (2.4 m × 3.6 m)	m^2	40	M47	0.003	M16	0.950
WD03	Window	Void	m^2	50	M34	0.000		
WP01	Waterproofing	Wet area waterproofing	m^2	10	M54	1.000		
WP02	Waterproofing	Void	m^2	10	M34	0.000		

APPENDIX 5

Appendix 5 offers the service life values of materials and assemblies used in the study, extracted from Rauf (2015). Appendix 5 was referred in Section 4.7.2.5.

Material	Material service life (minimum)	Material service life (average)	Material service life (maximum)	(Ding, 2004)	(Bowyer, 2009)	(Carre, 2011)	(Chapman & Izzo, 2002)	(CMHC, 2000)	(CRCCI, 2004)	IInterNACHI (2012)	RTA (2012)	Seiders *et al.* (2007)	(Ransley & Tyrrell, 1998)	LCCS (2001)	RE/COR (2011)	Conder (2008)	(Treloar, Fay, et al., 2001a)	(Alexander & Thomas, 2015)
<u>Roof</u>																		
Tiles - Concrete	30	40	60				50			75		Life time	40		30-40	60+		
Tiles - Clay/Terracotta	40	50	60										40			60+		
Sheet metal	20	35	50				20-50		18-49				25-35				40	
Insulation/batts	Life time	Life time	Life time							100+	20	Life time	35					
Gutters and downpipes	10	25	40				30		10-40	20	20	20-30	25-35					
Flashing	25	27	30										25-30					
<u>External openings</u>																		
Windows - Aluminium	10	25	40	40			10-20	19-29		15-20	20	15-20	30	25		25-40	30	30
Windows - Wood	15	40	65				20-50			30+	15	30+	30				30	

Curtain wall								28-64										
Door - Solid wood	25	32	40	80		25	30-40			30-100			30				30	
Door - Hollow core	15	22	30	30						20-30			15				30	
Wall systems																		
Concrete	Life time	Life time	Life time													50-100		Life time
Bricks	Life time	Life time	Life time				Life time	27-45		100+						100+		
Brick ties	Life time	Life time	Life time													50		
Fibre cement	30	40	50													30-50		
Polystyrene	30 ×	50 ×	70 ×															
Stucco-wall / Cement-based plaster	17	55	100					17-26				50-100				50+		
Paint - Exterior	7	11	15			10				7-10	8	15+				8-10		
Weatherboard, wood siding	25	45	60															
Interior finishes																		
Paint - Interior	5	10	15	10		10	5-10			10-15	4	15+	5-7				8-10	
Wall framing	Life time	Life time	Life time				Life time											
Gypsum wall plasterboard	20	35	70	25						70	20		35			50+		25
Floor																		
Carpet-Nylon	7	10	20	12	11		11	7-12		8-10	10	8-10				15-20	12	

Tile ceramic	20	60	100	25	50	70+	75-100	20+	30
Linoleum	15	25	35 ×				25	15-20	
uPVC								15-20	
Timber floor	15	29	50		40-50	15-25			
Concrete waste pipes	Life time	life time	life time			100+			
Appliances		13-25							13-25
Plumbing		25-75							25-75
Electrical		25-75				40			25-75

Source : Adapted from Rauf (2015)

- ∗ Proxy service life values

APPENDIX 6

Appendix 6 provides the wastage coefficients of building materials and assemblies used in the model. Values are extracted from Crawford (2004). Appendix 6 is referred in Section 4.7.3.1.

Material/ Assembly	Wastage Factor
Footing and pad concrete	1.05
Slab concrete	1.15
Trench mesh	1.10
Reinforcement sheet	1.05
Membrane	1.10
Sand	1.10
Screenings	1.30
Fabricated metal products	1.05
Timber flooring	1.05
Floor joists and bearers	1.05
Fixings metal	1.10
Roof framing timber	1.05
Concrete and Terracotta roof tiles	1.10
Metal decking	1.05
Reflective foil insulation	1.10
Bulk insulation	1.10
Face brickwork	1.05
Mortar	1.30
Damp proofing	1.05
Flashing	1.05
Timber exterior cladding	1.05
Timber framing	1.02
Insulation batts	1.10
Gutters and downpipes	1.05
Plasterboard	1.05
Fibre cement	1.05
Sheet timber (i.e. MDF)	1.05
Steel lintels	1.02
Timber lintels	1.05
Skirting	1.10
Timber joinery	1.05
Glass	1.03
Architraves	1.10
Window furniture	1.02
Door and frame	1.03
Door furniture	1.03
Ceramic tiles	1.05
Vinyl	1.05
Paint	1.05
Carpet	1.05
Prefabricated joinery	1.05
Laminate (sheet materials)	1.05
Sink, basin, toilet, etc	1.03
Tapware	1.03
Stove, refrigerator, heater etc.	1.00

UPVC piping	1.05
Copper pipe	1.05
Electrical wiring	1.03
Electrical equipment	1.03
Electrical fittings	1.03
Luminaires	1.00
Granite	1.30

Source : Crawford (2004)

APPENDIX 7

Appendix 7 provides the embodied energy coefficients and unit prices of the assemblies estimated in this study. This is referred in Sections 5.3.2.

Assembly id	Assembly name	Embodied energy coefficient (GJ/unit)	Unit price (AU$/unit)
RS01	Roof structure with Steel beams 530UB92	6.914	801.96
RS02	Roof structure with Glue Laminated Timber beams 535 x 85 mm Beam 21 and Colourbond sheets	4.097	805.42
CF01	Plasterboard lining with paint on timber frame	0.734	45.59
CF02	Wood planks with paint on timber frame	0.404	91.17
CF03	Plasterboard lining with paint on metal frame	0.648	44.32
CF04	Metal frame ceiling with Metal tiles	0.577	69.26
CF05	Metal frame ceiling with Cork tiles	0.306	52.64
CF06	Metal frame ceiling with Vinyl tiles	0.974	53.44
CL01	Glum Laminated Timber columns 150 x 150 mm	0.057	47.72
CL02	Steel columns 150 x 150 x 8 mm SHS	3.187	95.23
EW01	150 mm thick precast panel SL92 central with 1N16 trimmer bar central each edge	1.124	403.55
EW02	Insulated precast sandwich wall panels 220 mm thick	1.319	378.35
EW03	Cross laminated timber 205 mm thick (5-layer panel)	1.285	464.04
FF01	Vinyl planks with water barrier underlay	1.285	30.60
FF02	Cork boards with water barrier underlay	0.617	29.80
FF03	Linoleum sheets with water barrier underlay	0.945	35.91
FF04	Rubber carpet with double sided tape	0.915	32.52
FF05	Nylon carpet with underlay	1.230	81.88
FF06	Wool carpet with underlay	1.291	139.26

FF07	Polypropylene carpet with underlay	1.334	40.61
FF08	Ceramic tiling on 10 mm thick cement mortar screed	0.361	32.59
FF09	Terracotta tiles 10 mm thick cement mortar screed	0.891	104.15
FF10	Terrazzo with 100 mm infill slab 20 MPa	0.028	51.76
FF11	Bamboo planks	0.725	98.91
FF12	Laminated timber	0.629	67.06
FF13	Polished exposed aggregate concrete - gloss with 100 mm infill slab 20 MPa	0.466	52.50
FF14	Porcelain tiles 800 x 800 mm	0.431	71.54
FD01	Concrete Foundation (Slab on grade) 150 mm thick provide SL92 fabric top with general purpose Portland cement	2.448	98.23
FD02	Waffle raft slab 385 mm thick with N32 concrete	4.320	170.16
FD03	Concrete Foundation (Slab on grade) 150 mm thick provide SL92 fabric top with 40% fly ash cement	2.085	89.06
IW01	Brick walls (110 mm)	0.535	41.82
IW02	Block walls (140 mm)	0.807	53.88
IW03	Gypsum block wall (500 x 500 x 100 mm)	0.564	4.76
IW04	Steel stud walls (welded)	0.293	28.11
IW05	Calcium Silicate brickwork (110 mm)	0.481	73.93
IW06	Timber stud walls (90 x 45 mm)	0.409	36.18
LT01	Steel lintel 2400 x 150 x 100 x 6 mm galvanised angle	0.951	18.92
LT02	Concrete lintel	0.312	12.69
LT03	Timber lintel	0.011	0.44
WF01	Sheet metal cladding on metal frame - External	1.202	60.17
WF02	Water based paint on 10 mm thick cement mortar screed with white putty	0.133	11.63
WF03	10 mm thick cement mortar screed with white putty	0.021	7.70
WF04	Oil based paint on 10 mm thick cement mortar screed with white putty	0.138	11.24
WF05	Terrazzo tiles on 10 mm thick cement mortar screed	0.028	51.76
WF06	Water based paint on 10 mm plasterboard	0.330	9.28

WF07	Timber board cladding	0.045	64.35
WF08	Ceramic tiling on 10 mm thick cement mortar screed	0.358	30.65
WF09	Bamboo panels with panelling adhesives and finishing nails on timber frame	0.141	96.20
WF10	Vinyl tiles	0.715	33.90
WF11	Compressed fibre cement (CFC) façade panel - External	0.329	53.88
WD01	Metal framed glass windows (2.4 m x 3.6 m) size	7.386	117.17
WD02	Timber framed glass windows	7.162	119.74
WP01	Wet area waterproofing	0.274	27.67

APPENDIX 8

Appendix 8 illustrates the compatibility matrix of the assemblies in shops used in the model. This matrix is used to determine which assemblies could be used to generate assembly combinations for a specific shop type. This is referred in Sections 5.3.2 and 6.8.

Assembly id	Clothing	Food supply	Household	Multimedia and electronics	Gym	Leisure and entertainment	Other	Health and beauty	Café and restaurant	Shoes	Services	Supermarket	Department store	Common area	Centre structure	Toilets and sanitary
RS01	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
RS02	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
RS03	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE
CF01	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE
CF02	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE
CF03	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE
CF04	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE
CF05	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE
CF06	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE
CF07	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
CL01	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
CL02	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
CL03	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE
EW01	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	TRUE	FALSE
EW02	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	TRUE	FALSE

EW03	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	TRUE	FALSE
EW04	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE
FF01	TRUE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
FF02	FALSE	TRUE	TRUE	FALSE	TRUE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
FF03	FALSE	TRUE	TRUE	FALSE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
FF04	FALSE	TRUE	TRUE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
FF05	TRUE	FALSE	TRUE	FALSE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
FF06	TRUE	FALSE	TRUE	FALSE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
FF07	FALSE	TRUE	TRUE	FALSE	TRUE	FALSE	FALSE	TRUE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
FF08	FALSE	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE
FF09	FALSE	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE
FF10	FALSE	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE
FF11	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
FF12	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
FF13	FALSE	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE
FF14	FALSE	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE
FF15	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
FD01	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
FD02	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
FD03	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
FD04	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE
IW01	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE
IW02	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE
IW03	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE
IW04	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE
IW05	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE
IW06	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE

IW07	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE
LT01	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
LT02	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
LT03	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
LT04	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE
WF01	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
WF02	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE
WF03	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE
WF04	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE
WF05	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
WF06	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE
WF07	TRUE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	FALSE
WF08	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
WF09	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE
WF10	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
WF11	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
WF12	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
WD01	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
WD02	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
WD03	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE
WP01	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE
WP02	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE

APPENDIX 9

Appendix 9-A outlines all the shops available in the average case study (Case 1) shopping centre. This is referred in Section 5.3.3.

Shop id	Shop type id	Length	Width	Height	Span
CL_01_RF_5_7_15_4	CL_01_RF_5	7.00	15.00	4.00	0.00
CL_02_RF_5_7_20_4	CL_01_RF_5	7.00	20.00	4.00	0.00
CL_03_RF_5_13_12_4	CL_01_RF_5	13.00	12.00	4.00	0.00
FS_01_RF_5_18_10_4	FS_01_RF_5	18.00	10.00	4.00	0.00
FS_02_RF_5_9_10_4	FS_01_RF_5	9.00	10.00	4.00	0.00
FS_03_RF_5_12_12_4	FS_01_RF_5	12.00	12.00	4.00	0.00
FS_04_RF_5_15_14_4	FS_01_RF_5	15.00	14.00	4.00	0.00
FS_05_RF_5_21_12_4	FS_01_RF_5	21.00	12.00	4.00	0.00
FS_06_RF_5_18_23_4	FS_01_RF_5	18.00	23.00	4.00	0.00
HH_01_RF_5_24_62_4	HH_01_RF_5	24.00	62.00	4.00	0.00
HH_02_RF_5_18_15_4	HH_01_RF_5	18.00	15.00	4.00	0.00
HH_03_RF_5_21_25_4	HH_01_RF_5	21.00	25.00	4.00	0.00
HH_04_RF_5_10_4_4	HH_01_RF_5	10.00	4.00	4.00	0.00
GY_01_RF_5_16_25_4	GY_01_RF_5	16.00	25.00	4.00	0.00
LE_01_RF_5_9_10_4	LE_01_RF_5	9.00	10.00	4.00	0.00
HB_01_RF_5_15_9_4	HB_01_RF_5	15.00	9.00	4.00	0.00
HB_02_RF_5_14_8_4	HB_01_RF_5	14.00	8.00	4.00	0.00
HB_03_RF_5_8_5_4	HB_01_RF_5	8.00	5.00	4.00	0.00
HB_04_RF_5_5_5_4	HB_01_RF_5	5.00	5.00	4.00	0.00
HB_05_RF_5_5_10_4	HB_01_RF_5	5.00	10.00	4.00	0.00
HB_06_RF_5_23_20_4	HB_01_RF_5	23.00	20.00	4.00	0.00
HB_07_RF_5_9_10_4	HB_01_RF_5	9.00	10.00	4.00	0.00
HB_08_RF_5_8_8_4	HB_01_RF_5	8.00	8.00	4.00	0.00
CR_01_RF_5_11_16_4	CR_01_RF_5	11.00	16.00	4.00	0.00
CR_02_RF_5_14_10_4	CR_01_RF_5	14.00	10.00	4.00	0.00
CR_03_RF_5_6_12_4	CR_01_RF_5	6.00	12.00	4.00	0.00
CR_04_RF_5_8_12_4	CR_01_RF_5	8.00	12.00	4.00	0.00
CR_05_RF_5_8_19_4	CR_01_RF_5	8.00	19.00	4.00	0.00
CR_06_RF_5_10_14_4	CR_01_RF_5	10.00	14.00	4.00	0.00
CR_07_RF_5_9_12_4	CR_01_RF_5	9.00	12.00	4.00	0.00
SH_01_RF_5_7_16_4	SH_01_RF_5	7.00	16.00	4.00	0.00
SR_01_RF_5_20_14_4	SR_01_RF_5	20.00	14.00	4.00	0.00
SR_02_RF_5_9_10_4	SR_01_RF_5	9.00	10.00	4.00	0.00
SR_03_RF_5_9_20_4	SR_01_RF_5	9.00	20.00	4.00	0.00
SR_04_RF_5_14_10_4	SR_01_RF_5	14.00	10.00	4.00	0.00
SR_05_RF_5_6_8_4	SR_01_RF_5	6.00	8.00	4.00	0.00
SR_06_RF_5_5_10_4	SR_01_RF_5	5.00	10.00	4.00	0.00
SM_01_RF_20_73_52_8	SM_01_RF_20	73.00	52.00	8.00	0.00
SM_02_RF_20_26_58_8	SM_01_RF_20	26.00	58.00	8.00	0.00
DS_01_RF_20_93_58_8	DS_01_RF_20	93.00	58.00	8.00	0.00
CA_01_RF_10_180_21_9	CA_01_RF_10	180.00	21.00	9.00	0.00

TS_01_RF_10_11_14_4	TS_01_RF_10	11.00	14.00	4.00	0.00
CS_01_RF_50_240_88_10_9	CS_01_RF_50	240.00	88.00	10.00	9.00

APPENDIX 9

Appendix 9-B outlines all the shops available in the small case study (Case 2) shopping centre. This is referred in Section 5.4.3.

