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Abstract: As growth regions evolve to accommodate the increasing population, they need to develop a wider variety of residential properties to accommodate the varying needs of the residents. As a result, the new accommodation is denser which involves higher embodied water carbon and energy. This research compares the construction differences in metropolitan and growth regions of Melbourne to identify embodied carbon, water, and energy. Representative areas of 25 km^2 are selected from both regions. The growth region has 80% of the built area comprised of 2nd generation low-rise residential buildings whereas the prolific construction type in the Metropolitan region is mixed purpose industrial with 30% of the built area comprising of this type. The methodology implies open-source satellite imagery to build a spatial dataset in QGIS. The visual identification of the constructions in the study areas enables to identity the materials used in their construction. The total embodied carbon, water, and energy for the Metropolitan region are 32,895 tonnes, 4192 mL, and 3,694,412 GJ, respectively, whereas in the growth region, the totals are 179,376 tonnes carbon, 2533 mL water, and 2,243,571 GJ. Whilst Metropolitan has a significantly higher overall footprint when this is compared to the population of each region, it is shown that the growth region with its current construction type has a higher embodied carbon, water, and energy per head. The total per head for Metropolitan is 226.7 GJ energy, 257 kL water, and 20 tonnes carbon, whereas in the growth region, the embodied energy, water, and carbon, respectively, per head is 287.4 GJ, 324.6 kL, and 22 tonnes. The current performance per head of the growth region is considerably lower than that of Metropolitan. Using diverse residential construction types and efficient materials can serve the demanding needs of denser populated areas.

Keywords: urban planning; water footprint; embodied energy; carbon footprint; building construction; environmental attribute

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1. Introduction

Rapid urbanization and industrialization have created severe environmental challenges [1]. The challenge of achieving sustainable urban development also involves addressing additional factors such as energy consumption and water use [2]. Due to the increasing demand for energy conservation and reduction of greenhouse gas emissions, it is necessary to study the various causes of water and energy consumption in new buildings [3]. Buildings and construction account for a significant portion of the global energy consumption. Greenhouse gas emissions associated with these activities are mainly responsible for the combustion of fossil fuels and the transportation of materials [4]. The energy consumption and greenhouse gas emissions associated with the construction and renovation of buildings are directly related to the various phases of their construction [5]. It is therefore important that the construction industry should carefully plan and manage projects [6].

The construction sector is a critical driver in the global economy with some accounts placing its value at over $17 trillion annually as of 2019 [7]. The most prolific materials used within this sector are widely accepted to be concrete, timber, steel, and masonry [8]. In addition to the economic cost of these materials, there are embodied quantities attributed to energy, water, and carbon dioxide. The importance of managing these resources is becoming more profound as population pressure increases, placing a greater strain on natural resources and a subsequent increase in embodied quantities which can be detrimental to the environment.

Remote sensing is employed to overcome obstacles presented by in-person site visits and enables a larger area to be documented for a variety of purposes. It has been used to assess land erosion in New Mexico with great effect as well as to analyze urban sprawl and how land-use has changed within a region [9–11]. This research uses optical and satellite imagery to facilitate data gathering to better understand how embodied environmental attributes are used in construction.

Timber has been used in construction for many years and is now in a position to be used for larger-scale projects with the advancement of technologies in this space [12]. Although it is replenishable, it has been questioned as to whether it is as environmentally sound as initially thought. One element of this is the water required to grow the product, which is why a water-stressed nation such as Australia is of increased significance [13]. The embodied water of timber products has been documented for this study.

This research draws inspiration from water footprint analysis which offers a framework to calculate the embodied water within materials [14,15]. The water footprint is often used over large land areas which have been instrumental in calculating total water use in the agricultural and industrial sectors [16,17]. The framework has been applied at a smaller scale to identify water within steel and concrete production; but this has shown that there is often significant variation in the quantities of embodied water by region [18–20]. Research performed by Crawford, Stephan, and Prideaux has led to the creation of an extensive database of construction materials that are Australian-centered [21]. This database offers an opportunity to calculate embodied quantities but is limited by not having access to detailed costs of materials for construction projects. Research by De Wolf et al. into embodied carbon has led to a database that considers the material quantity by building type and area [22,23]. By interpreting these databases with the input of built areas, it is possible to gain an insight into embodied environmental factors for Melbourne and Werribee, which is considered as a typical growth community.