Shop id	Shop type id	Length	Width	Height	Span
CL_02_RF_5_7_20_4	CL_01_RF_5	7.00	20.00	4.00	0.00
CL_04_RF_5_7_17_4	CL_01_RF_5	7.00	17.00	4.00	0.00
CL_05_RF_5_8_14_4	CL_01_RF_5	8.00	14.00	4.00	0.00
CL_06_RF_5_7_16_4	CL_01_RF_5	7.00	16.00	4.00	0.00
CL_07_RF_5_5_16_4	CL_01_RF_5	5.00	16.00	4.00	0.00
FS_07_RF_5_7_13_4	FS_01_RF_5	7.00	13.00	4.00	0.00
FS_08_RF_5_15_13_4	FS_01_RF_5	15.00	13.00	4.00	0.00
FS_09_RF_5_7_15_4	FS_01_RF_5	7.00	15.00	4.00	0.00
HH_05_RF_5_5_13_4	HH_01_RF_5	5.00	13.00	4.00	0.00
HH_06_RF_5_5_17_4	HH_01_RF_5	5.00	17.00	4.00	0.00
HB_09_RF_5_7_13_4	HB_01_RF_5	7.00	13.00	4.00	0.00
HB_10_RF_5_5_9_4	HB_01_RF_5	5.00	9.00	4.00	0.00
HB_11_RF_5_5_13_4	HB_01_RF_5	5.00	13.00	4.00	0.00
HB_12_RF_5_11_15_4	HB_01_RF_5	11.00	15.00	4.00	0.00
HB_13_RF_5_7_11_4	HB_01_RF_5	7.00	11.00	4.00	0.00
SH_02_RF_5_4_19_4	SH_01_RF_5	4.00	19.00	4.00	0.00
SH_03_RF_5_7_13_4	SH_01_RF_5	7.00	13.00	4.00	0.00
SH_04_RF_5_9_8_4	SH_01_RF_5	9.00	8.00	4.00	0.00
SR_07_RF_5_5_19_4	SR_01_RF_5	5.00	19.00	4.00	0.00
SR_08_RF_5_5_11_4	SR_01_RF_5	5.00	11.00	4.00	0.00
SM_03_RF_20_52_64_8	SM_01_RF_20	52.00	64.00	8.00	0.00
DS_02_RF_20_52_105_8	DS_01_RF_20	52.00	105.00	8.00	0.00
CA_02_RF_10_38_11_9	CA_01_RF_10	38.00	11.00	9.00	0.00
TS_02_RF_10_7_9_4	TS_01_RF_10	7.00	9.00	4.00	0.00
CS_02_RF_50_52_230_10_9	CS_01_RF_50	52.00	230.00	10.00	9.00

APPENDIX 9

Appendix 9-C outlines all the shops available in the large case study (Case 3) shopping centre. This is referred in Section 5.5.2.

Shop id	Shop type id	Length	Width	Height	Span
CL_08_RF_5_4_12_4	CL_01_RF_5	4.00	12.00	4.00	0.00
CL_09_RF_5_9_13_4	CL_01_RF_5	9.00	13.00	4.00	0.00
CL_10_RF_5_16_8_4	CL_01_RF_5	16.00	8.00	4.00	0.00
CL_11_RF_5_8_12_4	CL_01_RF_5	8.00	12.00	4.00	0.00
CL_12_RF_5_16_6_4	CL_01_RF_5	16.00	6.00	4.00	0.00
CL_13_RF_5_8_13_4	CL_01_RF_5	8.00	13.00	4.00	0.00
CL_14_RF_5_6_12_4	CL_01_RF_5	6.00	12.00	4.00	0.00
CL_15_RF_5_8_8_4	CL_01_RF_5	8.00	8.00	4.00	0.00
CL_16_RF_5_16_16_4	CL_01_RF_5	16.00	16.00	4.00	0.00
FS_10_RF_5_8_24_4	FS_01_RF_5	8.00	24.00	4.00	0.00
FS_11_RF_5_6_13_4	FS_01_RF_5	6.00	13.00	4.00	0.00
FS_12_RF_5_11_8_4	FS_01_RF_5	11.00	8.00	4.00	0.00
FS_13_RF_5_13_24_4	FS_01_RF_5	13.00	24.00	4.00	0.00
FS_14_RF_5_9_16_4	FS_01_RF_5	9.00	16.00	4.00	0.00
HH_07_RF_5_35_38_4	HH_01_RF_5	35.00	38.00	4.00	0.00
HH_08_RF_5_17_9_4	HH_01_RF_5	17.00	9.00	4.00	0.00
HH_09_RF_5_11_6_4	HH_01_RF_5	11.00	6.00	4.00	0.00
HH_10_RF_5_9_9_4	HH_01_RF_5	9.00	9.00	4.00	0.00
HH_11_RF_5_24_14_4	HH_01_RF_5	24.00	14.00	4.00	0.00
HH_12_RF_5_14_11_4	HH_01_RF_5	14.00	11.00	4.00	0.00
OR_01_RF_5_5_5_4	OR_01_RF_5	5.00	5.00	4.00	0.00
OR_02_RF_5_9_9_4	OR_01_RF_5	9.00	9.00	4.00	0.00
OR_03_RF_5_6_16_4	OR_01_RF_5	6.00	16.00	4.00	0.00
OR_04_RF_5_11_8_4	OR_01_RF_5	11.00	8.00	4.00	0.00
LE_02_RF_5_8_13_4	LE_01_RF_5	8.00	13.00	4.00	0.00
HB_02_RF_5_14_8_4	HB_01_RF_5	14.00	8.00	4.00	0.00
HB_11_RF_5_5_13_4	HB_01_RF_5	5.00	13.00	4.00	0.00
HB_14_RF_5_8_11_4	HB_01_RF_5	8.00	11.00	4.00	0.00
HB_15_RF_5_6_16_4	HB_01_RF_5	6.00	16.00	4.00	0.00
HB_16_RF_5_6_12_4	HB_01_RF_5	6.00	12.00	4.00	0.00
HB_17_RF_5_9_5_4	HB_01_RF_5	9.00	5.00	4.00	0.00
HB_18_RF_5_13_13_4	HB_01_RF_5	13.00	13.00	4.00	0.00
HB_19_RF_5_11_9_4	HB_01_RF_5	11.00	9.00	4.00	0.00
HB_20_RF_5_14_16_4	HB_01_RF_5	14.00	16.00	4.00	0.00
HB_21_RF_5_4_12_4	HB_01_RF_5	4.00	12.00	4.00	0.00
CR_08_RF_5_4_12_4	CR_01_RF_5	4.00	12.00	4.00	0.00
CR_09_RF_5_5_12_4	CR_01_RF_5	5.00	12.00	4.00	0.00
CR_10_RF_5_9_6_4	CR_01_RF_5	9.00	6.00	4.00	0.00
CR_11_RF_5_26_8_4	CR_01_RF_5	26.00	8.00	4.00	0.00

CR_12_RF_5_5_6_4	CR_01_RF_5	5.00	6.00	4.00	0.00
CR_13_RF_5_12_6_4	CR_01_RF_5	12.00	6.00	4.00	0.00
CR_14_RF_5_19_16_4	CR_01_RF_5	19.00	16.00	4.00	0.00
CR_15_RF_5_6_8_4	CR_01_RF_5	6.00	8.00	4.00	0.00
CR_16_RF_5_6_13_4	CR_01_RF_5	6.00	13.00	4.00	0.00
CR_17_RF_5_5_8_4	CR_01_RF_5	5.00	8.00	4.00	0.00
CR_18_RF_5_5_16_4	CR_01_RF_5	5.00	16.00	4.00	0.00
CR_19_RF_5_9_9_4	CR_01_RF_5	9.00	9.00	4.00	0.00
SR_09_RF_5_16_8_4	SR_01_RF_5	16.00	8.00	4.00	0.00
SR_10_RF_5_26_9_4	SR_01_RF_5	26.00	9.00	4.00	0.00
SR_11_RF_5_4_9_4	SR_01_RF_5	4.00	9.00	4.00	0.00
SR_12_RF_5_8_8_4	SR_01_RF_5	8.00	8.00	4.00	0.00
SR_13_RF_5_8_16_4	SR_01_RF_5	8.00	16.00	4.00	0.00
SR_14_RF_5_16_11_4	SR_01_RF_5	16.00	11.00	4.00	0.00
SR_15_RF_5_16_5_4	SR_01_RF_5	16.00	5.00	4.00	0.00
SR_16_RF_5_8_22_4	SR_01_RF_5	8.00	22.00	4.00	0.00
SR_17_RF_5_11_5_4	SR_01_RF_5	11.00	5.00	4.00	0.00
SR_18_RF_5_5_6_4	SR_01_RF_5	5.00	6.00	4.00	0.00
SR_19_RF_5_13_9_4	SR_01_RF_5	13.00	9.00	4.00	0.00
SM_04_RF_20_56_63_8	SM_01_RF_20	56.00	63.00	8.00	0.00
SM_05_RF_20_27_47_8	SM_01_RF_20	27.00	47.00	8.00	0.00
SM_06_RF_20_63_55_8	SM_01_RF_20	63.00	55.00	8.00	0.00
SM_07_RF_20_24_63_8	SM_01_RF_20	24.00	63.00	8.00	0.00
DS_03_RF_20_98_55_8	DS_01_RF_20	98.00	55.00	8.00	0.00
CA_03_RF_10_88_75_9	CA_01_RF_10	88.00	75.00	9.00	0.00
TS_03_RF_10_8_40_4	TS_01_RF_10	8.00	40.00	4.00	0.00
CS_03_RF_50_173_173_10_9	CS_01_RF_50	173.00	173.00	10.00	9.00

APPENDIX 10

Appendix 10 shows all the shop types available in the shopping centres. It states the refurbishment frequency of the shop along with the assemblies that are used in the business as usual scenario of the shopping centre. This is referred in Section 6.3.2.3.

Shop type ID	Shop type name	Refurbishment frequency	Roof structure	Ceiling finish	Column	External wall	Floor finish	Foundation	Internal wall	Lintel	Wall finish	Window	Water proofing
CL_01_RF_5	Clothing	5	RS03	CF06	CL03	EW04	FF12	FD04	IW06	LT04	WF07	WD03	WP02
FS_01_RF_5	Food supplies	5	RS03	CF06	CL03	EW04	FF10	FD04	IW04	LT04	WF06	WD03	WP02
HH_01_RF_5	Household	5	RS03	CF01	CL03	EW04	FF01	FD04	IW04	LT04	WF06	WD03	WP02
ME_01_RF_5	Multimedia and electronics	5	RS03	CF01	CL03	EW04	FF09	FD04	IW04	LT04	WF06	WD03	WP02
GY_01_RF_5	Gym	5	RS03	CF01	CL03	EW04	FF07	FD04	IW04	LT04	WF06	WD03	WP02
LE_01_RF_5	Leisure and entertainment	5	RS03	CF01	CL03	EW04	FF09	FD04	IW04	LT04	WF06	WD03	WP02
HB_01_RF_5	Health and beauty	5	RS03	CF02	CL03	EW04	FF01	FD04	IW04	LT04	WF07	WD03	WP02
CR_01_RF_5	Coffee and restaurant	5	RS03	CF02	CL03	EW04	FF08	FD04	IW06	LT04	WF07	WD03	WP02
OR_01_RF_5	Other retail	5	RS03	CF01	CL03	EW04	FF09	FD04	IW04	LT04	WF06	WD03	WP02
SH_01_RF_5	Shoes	5	RS03	CF06	CL03	EW04	FF12	FD04	IW04	LT04	WF07	WD03	WP02
SR_01_RF_5	Services	5	RS03	CF01	CL03	EW04	FF09	FD04	IW04	LT04	WF06	WD03	WP02
SM_01_RF_20	Supermarket	20	RS03	CF06	CL03	EW01	FF14	FD04	IW07	LT04	WF02	WD03	WP02
DS_01_RF_20	Discount department store	20	RS03	CF01	CL03	EW01	FF14	FD04	IW07	LT04	WF02	WD03	WP02
CA_01_RF_10	Common area	10	RS03	CF02	CL03	EW04	FF14	FD04	IW07	LT04	WF02	WD03	WP02
TS_01_RF_10	Toilets and sanitary	10	RS03	CF06	CL03	EW04	FF08	FD04	IW04	LT04	WF06	WD03	WP01
CS_01_RF_50	Centre structure	50	RS01	CF07	CL02	EW01	FF15	FD01	IW07	LT01	WF01	WD01	WP02

APPENDIX 11

Appendix 11 outlines all the variables used in the algorithms to quantify different assembly types in the shops. This is referred in Section 6.6.

Variable name	Unit	Data type	Description
get_quantity_gfa	m^2	float	Quantity of gross floor area of the shop
get_quantity_foundation	m^2	float	Quantity of plan area of the foundation of the centre structure
get_quantity_roof_structure	m^2	float	Quantity of plan area of the roof structure of the centre structure
get_quantity_column	m	float	Quantity of the columns of the centre structure in linear m
get_quantity_external_wall	m^2	float	Quantity of the external wall area of the shop
get_quantity_internal_wall	m^2	float	Quantity of the internal wall area of the shop
get_quantity_window	m^2	float	Quantity of the window area of the shop
get_quantity_lintel	m	float	Quantity of the lintel of the shop in linear m
get_quantity_wall_finish	m^2	float	Quantity of the wall finishes area of the shop
get_quantity_floor_finish	m^2	float	Quantity of the floor finishes area of the shop
get_quantity_ceiling_finish	m^2	float	Quantity of the ceiling finishes area of the shop
get_quantity_waterproofing	m^2	float	Quantity of the waterproofing area of the shop

APPENDIX 12

Appendix 12 illustrates the matrix of assembly compatibility with each other. This is also used as a constraint in generating combinations. This is referred in Section 6.8.

	RS01	RS02	RS03	CF01	CF02	CF03	CF04	CF05	CF06	CF07	CL01	CL02	CL03	EW01	EW02	EW03	EW04	FF01	FF02	FF03	FF04	FF05	FF06	FF07	FF08	FF09	FF10	FF11	FF12	FF13	FF14	FF15	FD01	FD02	FD03	FD04	IW01	IW02	IW03	IW04	IW05	IW06	IW07	LT01	LT02	LT03	LT04	WF01	WF02	WF03	WF04	WF05	WF06	WF07	WF08	WF09	WF10	WF11	WF12	WD01	WD02	WD03	WP01	WP02
RS01	T	F	F	T	T	T	T	T	T	T	F	T	T	T	T	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
RS02	F	T	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
RS03	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
CF01	T	T	T	T	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
CF02	T	T	T	F	T	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
CF03	T	T	T	F	F	T	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
CF04	T	T	T	F	F	F	T	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
CF05	T	T	T	F	F	F	F	T	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
CF06	T	T	T	F	F	F	F	F	T	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
CF07	T	T	T	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
CL01	F	T	T	T	T	T	T	T	T	T	T	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
CL02	T	T	T	T	T	T	T	T	T	T	F	T	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
CL03	T	T	T	T	T	T	T	T	T	T	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
EW01	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	F	F	T	F	F	F	T	T	T	T	T	T	T
EW02	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	F	F	T	F	F	F	T	T	T	T	T	T	T
EW03	F	T	T	T	T	T	T	T	T	T	T	T	T	F	F	T	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	T	T	T	F	F	F	F	F	T	F	T	F	T	T	T	T	T	T	T
EW04	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF01	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF02	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	F	F	F	F	F	F	F	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF03	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	T	F	F	F	F	F	F	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF04	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	F	F	F	F	F	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF05	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	T	F	F	F	F	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF06	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	T	F	F	F	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF07	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	T	F	F	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF08	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	F	T	F	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF09	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	F	F	T	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF10	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F	T	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF11	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F	F	T	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF12	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F	F	F	T	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF13	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F	F	F	F	T	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF14	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F	F	F	F	F	T	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FF15	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FD01	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FD02	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FD03	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	T	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
FD04	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
IW01	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	F	T	T	F	T	T	T	T	T	T	T	T
IW02	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	F	F	F	F	F	T	T	T	T	T	T	T	T	T	F	T	T	F	T	T	T	T	T	T	T	T
IW03	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	T	F	F	F	F	T	T	T	T	T	T	T	T	T	F	T	T	F	T	T	T	T	T	T	T	T
IW04	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	F	F	F	T	F	F	T	T	F	F	F	F	T	T	F	T	F	T	T	T	T	T	T	T
IW05	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	T	F	F	T	T	T	T	T	T	T	T	T	F	F	T	F	T	T	T	T	T	T	T	T
IW06	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	T	F	F	F	T	T	T	F	F	F	F	T	T	F	T	F	T	T	T	T	T	T	T
IW07	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
LT01	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
LT02	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	F	T	F	T	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
LT03	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	F	F	T	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
LT04	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
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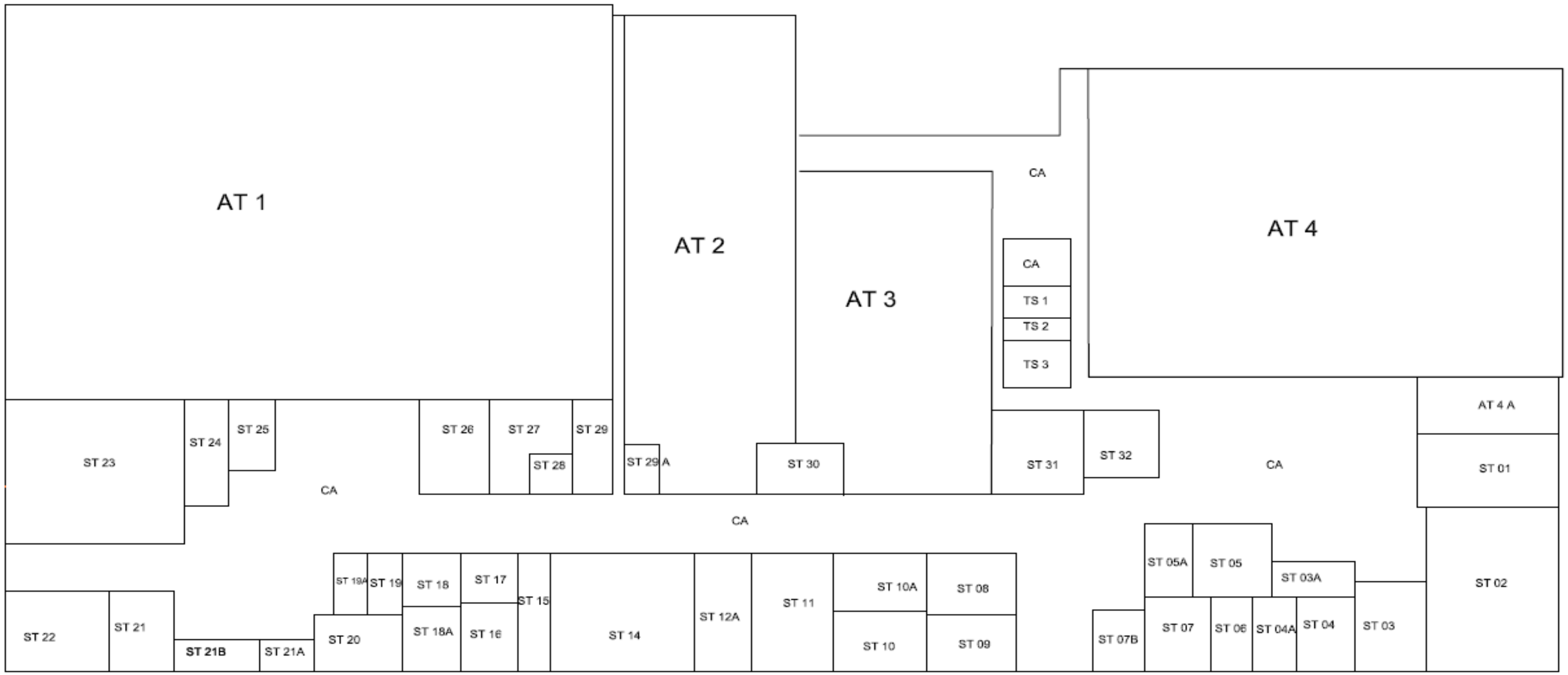
WF03	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	F	T	T	T	T	T	F	F	T	F	F	F	F	F	F	F	F	F	T	T	T	T	T
WF04	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	F	T	T	T	T	T	F	F	F	T	F	F	F	F	F	F	F	F	T	T	T	T	T
WF05	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	F	T	T	T	T	T	F	F	F	F	T	F	F	F	F	F	F	F	T	T	T	T	T
WF06	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	F	T	T	T	T	T	T	F	F	F	F	F	T	F	F	F	F	F	F	T	T	T	T	T
WF07	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	T	T	T	T	T	T	F	F	F	F	F	F	T	F	F	F	F	F	T	T	T	T	T
WF08	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	F	T	T	T	T	T	F	F	F	F	F	F	F	T	F	F	F	F	T	T	T	T	T
WF09	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	F	T	T	T	T	T	T	F	F	F	F	F	F	F	F	T	F	F	F	T	T	T	T	T
WF10	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	F	T	T	T	T	T	F	F	F	F	F	F	F	F	F	T	F	F	T	T	T	T	T
WF11	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F	F	T	F	T	T	T	T	T
WF12	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	F	F	F	F	F	F	F	F	F	T	T	T	T	T	T
WD01	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	T	T
WD02	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T	F	T	T
WD03	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	F	T	T	T
WP01	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F
WP02	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	F	T

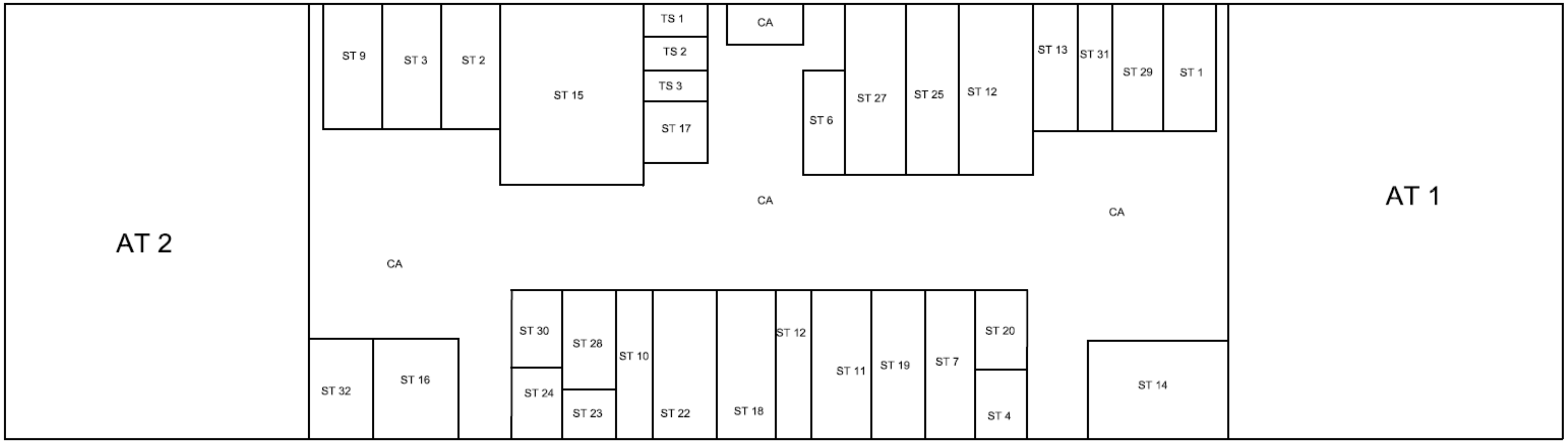
APPENDIX 13

Appendix 13-A shows the simplified floor plan of the average shopping centre (case study 1). This is referred in Section 6.10.3.



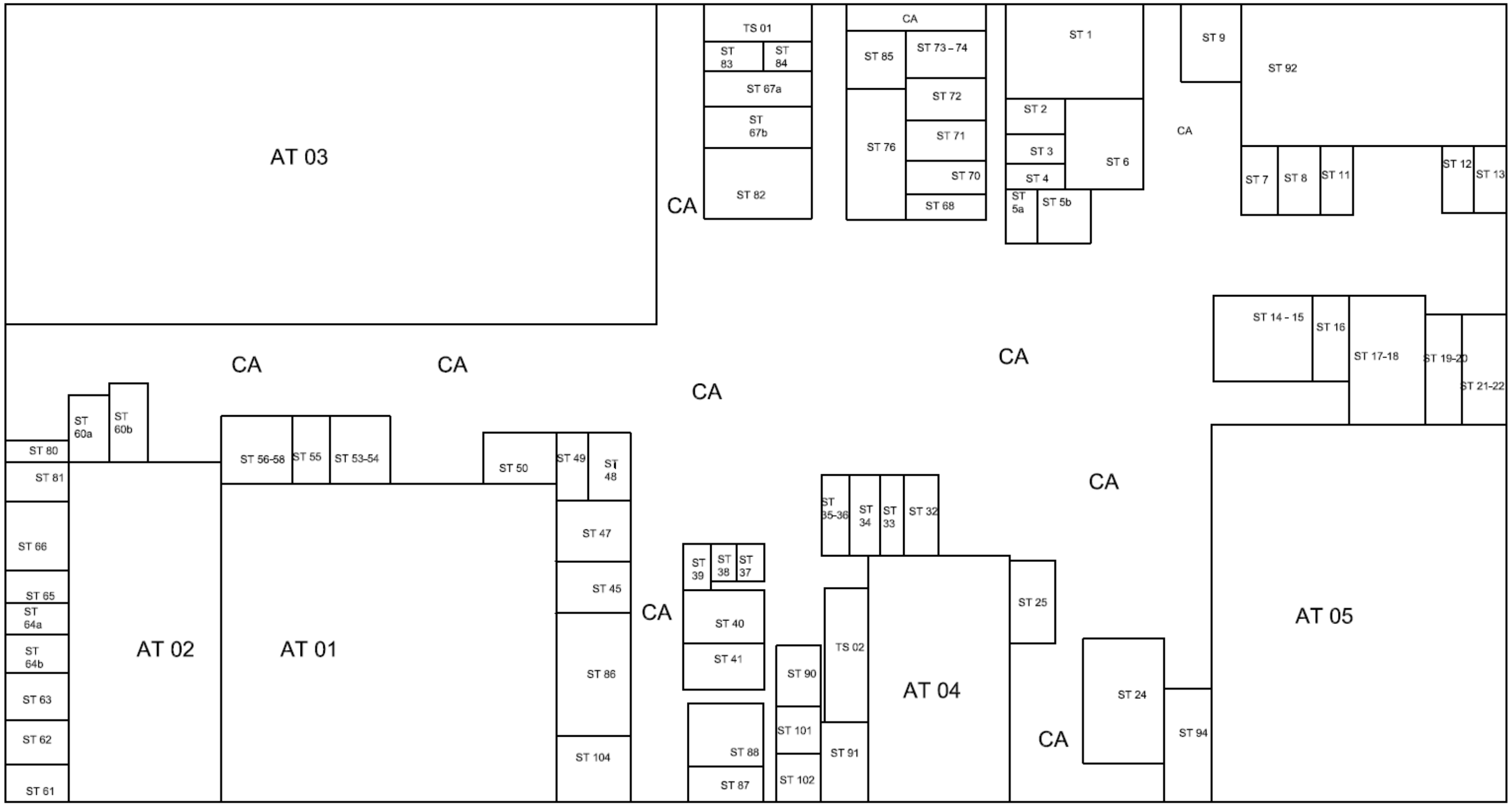
APPENDIX 13

Appendix 13-B shows the simplified floor plan of the small shopping centre (case study 2). This is referred in Section 6.10.3.



APPENDIX 13

Appendix 13-C shows the simplified floor plan of the large shopping centre (case study 3). This is referred in Section 6.10.3.



APPENDIX 14

Appendix 14 demonstrates the different life cycle embodied energy and material cost intensities of assemblies used in the study, when they are installed in shops with different refurbishment frequencies. N/A indicates that the assemblies cannot be used in that type of shops. This appendix is referred in Section 7.6.

Assembly name	Refurbishment frequency 5: LCEE/m^2	Refurbishment frequency 5: LCMC/m^2	Refurbishment frequency 10: LCEE/m^2	Refurbishment frequency 10: LCMC/m^2	Refurbishment frequency 20: LCEE/m^2	Refurbishment frequency 20: LCMC/m^2	Refurbishment frequency 50: LCEE/m^2	Refurbishment frequency 50: LCMC/m^2
Concrete foundation	N/A	N/A	N/A	N/A	N/A	N/A	2.45	98.23
Waffle raft slab	N/A	N/A	N/A	N/A	N/A	N/A	4.32	170.16
Concrete foundation with 40% fly ash	N/A	N/A	N/A	N/A	N/A	N/A	2.09	89.06
Glue-laminated timber columns	N/A	N/A	N/A	N/A	N/A	N/A	0.06	47.72
Steel columns	N/A	N/A	N/A	N/A	N/A	N/A	3.19	95.23
Steel roof	N/A	N/A	N/A	N/A	N/A	N/A	6.91	801.96
Engineered timber roof	N/A	N/A	N/A	N/A	N/A	N/A	4.10	805.42
Precast reinforced concrete wall	N/A	N/A	N/A	N/A	N/A	N/A	1.12	403.55
Insulated precast sandwich wall	N/A	N/A	N/A	N/A	N/A	N/A	1.32	378.35
Cross-laminated timber wall	N/A	N/A	N/A	N/A	N/A	N/A	1.29	464.04
Brick wall (110 mm)	5.35	314.54	2.68	162.71	N/A	N/A	N/A	N/A
Block wall (140 mm)	8.07	405.25	4.04	209.63	N/A	N/A	N/A	N/A
Gypsum block wall (100 mm)	5.64	35.80	2.82	18.52	N/A	N/A	N/A	N/A
Steel stud walls (welded)	2.93	211.42	1.47	109.36	N/A	N/A	N/A	N/A
Calcium Silicate brickwork (110 mm)	4.81	556.05	2.41	287.63	N/A	N/A	N/A	N/A
Timber stud walls (90 × 45 mm)	4.09	272.12	2.05	140.76	N/A	N/A	N/A	N/A

Metal framed glass windows	N/A	N/A	N/A	N/A	N/A	N/A	14.77	188.00
Timber framed glass windows	N/A	N/A	N/A	N/A	N/A	N/A	14.32	192.12
Steel lintel	N/A	N/A	N/A	N/A	N/A	N/A	0.95	18.92
Concrete lintel	N/A	N/A	N/A	N/A	N/A	N/A	0.31	12.69
Timber lintel	N/A	N/A	N/A	N/A	N/A	N/A	0.01	0.44
Plasterboard on timber frame	7.34	342.81	N/A	N/A	2.20	107.59	N/A	N/A
Wood planks on timber frame	4.04	685.61	2.02	354.66	N/A	N/A	N/A	N/A
Plasterboard on metal frame	6.48	333.26	N/A	N/A	1.94	104.59	N/A	N/A
Metal tiles on metal frame	5.77	520.84	N/A	N/A	N/A	N/A	N/A	N/A
Cork tiles on metal frame	3.06	395.87	N/A	N/A	N/A	N/A	N/A	N/A
Vinyl tiles on metal frame	9.74	401.90	N/A	N/A	N/A	N/A	N/A	N/A
Vinyl plank flooring	12.85	230.14	N/A	N/A	N/A	N/A	N/A	N/A
Corkboards flooring	6.17	224.11	N/A	N/A	N/A	N/A	N/A	N/A
Linoleum flooring	9.45	270.01	N/A	N/A	N/A	N/A	N/A	N/A
Rubber carpet flooring	9.15	244.58	N/A	N/A	N/A	N/A	N/A	N/A
Nylon carpet flooring	12.30	615.76	N/A	N/A	N/A	N/A	N/A	N/A
Wool carpet flooring	12.91	1047.24	N/A	N/A	N/A	N/A	N/A	N/A
Polypropylene carpet flooring	13.34	305.40	N/A	N/A	N/A	N/A	N/A	N/A
Ceramic tiled flooring	3.61	245.10	1.81	126.78	1.08	76.92	N/A	N/A
Terracotta tiled flooring	8.91	783.21	3.56	317.66	2.67	245.79	N/A	N/A
Terrazzo flooring	0.28	389.25	0.01	201.36	0.08	122.16	N/A	N/A
Bamboo plank flooring	7.25	743.77	N/A	N/A	N/A	N/A	N/A	N/A
Laminated timber flooring	6.29	504.29	N/A	N/A	N/A	N/A	N/A	N/A
Polished exposed aggregate concrete	4.66	394.80	1.40	204.23	1.86	160.13	N/A	N/A
Porcelain tiled flooring	4.31	538.01	N/A	N/A	1.29	168.84	N/A	N/A
Sheet metal cladding wall	N/A	N/A	N/A	N/A	N/A	N/A	2.40	101.09

Water-based paint on cement mortar	1.33	87.45	1.33	87.45	1.33	87.45	N/A	N/A
Cement mortar screed with white putty	0.21	57.94	N/A	N/A	0.21	57.94	N/A	N/A
Oil-based paint on cement mortar	1.38	84.53	N/A	N/A	1.38	84.53	N/A	N/A
Water-based paint on plasterboard	3.30	389.25	N/A	N/A	N/A	N/A	N/A	N/A
Timber board cladding wall	0.45	69.82	0.22	250.34	0.18	28.32	0.18	196.28
Bamboo panels on timber frame	1.41	483.94	N/A	N/A	0.42	151.88	N/A	N/A
Vinyl tiled walls	7.15	230.46	3.57	131.88	N/A	N/A	N/A	N/A
Compressed fibre cement façade panel	N/A	N/A	N/A	N/A	N/A	N/A	1.31	164.35

APPENDIX 15

Appendix 15-A shows the combinations of assemblies achieving different objectives in clothing shops. This appendix is referred in Sections 7.3.1.5, 7.3.3, 8.4 and 9.4.

Internal wall	Wall finish	Floor finish	Ceiling finish
Optimal: Minimising life cycle embodied energy and life cycle material cost			
Gypsum block wall (100 mm)	Water-based paint on cement mortar screed with white putty	Laminated timber flooring	Metal framed ceiling with Vinyl tiles
Gypsum block wall (100 mm)	Oil-based paint on cement mortar screed with white putty	Laminated timber flooring	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Water-based paint on cement mortar screed with white putty	Laminated timber flooring	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil-based paint on cement mortar screed with white putty	Laminated timber flooring	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water-based paint on cement mortar screed with white putty	Vinyl planks with water barrier underlay	Metal frame ceiling with Cork tiles
Steel stud walls (welded)	Water-based paint on 10 mm plasterboard	Laminated timber flooring	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Oil-based paint on cement mortar screed with white putty	Vinyl planks with water barrier underlay	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Water-based paint on cement mortar screed with white putty	Laminated timber flooring	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Oil-based paint on cement mortar screed with white putty	Laminated timber flooring	Metal frame ceiling with Cork tiles
Gypsum block wall (500 × 500 × 100 mm)	Water-based paint on cement mortar screed with white putty	Laminated timber flooring	Plasterboard lining with paint on timber frame
Minimising life cycle embodied energy			
Timber stud walls (90 × 45 mm)	Timber board cladding	Laminated timber flooring	Metal frame ceiling with Cork tiles

Steel stud walls (welded)	Bamboo panels with panelling adhesives and finishing nails on timber frame	Laminated timber flooring	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Timber board cladding	Laminated timber flooring	Metal frame ceiling with Cork tiles
Timber stud walls (90 × 45 mm)	Timber board cladding	Bamboo planks	Metal frame ceiling with Cork tiles
Timber stud walls (90 × 45 mm)	Timber board cladding	Laminated timber flooring	Timber framed ceiling with wood planks
Gypsum block wall (100 mm)	Timber board cladding	Laminated timber flooring	Metal frame ceiling with Cork tiles
Timber stud walls (90 × 45 mm)	Bamboo panels with panelling adhesives and finishing nails on timber frame	Laminated timber flooring	Metal frame ceiling with Cork tiles
Steel stud walls (welded)	Bamboo panels with panelling adhesives and finishing nails on timber frame	Bamboo planks	Metal frame ceiling with Cork tiles
Steel stud walls (welded)	Bamboo panels with panelling adhesives and finishing nails on timber frame	Laminated timber flooring	Timber framed ceiling with wood planks
Brick walls (110 mm)	Timber board cladding	Bamboo planks	Metal frame ceiling with Cork tiles
Minimising life cycle material cost			
Steel stud walls (welded)	Water based paint on 10 mm plasterboard	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Steel stud walls (welded)	Water based paint on 10 mm plasterboard	Vinyl planks with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on timber frame
Timber stud walls (90 × 45 mm)	Water based paint on 10 mm plasterboard	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Timber stud walls (90 × 45 mm)	Water based paint on 10 mm plasterboard	Vinyl planks with water barrier underlay	Plasterboard lining with paint on timber frame

Steel stud walls (welded)	Water based paint on 10 mm plasterboard	Vinyl planks with water barrier underlay	Metal frame ceiling with Cork tiles
Steel stud walls (welded)	Water based paint on 10 mm plasterboard	Vinyl planks with water barrier underlay	Metal frame ceiling with Vinyl tiles

APPENDIX 15

Appendix 15-B shows the combinations of assemblies achieving different objectives in supermarket shops. This appendix is referred in Sections 7.3.1.5, 7.3.3, 8.4 and 9.4.

Structural wall	Wall finish	Floor finish	Ceiling finish
Optimal: Minimising life cycle embodied energy and life cycle material cost			
Insulated precast sandwich wall panels 220 mm thick	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on metal frame
150 mm thick precast panel walls	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on metal frame
Insulated precast sandwich wall panels 220 mm thick	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
150 mm thick precast panel walls	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on metal frame
150 mm thick precast panel walls	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
Minimising life cycle embodied energy			
150 mm thick precast panel walls	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on metal frame
150 mm thick precast panel walls	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on metal frame
Cross laminated timber 205 mm thick	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on metal frame
Insulated precast sandwich wall panels 220 mm thick	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on metal frame
Insulated precast sandwich wall panels 220 mm thick	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on metal frame

Cross laminated timber 205 mm thick	Bamboo panel walls	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on metal frame
150 mm thick precast panel walls	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on timber frame
150 mm thick precast panel walls	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on timber frame
Cross laminated timber 205 mm thick	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on timber frame
Insulated precast sandwich wall panels 220 mm thick	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on timber frame
Minimising life cycle material cost			
Insulated precast sandwich wall panels 220 mm thick	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
Insulated precast sandwich wall panels 220 mm thick	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on timber frame
150 mm thick precast panel walls	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
150 mm thick precast panel walls	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on timber frame
Insulated precast sandwich wall panels 220 mm thick	Oil based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
Insulated precast sandwich wall panels 220 mm thick	Water based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
Insulated precast sandwich wall panels 220 mm thick	Oil based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on timber frame
150 mm thick precast panel walls	Oil based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
Insulated precast sandwich wall panels 220 mm thick	Water based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on timber frame
150 mm thick precast panel walls	Water based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame

APPENDIX 15

Appendix 15-C shows the combinations of assemblies achieving different objectives in the centre structure. This appendix is referred in Sections 7.3.1.5, 7.3.3, 8.4 and 9.4.

Roof structure	Column	External wall	Foundation	Lintel	Wall finish	Window
Optimal: Minimising life cycle embodied energy and life cycle material cost						
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Concrete lintel	Timber board cladding	Timber framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Concrete lintel	Timber board cladding	Metal framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	150 mm thick precast panel walls	Slab on grade with 40% fly ash cement	Concrete lintel	Timber board cladding	Timber framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	150 mm thick precast panel walls	Slab on grade with 40% fly ash cement	Concrete lintel	Compressed fibre cement façade panel	Timber framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Concrete lintel	Compressed fibre cement façade panel	Timber framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Concrete lintel	Compressed fibre cement façade panel	Metal framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	150 mm thick precast panel walls	Slab on grade with 40% fly ash cement	Concrete lintel	Sheet metal cladding on metal frame	Timber framed glass windows

Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Concrete lintel	Sheet metal cladding on metal frame	Timber framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Concrete lintel	Sheet metal cladding on metal frame	Metal framed glass windows
Minimising life cycle embodied energy						
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	150 mm thick precast panel walls	Slab on grade with 40% fly ash cement	Concrete lintel	Timber board cladding	Timber framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	150 mm thick precast panel walls	Slab on grade with 40% fly ash cement	Steel lintel	Timber board cladding	Timber framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Cross laminated timber 205 mm thick	Slab on grade with 40% fly ash cement	Timber lintel	Timber board cladding	Timber framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Concrete lintel	Timber board cladding	Timber framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	150 mm thick precast panel walls	Slab on grade with 40% fly ash cement	Concrete lintel	Timber board cladding	Metal framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Steel lintel	Timber board cladding	Timber framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	150 mm thick precast panel walls	Slab on grade with 40% fly ash cement	Steel lintel	Timber board cladding	Metal framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Cross laminated timber 205 mm thick	Slab on grade with 40% fly ash cement	Timber lintel	Timber board cladding	Metal framed glass windows

Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Concrete lintel	Timber board cladding	Metal framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Steel lintel	Timber board cladding	Metal framed glass windows
Minimising life cycle material cost						
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Concrete lintel	Sheet metal cladding on metal frame	Metal framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Steel lintel	Sheet metal cladding on metal frame	Metal framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Concrete lintel	Sheet metal cladding on metal frame	Metal framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Steel lintel	Sheet metal cladding on metal frame	Timber framed glass windows
Roof structure with steel beams and Colourbond sheets	Steel columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Concrete lintel	Sheet metal cladding on metal frame	Metal framed glass windows
Roof structure with steel beams and Colourbond sheets	Steel columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Steel lintel	Sheet metal cladding on metal frame	Metal framed glass windows
Roof structure with steel beams and Colourbond sheets	Steel columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Concrete lintel	Sheet metal cladding on metal frame	Timber framed glass windows
Roof structure with steel beams and Colourbond sheets	Steel columns	Insulated precast sandwich wall panels 220 mm thick	Slab on grade with 40% fly ash cement	Steel lintel	Sheet metal cladding on metal frame	Timber framed glass windows
Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	150 mm thick precast panel walls	Slab on grade with 40% fly ash cement	Concrete lintel	Sheet metal cladding on metal frame	Metal framed glass windows

Roof structure with glue laminated timber beams and Colourbond sheets	Glum Laminated Timber columns	150 mm thick precast panel walls	Slab on grade with 40% fly ash cement	Steel lintel	Sheet metal cladding on metal frame	Metal framed glass windows

APPENDIX 15

Appendix 15-D shows the combinations of assemblies achieving different objectives in common areas. This appendix is referred in Sections 7.3.1.5, 7.3.3, 8.4 and 9.4.

Ceiling finish	Floor finish	Wall finish
Optimal: Minimising life cycle embodied energy and life cycle material cost		
Wood planks with paint on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Timber board cladding
Wood planks with paint on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Water based paint on 10 mm thick cement mortar screed with white putty
Wood planks with paint on timber frame	Ceramic tiling on 10 mm thick cement mortar screed	Vinyl tiles
Minimising life cycle embodied energy		
Wood planks with paint on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Timber board cladding
Wood planks with paint on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Water based paint on 10 mm thick cement mortar screed with white putty
Wood planks with paint on timber frame	Ceramic tiling on 10 mm thick cement mortar screed	Timber board cladding
Wood planks with paint on timber frame	Porcelain tiles 800 × 800 mm on cement mortar screed	Timber board cladding
Wood planks with paint on timber frame	Polished exposed aggregate concrete - gloss with 100 mm infill	Timber board cladding
Wood planks with paint on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Vinyl tiles
Wood planks with paint on timber frame	Porcelain tiles 800 × 800 mm on cement mortar screed	Water based paint on 10 mm thick cement mortar screed with white putty
Wood planks with paint on timber frame	Polished exposed aggregate concrete - gloss with 100 mm infill	Water based paint on 10 mm thick cement mortar screed with white putty
Wood planks with paint on timber frame	Terracotta tiles 10 mm thick cement mortar screed	Timber board cladding
Wood planks with paint on timber frame	Ceramic tiling on 10 mm thick cement mortar screed	Vinyl tiles
Minimising life cycle material cost		
Wood planks with paint on timber frame	Ceramic tiling on 10 mm thick cement mortar screed	Vinyl tiles

Wood planks with paint on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Water based paint on 10 mm thick cement mortar screed with white putty
Wood planks with paint on timber frame	Polished exposed aggregate concrete - gloss with 100 mm infill	Water based paint on 10 mm thick cement mortar screed with white putty
Wood planks with paint on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Vinyl tiles
Wood planks with paint on timber frame	Polished exposed aggregate concrete - gloss with 100 mm infill	Vinyl tiles
Wood planks with paint on timber frame	Ceramic tiling on 10 mm thick cement mortar screed	Timber board cladding
Wood planks with paint on timber frame	Porcelain tiles 800 × 800 mm on cement mortar screed	Water based paint on 10 mm thick cement mortar screed with white putty
Wood planks with paint on timber frame	Porcelain tiles 800 × 800 mm on cement mortar screed	Vinyl tiles
Wood planks with paint on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Timber board cladding
Wood planks with paint on timber frame	Polished exposed aggregate concrete - gloss with 100 mm infill	Timber board cladding

APPENDIX 15

Appendix 15-E shows the combinations of assemblies achieving different objectives in food supply shops. This appendix is referred in Sections 7.3.1.5, 7.3.3, 8.4 and 9.4.

Internal wall	Wall finish	Floor finish	Ceiling finish
Optimal: Minimising life cycle embodied energy and life cycle material cost			
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Minimising life cycle embodied energy			
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Wood planks with paint on timber frame
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Wood planks with paint on timber frame
Calcium Silicate brickwork (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles

Calcium Silicate brickwork (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Wood planks with paint on timber frame
Brick walls (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Minimising life cycle material cost			
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Linoleum sheets with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on metal frame

APPENDIX 15

Appendix 15-F shows the combinations of assemblies achieving different objectives in household shops. This appendix is referred in Sections 7.3.1.5, 7.3.3, 8.4 and 9.4.

Internal wall	Wall finish	Floor finish	Ceiling finish
Optimal: Minimising life cycle embodied energy and life cycle material cost			
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Minimising life cycle embodied energy			
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Wood planks with paint on timber frame
Calcium Silicate brickwork (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles

Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Wood planks with paint on timber frame
Brick walls (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Block walls (140mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Minimising life cycle material cost			
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame

APPENDIX 15

Appendix 15-G shows the combinations of assemblies achieving different objectives in gym shops. This appendix is referred in Sections 7.3.1.5, 7.3.3, 8.4 and 9.4.

Internal wall	Wall finish	Floor finish	Ceiling finish
Optimal: Minimising life cycle embodied energy and life cycle material cost			
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Minimising life cycle embodied energy			
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Calcium Silicate brickwork (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Calcium Silicate brickwork (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Brick walls (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame

Block walls (140 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Brick walls (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Block walls (140 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Minimising life cycle material cost			
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on metal frame

APPENDIX 15

Appendix 15-H shows the combinations of assemblies achieving different objectives in leisure and entertainment shops. This appendix is referred in Sections 7.3.1.5, 7.3.3, 8.4 and 9.4.

Internal wall	Wall finish	Floor finish	Ceiling finish
Optimal: Minimising life cycle embodied energy and life cycle material cost			
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
Minimising life cycle embodied energy			
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Wood planks with paint on timber frame
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Wood planks with paint on timber frame

Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Wood planks with paint on timber frame
Calcium Silicate brickwork (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Block walls (140 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Minimising life cycle material cost			
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on metal frame
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame

APPENDIX 15

Appendix 15 - I shows the combinations of assemblies achieving different objectives in health and beauty shops. This appendix is referred in Sections 7.3.1.5, 7.3.3, 8.4 and 9.4.

Internal wall	Wall finish	Floor finish	Ceiling finish
Optimal: Minimising life cycle embodied energy and life cycle material cost			
Timber stud walls (90 × 45 mm)	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Minimising life cycle embodied energy			
Timber stud walls (90 × 45 mm)	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Steel stud walls (welded)	Bamboo panels on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles

Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Timber stud walls (90 × 45 mm)	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Wood planks with paint on timber frame
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Wood planks with paint on timber frame
Timber stud walls (90 × 45 mm)	Bamboo panels on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Minimising life cycle material cost			
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame

APPENDIX 15

Appendix 15 - J shows the combinations of assemblies achieving different objectives in café and restaurant shops. This appendix is referred in Sections 7.3.1.5, 7.3.3, 8.4 and 9.4.

Internal wall	Wall finish	Floor finish	Ceiling finish
Optimal: Minimising life cycle embodied energy and life cycle material cost			
Calcium Silicate brickwork (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Minimising life cycle embodied energy			
Timber stud walls (90 × 45 mm)	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles

Steel stud walls (welded)	Bamboo panels on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Timber stud walls (90 × 45 mm)	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Wood planks with paint on timber frame
Timber stud walls (90 × 45 mm)	Bamboo panels on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Steel stud walls (welded)	Bamboo panels on timber frame	Terrazzo with 100 mm infill slab 20 MPa	Wood planks with paint on timber frame
Brick walls (110 mm)	Timber board cladding	Terrazzo with 100 mm infill slab 20 MPa	Wood planks with paint on timber frame
Minimising life cycle material cost			
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on timber frame

Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame

APPENDIX 15

Appendix 15 - K shows the combinations of assemblies achieving different objectives in shoes and accessories shops. This appendix is referred in Sections 7.3.1.5, 7.3.3, 8.4 and 9.4.

Internal wall	Wall finish	Floor finish	Ceiling finish
Optimal: Minimising life cycle embodied energy and life cycle material cost			
Timber stud walls (90 × 45 mm)	Timber board cladding	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Timber board cladding	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Minimising life cycle embodied energy			
Timber stud walls (90 × 45 mm)	Timber board cladding	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Timber stud walls (90 × 45 mm)	Timber board cladding	Laminated timber	Metal frame ceiling with Cork tiles
Steel stud walls (welded)	Bamboo panels on timber frame	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles

Steel stud walls (welded)	Bamboo panels on timber frame	Laminated timber	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Timber board cladding	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Timber stud walls (90 × 45 mm)	Timber board cladding	Cork boards with water barrier underlay	Wood planks with paint on timber frame
Brick walls (110 mm)	Timber board cladding	Laminated timber	Metal frame ceiling with Cork tiles
Timber stud walls (90 × 45 mm)	Timber board cladding	Bamboo planks	Metal frame ceiling with Cork tiles
Timber stud walls (90 × 45 mm)	Timber board cladding	Laminated timber	Wood planks with paint on timber frame
Gypsum block wall (100 mm)	Timber board cladding	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Minimising life cycle material cost			
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on metal frame

APPENDIX 15

Appendix 15 - L shows the combinations of assemblies achieving different objectives in services shops. This appendix is referred in Sections 7.3.1.5, 7.3.3, 8.4 and 9.4.

Internal wall	Wall finish	Floor finish	Ceiling finish
Optimal: Minimising life cycle embodied energy and life cycle material cost			
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Metal frame ceiling with Cork tiles
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Minimising life cycle embodied energy			
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles

Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Wood planks with paint on timber frame
Calcium Silicate brickwork (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Calcium Silicate brickwork (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Wood planks with paint on timber frame
Brick walls (110 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Brick walls (110 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Block walls (140mm)	10 mm thick cement mortar screed with white putty	Terrazzo with 100 mm infill slab 20 MPa	Metal frame ceiling with Cork tiles
Minimising life cycle material cost			
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on timber frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Ceramic tiling on 10 mm thick cement mortar screed	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame

Gypsum block wall (100 mm)	Water based paint on 10 mm thick cement mortar screed with white putty	Cork boards with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	Oil based paint on 10 mm thick cement mortar screed with white putty	Vinyl planks with water barrier underlay	Plasterboard lining with paint on metal frame
Gypsum block wall (100 mm)	10 mm thick cement mortar screed with white putty	Rubber carpet with double sided tape	Plasterboard lining with paint on timber frame

APPENDIX 16

Appendix 16 presents the benchmark values of different shop types in shopping centres.

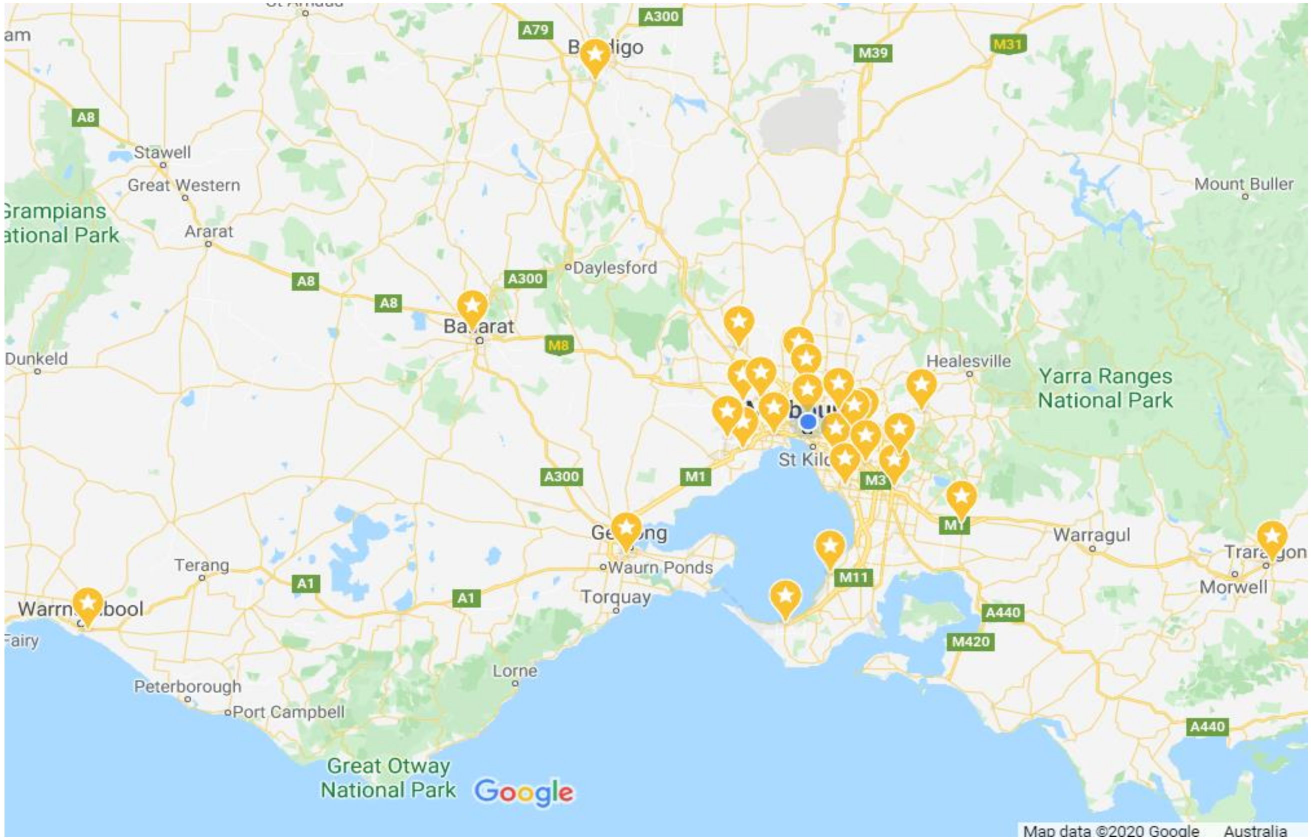
Shop type	Benchmark (Average and range)	LCEE (GJ/m²)	LCMC (AU$/m²)	LCEGHGE (tonne CO_2e/m²)	LCMCWT (AU$/m²)
Clothing	Average	23.86	1,665.34	1.40	3,304.45
	Lower	11.39	653.90	0.67	1,872.96
	Upper	50.94	3,925.91	2.99	6,103.63
Food supply	Average	20.54	988.33	1.21	2,399.55
	Lower	10.80	608.18	0.63	1,429.82
	Upper	32.76	1,639.05	1.93	3,464.52
Household	Average	22.11	1,159.89	1.30	2,678.83
	Lower	9.88	581.40	0.58	1,329.65
	Upper	37.31	2,692.15	2.19	4,738.01
Gymnasium	Average	19.13	810.14	1.12	2,124.23
	Lower	14.29	610.28	0.84	1,609.62
	Upper	26.73	1,684.73	1.57	3,432.28
Leisure and entertainment	Average	16.53	1,264.29	0.97	2,400.16
	Lower	7.06	691.59	0.42	1,423.77
	Upper	26.94	2,021.98	1.58	3,466.27
Health and beauty	Average	22.76	1,603.99	1.34	3,167.79
	Lower	4.76	604.81	0.28	1,177.71
	Upper	57.34	4,384.37	3.37	6,757.38
Café and restaurant	Average	21.35	1,618.72	1.25	3,085.45
	Lower	5.19	639.78	0.31	1,314.61
	Upper	53.87	3,891.06	3.17	5,891.50
Shoes	Average	24.95	1,666.71	1.47	3,380.68
	Lower	12.88	713.72	0.76	1,835.98
	Upper	48.20	3,714.77	2.83	5,802.56

Services	Average	20.91	1,304.24	1.23	2,740.55
	Lower	5.38	621.77	0.32	1,241.13
	Upper	38.03	2,740.88	2.24	4,825.93
Supermarkets	Average	5.04	467.35	0.30	813.38
	Lower	2.29	268.33	0.13	473.81
	Upper	9.18	813.52	0.54	1,388.34
Discount department store	Average	4.72	385.36	0.28	709.33
	Lower	2.23	248.81	0.13	449.60
	Upper	8.21	596.27	0.48	1,136.43
Common area	Average	6.09	779.14	0.36	1,197.26
	Lower	2.24	526.96	0.13	766.39
	Upper	13.66	1,263.19	0.80	1,963.34
Centre structure	Average	10.19	1,084.99	0.60	1,784.78
	Lower	7.80	982.67	0.46	1,533.01
	Upper	14.52	1,252.61	0.85	2,183.61

LCEE: Life cycle embodied energy; LCMC: Life cycle material cost; LCEGHGE: Life cycle embodied greenhouse gas emission; LCMCWT: Life cycle material cost with carbon tax

APPENDIX 17

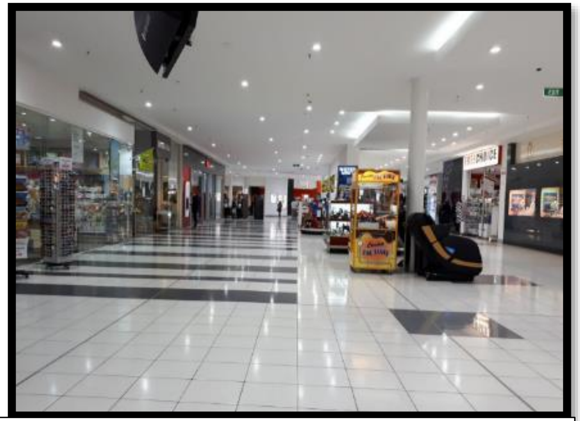
Appendix 17 presents the location map of subregional shopping centres selected for on-site observations.



Source: (Google, 2020b)

APPENDIX 18

Appendix 18 presents the photographs of a few observed sites and a few sample drawings and specifications of the projects.



Picture 1: 21/11/2017

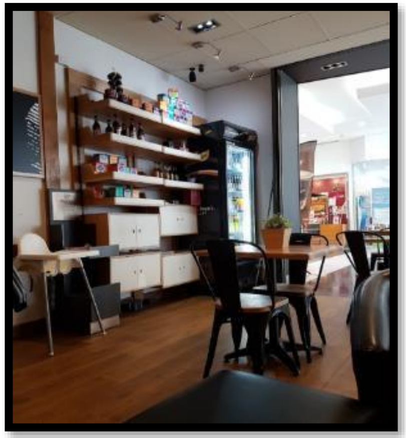
Picture 2: 13/1/2018

Picture 3: 13/1/2018

Picture 4: 20/4/2018

Picture 5: 13/1/2018

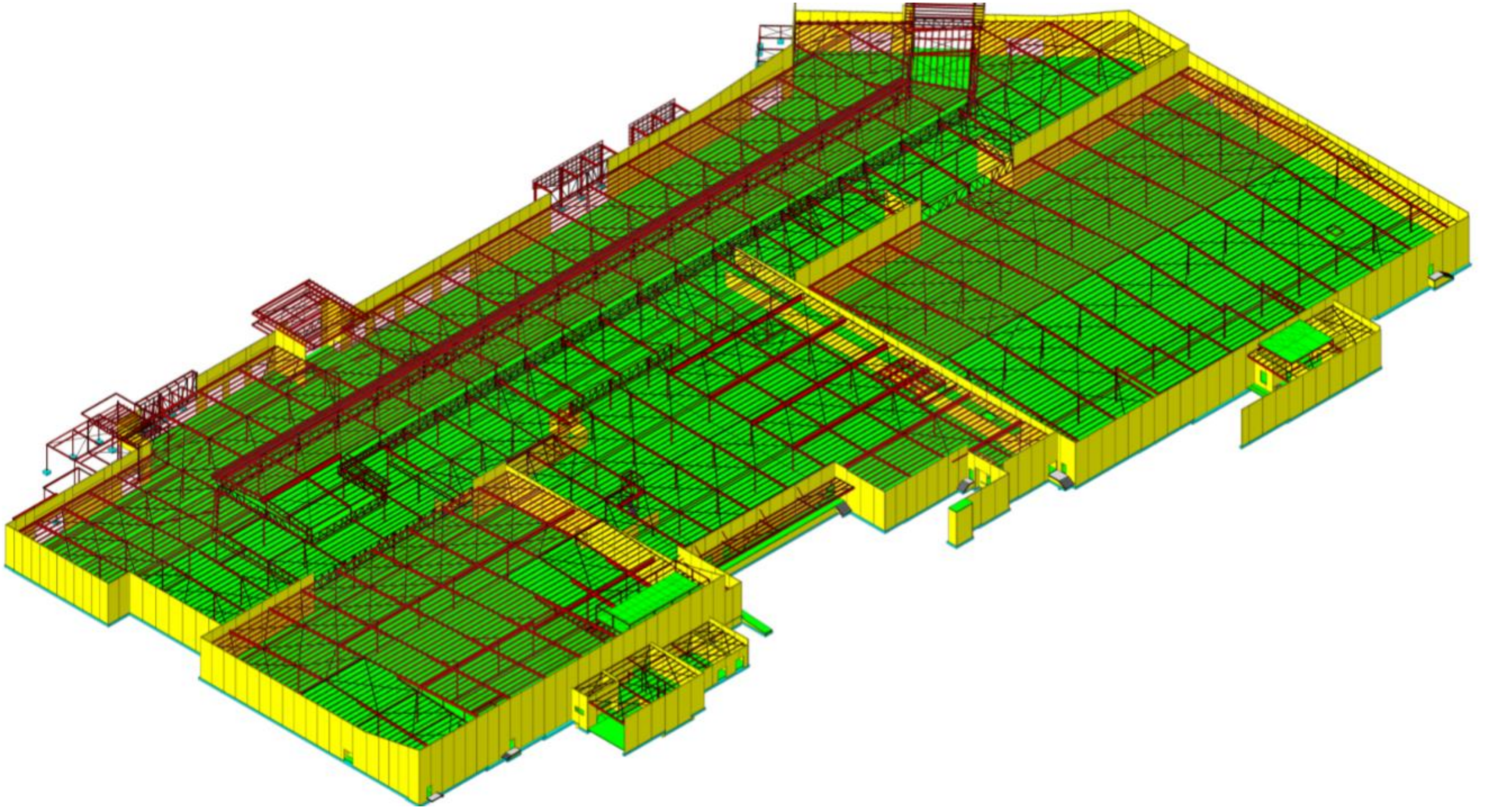
Picture 6: 20/4/2018	Picture 7: 4/6/2018



Picture 8: 20/4/2018	Picture 9: 4/6/2018	Picture 10: 4/6/2018

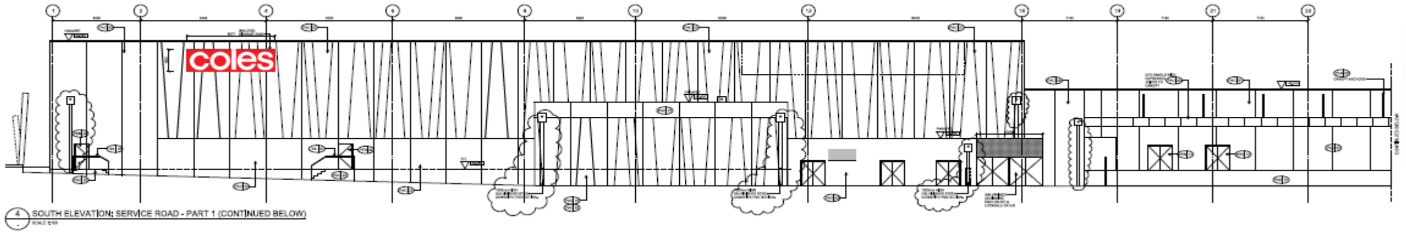
Source: Observations on-sites

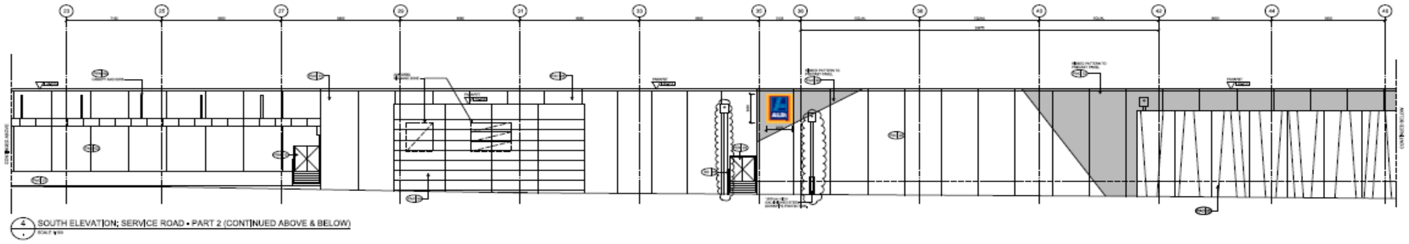
Overall plan of Case 1 shopping centre

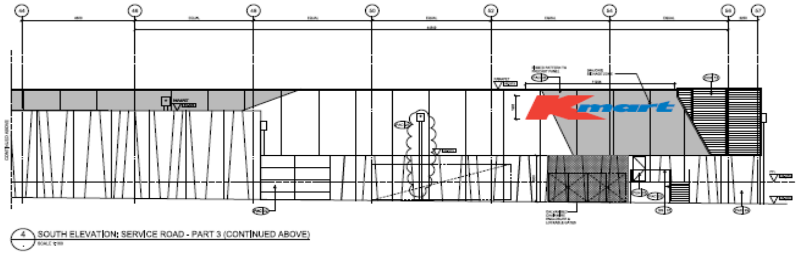


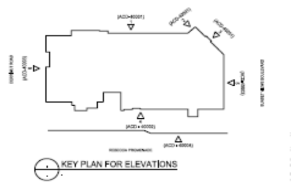
Source: Case 1 project documents

Elevations









Source: Project documents

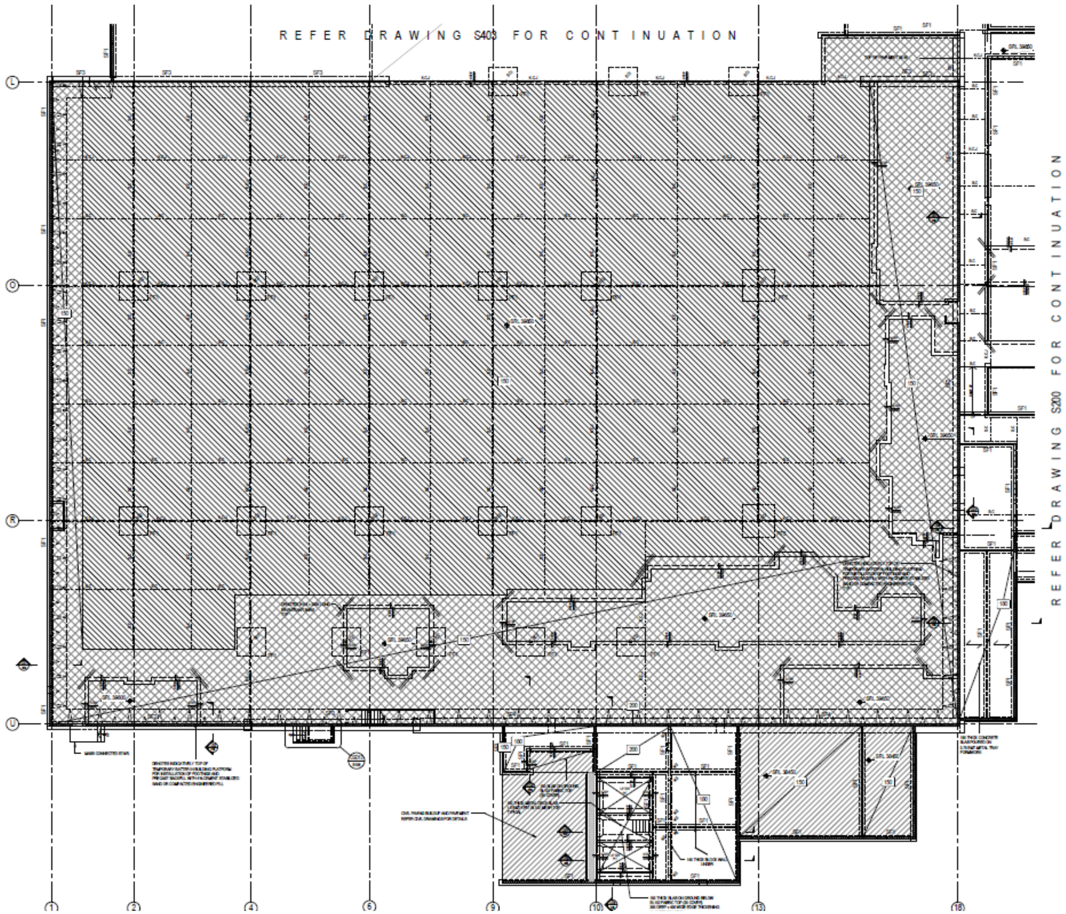
Material specifications

CODE	ELEMENT / RANGE / COLOUR	SIZE / FINISH	SUPPLIER	GENERAL NOTES	REV	BY
AAC	AUTOCLAVED AERATED CONCRETE	Refer Specification Sections:	03300 - CONCRETE & CONCRETE FINISHES			
AAC-01						
AAC-02						
AAC-03						
ACR	ACRYLIC	Refer Specification Sections:	08800 - GLAZING & GLAZED ROOFS			
ACR-01						
AL	ALUMINIUM	Refer Specification Sections:	08800 - GLAZING & GLAZED ROOFS (Windowframes) 09100 - STUD WALLS & PARTNS (Skirtings)			
AL-01	Element: Shopfront Glazing Range: Capral 419 Flushline (150)	Size : 150 Finish; Powder Coated	Supplier: Capral C: Catherine Pitliangas Ph: (03) 93153781 M: 0448 300 120	Location: Refer to Elevations		
AN	ANODISED FINISH	Refer Specification Sections:	05500 - FABRICATED METALWORK			
AN-01	Anodised - Natural			Aldi: Shopfront Entry Roller Shutter		
AT	ACOUSTIC TILE	Refer Specification Sections:	09500 - CEILINGS & SOFFITS			
AT-01						
BL	BLOCKWORK - Refer to Drawing's Cover Sheet	Refer Specification Sections:	04200 - MASONRY			
BR	BRICKWORK - Refer to Drawing's Cover Sheet	Refer Specification Sections:	04200 - MASONRY			
CAM	COMPOSITE ALUMINIUM MATERIAL	Refer Specification Sections:	07500 - CLADDING			
CAM-01	Element: Canopy Fascias & Cladding Range: Alucobond Plus Colour: TBA Code: TBA		Supplier: Alucobond C: Marie Alessi Ph: (03) 9394 3130 M: 0418 929 886	Location: Refer to Elevations for location & extent		
CAM-02	Element: Canopy Fascias & Cladding Range: Alucobond Plus Colour: TBA Code: TBA		Supplier: Alucobond C: Marie Alessi Ph: (03) 9394 3130 M: 0418 929 886	Location: Refer to Elevations for location & extent		
CAM-03	Element: Canopy Fascias & Cladding Range: Alucobond Plus Colour: TBA Code: TBA		Supplier: Alucobond C: Marie Alessi Ph: (03) 9394 3130 M: 0418 929 886	Location: Refer to Elevations for location & extent		
CAM-04	Element: Canopy Fascias & Cladding Range: Alucobond Plus Colour: TBA Code: TBA		Supplier: Alucobond C: Marie Alessi Ph: (03) 9394 3130 M: 0418 929 886	Location: Refer to Elevations for location & extent		
CFC	COMPRESSED FIBRE-CEMENT	Refer Specification Sections:	07500 - CLADDING			

CODE	ELEMENT / RANGE / COLOUR	SIZE / FINISH	SUPPLIER	GENERAL NOTES	REV	BY
CFC-01	Element: Soffit Lining & Fascia Range: Villaboard Lining	Size: 9mm, paint finish	Supplier: James Hardie C: Florent Hostein Ph: 13 11 03 M: 0404 482 361	Location: Soffit lining & fascia Refer to Drawings for location and extent		
COB	COLOURBOND-FINISHED STEEL	Refer Specification Sections:	07400 - METAL ROOFING			
COB-01	Element: Coles Roof Range: Kingspan 100mm KS1000RW Colour: TBA Code: TBA		Supplier: Kingspan C: Mark Playdon Ph: (02) 8889 30000 M: 0420 414 844	Location: Coles Roof		
COB-10	Element: Façade Cladding Range: Lysaght Custom Orb Accent 21 Colour: TBA Code: TBA	Finish: Colorbond	Supplier: Bluescope Steel C: Paul Hogan Ph: 1800 022 999 M: 0404 482 361	Location: Refer to Elevations for location & extent		
COB-11	Element: Façade Cladding Range: Lysaght Custom Orb Accent 21 Colour: TBA Code: TBA	Finish: Colorbond	Supplier: Bluescope Steel C: Paul Hogan Ph: 1800 022 999 M: 0404 482 361	Location: Refer to Elevations for location & extent		
COB-12	Element: Façade Cladding Range: Lysaght Spandek Colour: TBA Code: TBA	Finish: Colorbond	Supplier: Bluescope Steel C: Paul Hogan Ph: 1800 022 999 M: 0404 482 361	Location: Refer to Elevations for location & extent		
CPT	CARPET	Refer Specification Sections:	09680 - CARPET			
CPT-01	Element: Carpet Tile Range: Long Grain Colour : Storm Grey Code: 770	500x500 complete with cushion bac	Supplier: Godfrey Hirst C: Jodi Beare-Uberman PH: 03 9368 8100 M: 0412 016 301	Location: Centre Management Office		
GL	GLASS	Refer Specification Sections:	08800 - WINDOWS & GLAZING			
GL-01	6mm Perfroma Tech 206 Toughened/12mm Argon/8.38mm V-lam Clear	U-Value 2.7 SHGC 0.31	Viridian 1800 810 403	Location: North, North East, North West & West Façade Shopfront Glazing		
GL-02	6mm Sunergy Clear Toughened/12mm Argon/8.38mm V-Lam grey	U-Value 3.1 SHGC 0.44	Viridian 1800 810 403	Location: Skylights		
GL-03	6mm V-Float Clear Toughened		Viridian 1800 810 403	Location: Signage Areas		
GL-04	Single-Glazing Clear Laminated 10.38mm Toughened Safety Glass		Viridian 1800 810 403	Aldi Shopfront & Centre Management		
FAB	FABRICS	Refer Specification Sections:	12300 - FABRICS & UPHOSLTERY			
FAB-51	Element:Parents Room Feeding Alcove Range: Cosmic Colour: TBA	Finish: Code:	Mac Textiles T: 03 93498888	Install with Curtain Track supplied by Silent Gliss. 6350 Chord Operated Track.	T02	RL
LAM	LAMINATE	Refer Specification Sections:	06400 - JOINERY			

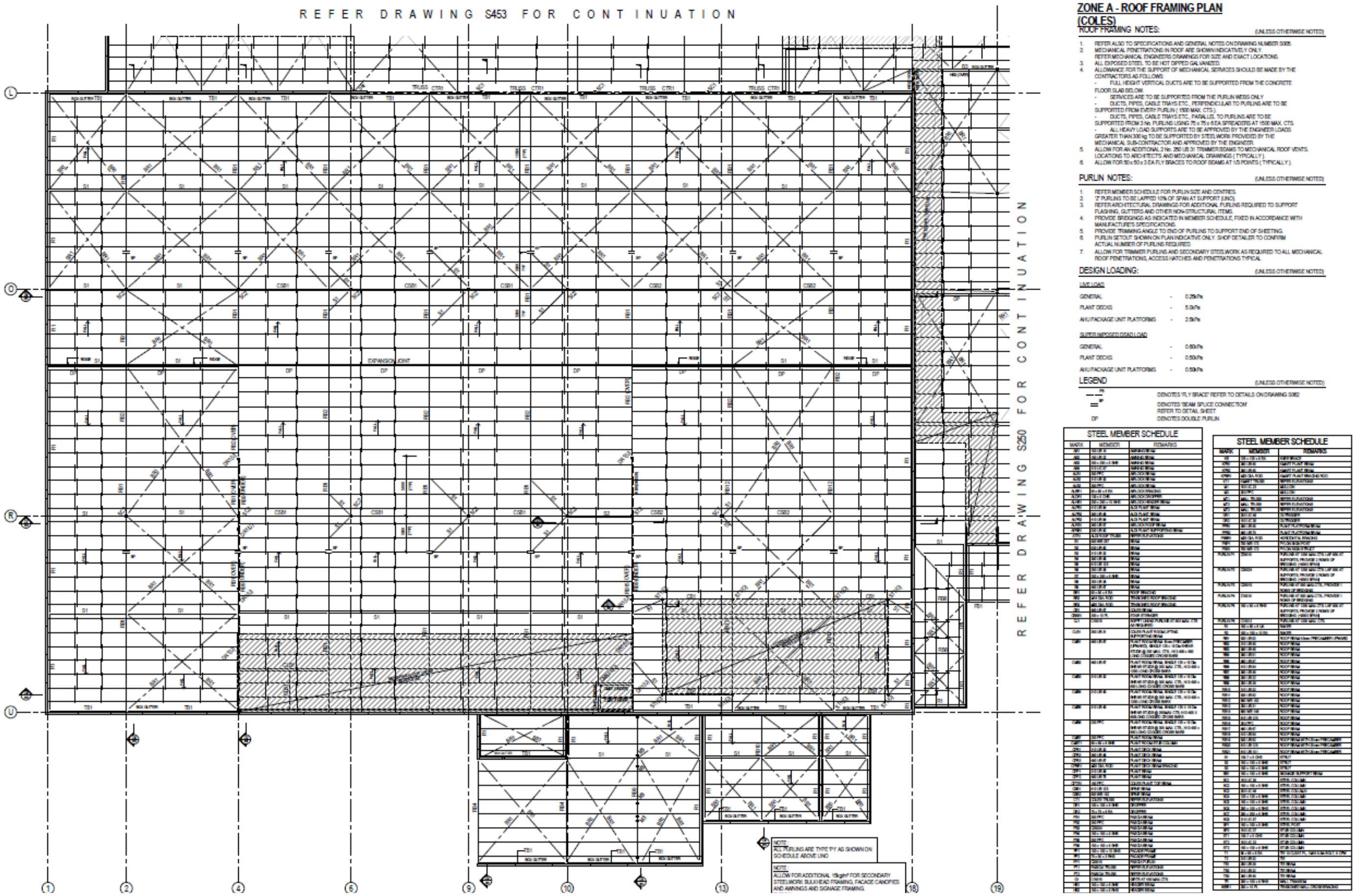
Source: Project documents

Structural plans of slabs



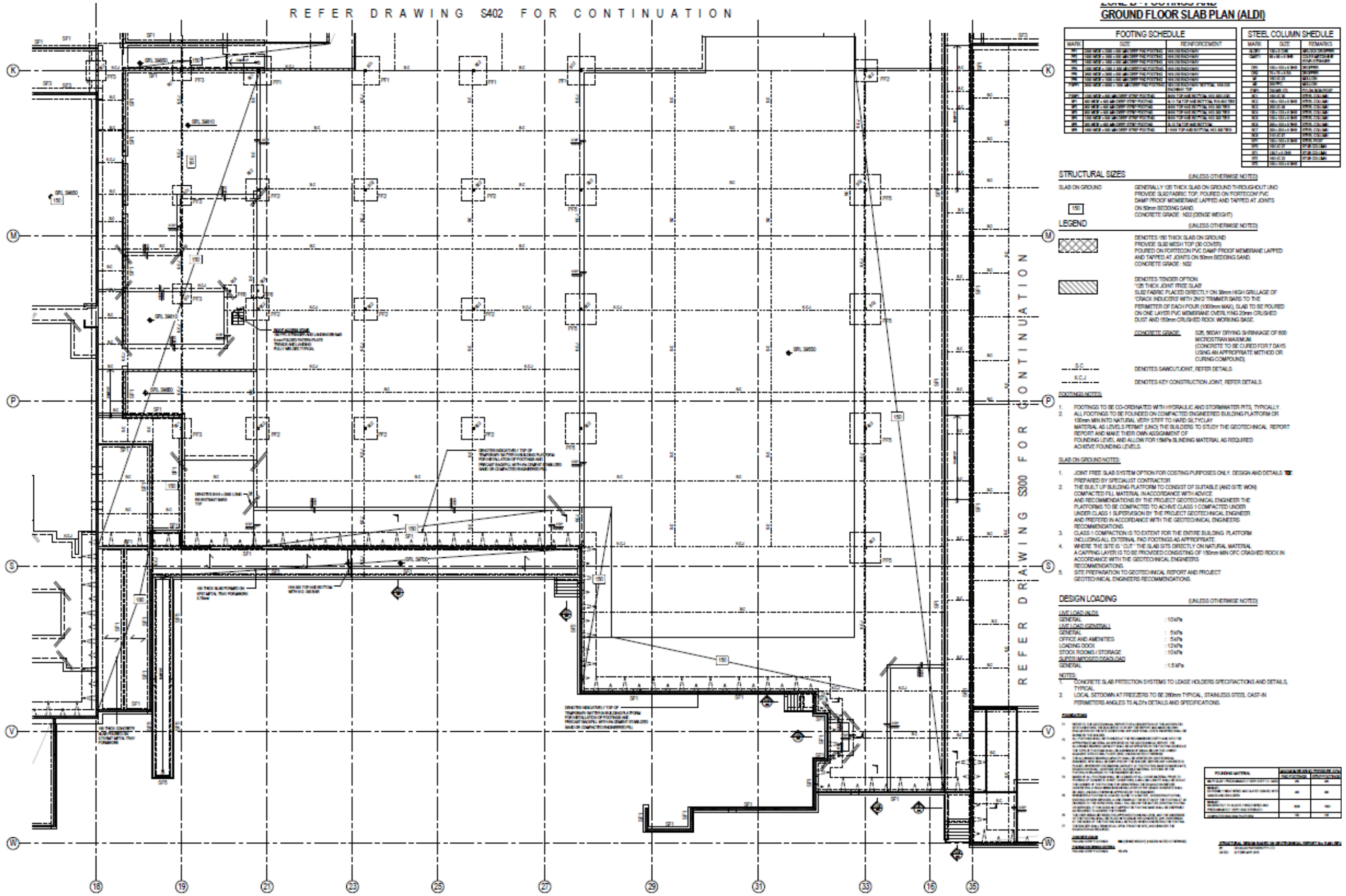
Source: Project documents

Structural plans of roof structure



Source: Project documents

Structural plans of footings and ground slab



Source: Project documents

APPENDIX 19

Appendix 19 presents a sample of the directory of shopping centres published by Property Council of Australia.

	A	B	C	J	K	V	Z	AP	AQ	AR	AS	AT	AU	A
1	Centre Name	Type	SCD-Region	Suburb	Stat	Centre Owner	Management-Co-Name	No-Major-Tenan	Major-Tenants-GL	No-Specialty-Stor	Specialty-Lev	Specialty-GLAR	Total-Centre-GLAR	Retail Vacar
46	Vermont South Shopping Centre	Sub Regional	Melbourne	Vermont South	VIC	Strata Plan (24525A)	StrataPrime Pty Ltd	2	6,662	41	1	3,979	10,741	
59	Sunbury Square Shopping Centre	Sub Regional	Melbourne	Sunbury	VIC	Sunbury Shopping Centre Pty Ltd	Orbach Group	3	6,147	37	1	4,858	11,105	
72	Mornington Shopping Centre	Sub Regional	Melbourne	Mornington	VIC	Vicinity Centres	Vicinity Centres	0	0	36	1	11,781	11,781	
85	Warringal Shopping Centre	Sub Regional	Melbourne	Heidelberg	VIC	Newside Pty Ltd	PRPT	3	6,926	34	1	3,801	10,927	
103	North Blackburn Shopping Centre	Sub Regional	Melbourne	Blackburn	VIC	Australian Unity Property Syndicate	Savills	3	6,844	47	1	4,301	11,402	
149	Horsham Plaza	Sub Regional	Wimmera	Horsham	VIC	Chesed 18 Pty Ltd	Retpro Group Pty Ltd	4	10,281	27	1	2,345	12,698	
209	Milleara Shopping Centre	Sub Regional	Melbourne	East Keilor	VIC	Lygon Property Group	Liuzzi Property Group	2	4,676	33	1	6,531	11,579	
296	Oakleigh Central	Sub Regional	Melbourne	Oakleigh	VIC	Vicinity Centres	Vicinity Centres	0	0	44	1	13,939	13,939	
301	Carnegie Central	Sub Regional	Melbourne	Carnegie	VIC	Glenwaye Pty Ltd	Richard O'Brien Associates	4	11,102	17	2	2,509	14,019	
304	Belmont Shopping Village	Sub Regional	Barwon	Belmont	VIC	Undisclosed Private Investor	Colliers International	0	0	17	1	14,034	14,034	
351	Armada Gateway Plaza	Sub Regional	Western District	Warrnambool	VIC	Australian Executor Trustees	Retpro Group Pty Ltd	4	11,244	26	1	2,543	13,952	
365	Box Hill Shopping Centre (North)	Sub Regional	Melbourne	Box Hill	VIC	Vicinity Centres	Vicinity Centres	0	0	84	2	14,599	14,599	
411	Pakenham Place Shopping Centre	Sub Regional	Melbourne	Pakenham	VIC	QICGRE	QICGRE	3	12,405	16	1	2,465	14,870	
460	Malvern Central	Sub Regional	Melbourne	Malvern	VIC	AMP Capital Investors (UniSuper)	AMP Capital Shopping Centres Pty Ltd	2	10,637	47	2	4,611	15,358	
478	Sunshine Plaza Shopping Centre	Sub Regional	Melbourne	Sunshine	VIC	328 Hampshire Road Pty Ltd	Colliers International	4	8,103	28	1	3,316	12,658	
484	Wodonga Plaza	Sub Regional	Ovens-Murray	Wodonga	VIC	M Group	M Group	2	9,655	38	1	5,832	15,487	
605	Shepparton Marketplace	Sub Regional	Goulburn	Shepparton	VIC	dexus	dexus	2	11,660	41	1	3,665	15,513	
638	Summerhill Shopping Centre	Sub Regional	Melbourne	Reservoir	VIC	LaSalle BAEV	JLL	3	10,977	33	7	5,330	16,519	
670	Pakenham Central Marketplace	Sub Regional	Melbourne	Pakenham	VIC	SCA Property Group	Colliers International	3	12,311	42	1	4,440	16,794	
678	Bulleen Plaza Shopping Centre	Sub Regional	Melbourne	Bulleen	VIC	Body Corporate	Bulleen Plaza Management	1	2,500	60	2	9,514	12,514	
782	Barkly Square	Sub Regional	Melbourne	Brunswick	VIC	ISPT	JLL	3	12,244	38	1	5,091	17,346	
821	Campbellfield Plaza	Sub Regional	Melbourne	Campbellfield	VIC	Charter Hall Retail REIT	Charter Hall Real Estate Management Services	3	14,422	18	1	3,324	17,906	
834	Moonee Ponds Central	Sub Regional	Melbourne	Moonee Ponds	VIC	Mirvac Property Trust	Mirvac Real Estate Pty Ltd	3	9,949	54	1	3,207	13,595	
848	670 Chapel	Sub Regional	Melbourne	South Yarra	VIC	MTAA	JLL	2	11,908	27	0	5,971	18,176	
881	Ringwood Square Shopping Centre	Sub Regional	Melbourne	Ringwood	VIC	Demi Nominees Pty Ltd	Demi Nominees Pty Ltd	4	14,325	34	1	3,894	18,685	
963	Stockland Traralgon	Sub Regional	Gippsland	Traralgon	VIC	Stockland	Stockland Property Management	1	12,844	56	1	6,743	19,587	
967	Keilor Central	Sub Regional	Melbourne	Keilor Downs	VIC	Fort Street Real Estate Capital	Retpro Group Pty Ltd	0	0	68	1	19,601	19,601	
1008	Kingston Central Plaza	Sub Regional	Melbourne	Mentone	VIC	Goodman	Goodman	8	10,797	13	1	4,744	19,905	
1032	Mildura Central	Sub Regional	Mallee	Mildura	VIC	Vicinity Centres	Vicinity Centres	0	0	69	1	20,315	20,315	
1064	Tarneit Central Shopping Centre	Sub Regional	Melbourne	Tarneit	VIC	Ranfurlie	JLL	3	12,224	42	1	5,517	18,276	
1079	CS Square	Sub Regional	Melbourne	Caroline Springs	VIC	Lend lease	Lendlease Property Management	4	14,654	60	1	2,910	17,564	
1116	Lilydale Marketplace	Sub Regional	Melbourne	Lilydale	VIC	SCA Property Group	Colliers International	4	13,318	49	1	7,075	21,023	
1168	South Melbourne Central	Sub Regional	Melbourne	South Melbourne	VIC	SPG Investments Pty Ltd	Richard O'Brien Associates	1	3,796	27	2	6,875	10,671	
1175	Gippsland Centre	Sub Regional	East Gippsland	Sale	VIC	Alceon Group Pty Ltd	JLL	3	13,902	41	1	6,272	20,321	
1176	Brandon Park	Sub Regional	Melbourne	Wheelers Hill	VIC	Newmark Capital	Newmark Capital	3	11,694	89	2	11,111	22,805	
1185	Mountain Gate Shopping Centre	Sub Regional	Melbourne	Ferntree Gully	VIC	Strata Plan	Abley Real Estate	2	5,024	53	1	13,270	18,894	
1197	Box Hill Shopping Centre (South)	Sub Regional	Melbourne	Box Hill	VIC	Vicinity Centres	Vicinity Centres	0	0	113	1	23,829	23,829	
1199	Lansell Square	Sub Regional	Loddon	Kangaroo Flat	VIC	Charter Hall Retail REIT	Charter Hall Real Estate Management Services	3	14,798	46	1	3,253	18,415	

Cover | Centre Details | Sheet1 | Tenants List (Part 1) | Tenants List (Part 2) | Specialties List

Source: Property Council of Australia (2017)

APPENDIX 20

Appendix 20 presents the subdivided figures of 7.2 and 7.3 for clarity as mentioned in Sections 7.2.2 and 7.2.3.

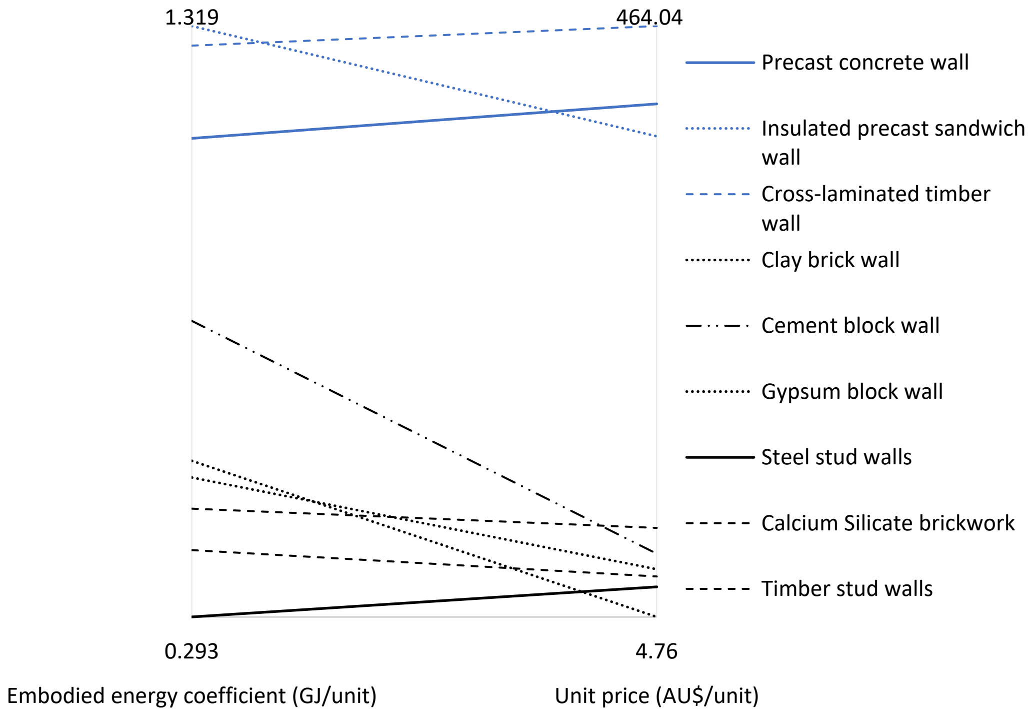


Figure 7.2 A: Parallel coordinates graph of embodied energy coefficients and unit prices of structural envelope assemblies

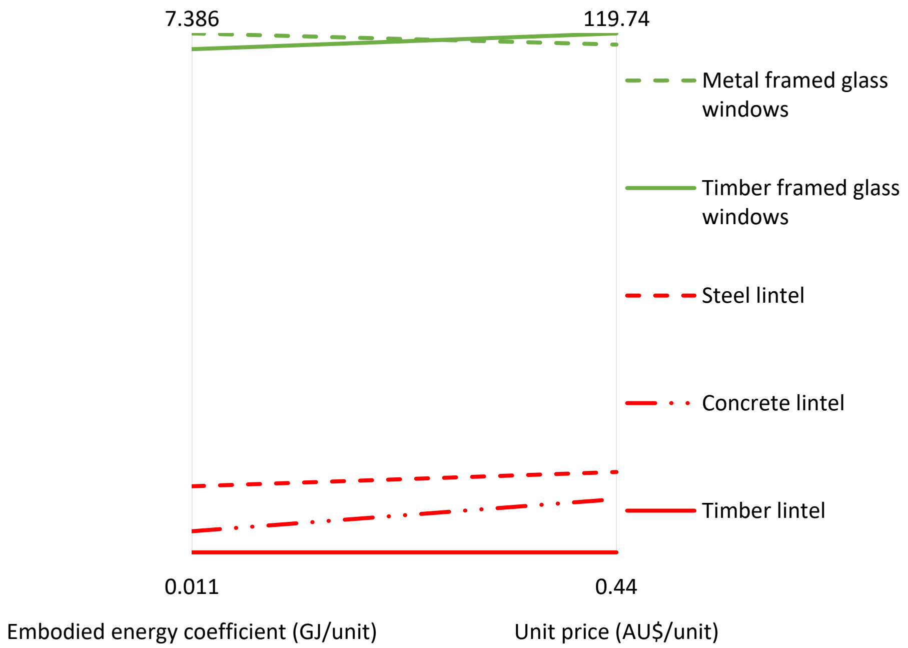


Figure 7.2 B: Parallel coordinates graph of embodied energy coefficients and unit prices of non-structural envelope assemblies

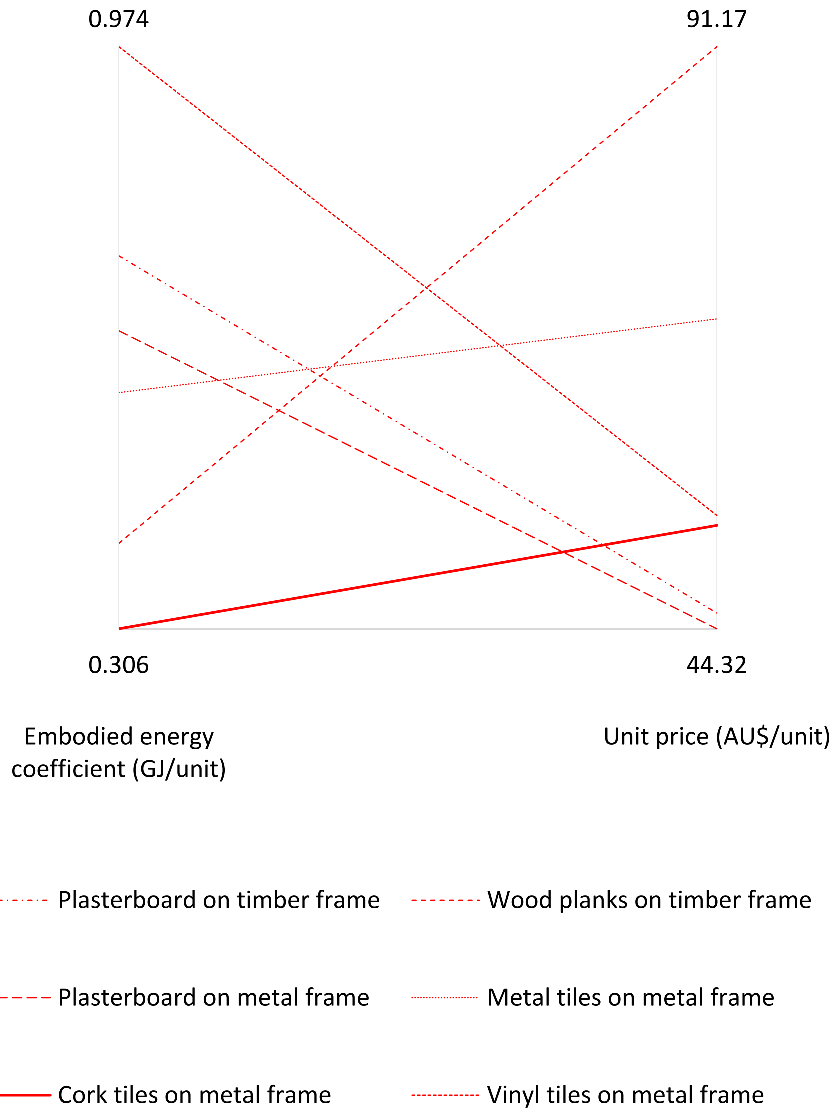


Figure 7.3 A: Parallel coordinates graph of embodied energy coefficients and unit prices of ceiling finishes assemblies

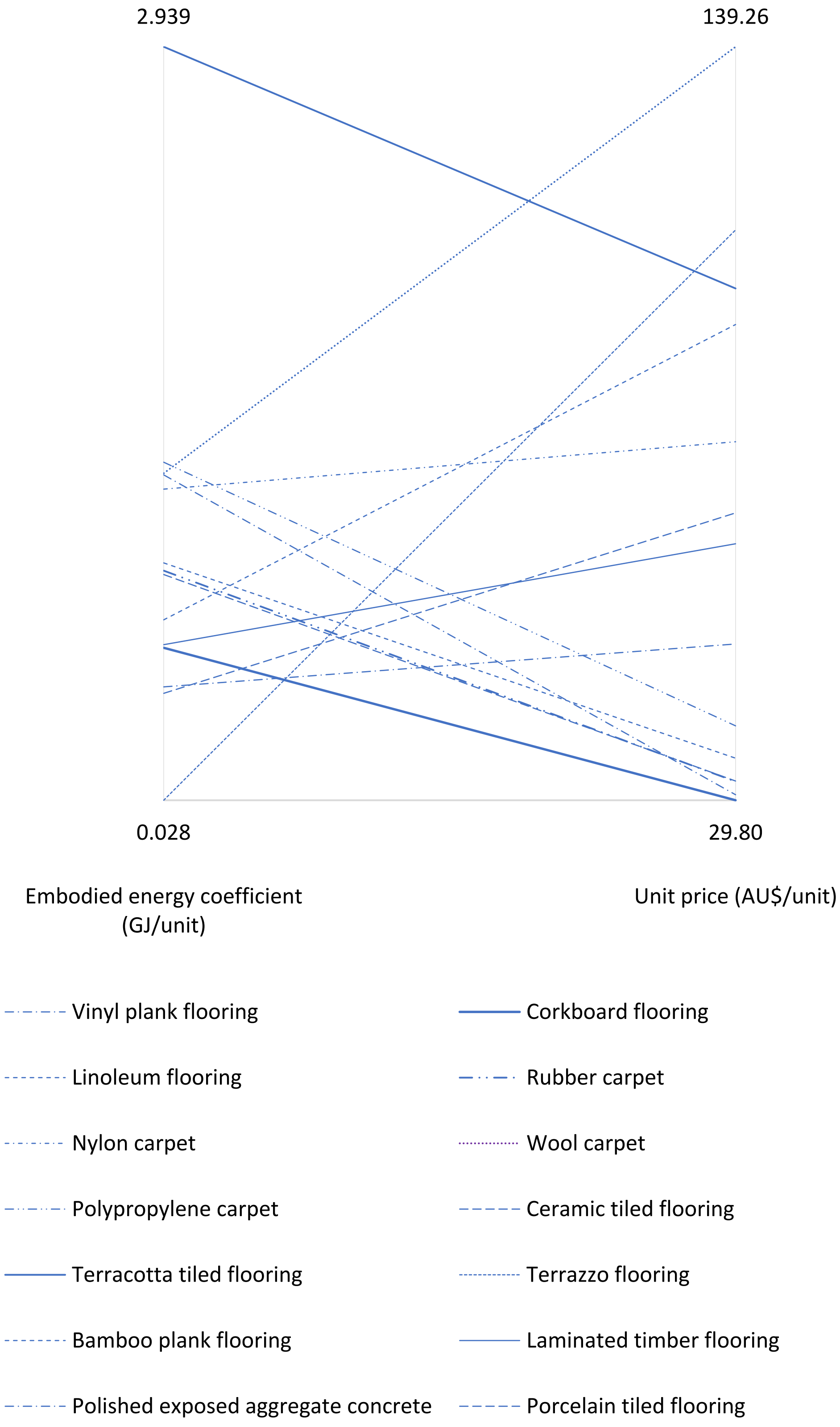


Figure 7.3 B: Parallel coordinates graph of embodied energy coefficients and unit prices of floor finishes assemblies

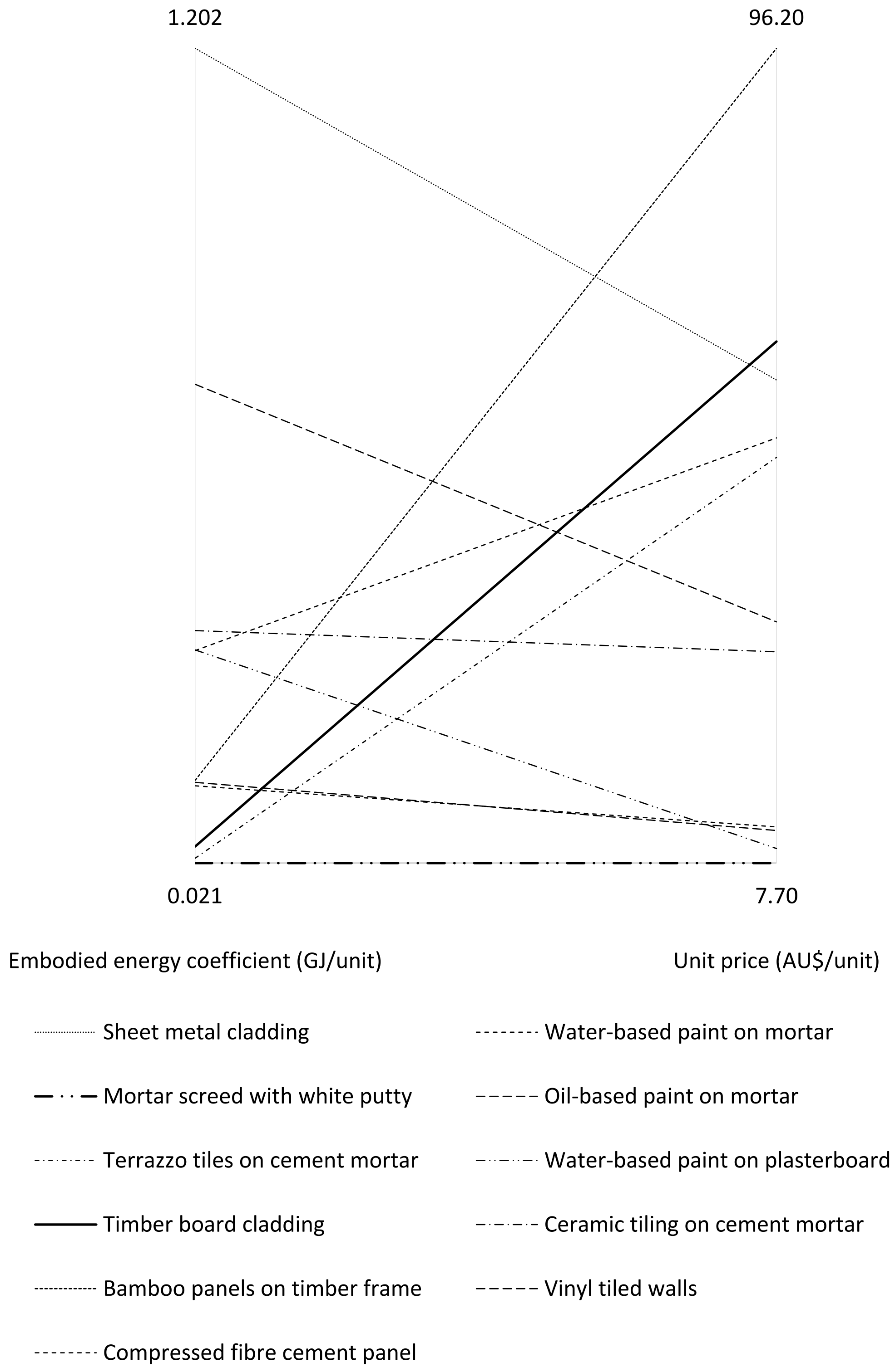


Figure 7.3 C: Parallel coordinates graph of embodied energy coefficients and unit prices of wall finishes assemblies

Author/s:
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Title:
Assessment of life cycle embodied energy and material cost in Australian shopping centres: Implications for material selection

Date:
2020