Identification of building types is the most critical task for estimating environmental attributes in the construction work. In addition, estimating the embodied quantities of environmental attributes in different building types is not easy; the use of modern techniques to speed up the identification, calculation, and estimation processes is inevitable. Sun et. al. and Ogawa et al. [24,25] successfully utilized GIS to identify building footprints in a large-scale urban area using TerraSAR-X High Resolution SpotLight image. In a similar way, Chen et al. [26] used 2D images collected by an unmanned ariel vehicle to identify the façade of a building without going into 3D. Even publicly available images have already been used for building classification using various building shape indices [27].

In a country like Australia, where significant rainfall reductions are observed due to climate change, the sensible use of water is mandatory [28]. Over the last century, Australia has experienced a steady warming trend that is consistent with global trends [29]. Climate change is expected to make these impacts more severe [30]. It also triggers further increases in frequency and severity of these impacts. Climate change is also expected to increase the stress on Australia's water resource systems in the following decades. In the longer term, it could lead to a reduction in the amount of rainfall that is available for the whole continent [31].

In addition, most of Australia's major cities will experience significant population growth within the next couple of decades. To meet these needs, various water sources will be needed. Cities and regions will require careful management of their water sources [32,33]. The IPCC emphasized that the carbon reductions needed to avoid dangerous climate change are due by now. One way to do so is by reducing the emissions from demolition and construction [12].

2. Literature Review

To derive a suitable methodology, an extensive literature review was performed. Water footprint analysis provides the starting point with the initial goal to calculate embodied water for primary construction materials of steel, timber, and concrete in Victoria. Research performed in China and India shows the regional variation of the water footprint in steel production, where the water footprint is 6.26 m^3/t for India and 6.39 m^3/t for China [34,35]. This led to a further investigation into how embodied water can vary in timber production [36]. Concrete's prevalence in construction globally is an interesting structural material as embodied water can change significantly based on the mix design and the decision to include fly ash or other additives. For the water footprint of concrete, two mix designs are compared, and despite having the same quantity of water added directly, there is significant variation once all elements are considered [19]. Both mix designs in this resource are 40 MPa and 45 MPa, with a water footprint of 987 L/t and 962 L/t.

The carbon footprint is increased too, owing to the increased energy requirements of making the raw materials. Although high-performance concrete is available, it is not as ubiquitous as lower stress concrete as used in most construction. By including the water footprint of energy production into the initial objective, it is possible to consider a broader spectrum of study and embrace carbon and energy into an analysis of embodied quantities for construction materials. Fortunately, research into these embodied quantities has been performed and has resulted in the Environmental Performance in Construction database (EPiC Database) [21].

An analysis of the embodied energy of Australian office buildings by height showed that high-rise buildings had 60% more energy embodied across the total floor area when compared to smaller buildings [37]. An embodied energy analysis of a typical Victorian home shows that structural components are the significant contributors to the embodied energy in this realm too, accounting for over 30% of the overall embodied energy in the building [38]. The period of construction is also significant in establishing how the embodied quantities vary, the embodied energy of building materials in houses, and considering embodied energy and carbon in heritage buildings [38]. Until recently, it has been incorrectly assumed that the building's operating energy is higher than that of its embodied energy [23,39]. Embodied and operational energy consumption of cities has been performed, which has indicated that industrial centers have a greater embodied energy per unit area than outer regions [40].

Finding accurate information on the quantities and classifications of buildings is an ongoing challenge without access to the integrated databases of large construction companies. To overcome this limitation, typical building materials for different building types must be evaluated. Luo et al. developed a generalized approach to this by considering the proportion of materials in different buildings by mass [41,42]. Using the varying mass and embodied carbon of each material carbon use per unit area is calculated. The overall mass of a building can be indicative of the types of material that have been used in its construction. Victoria has a diverse range of buildings spanning the years since its colonization by European settlers. Housing and commercial properties from the booming days of Victoria's gold rush still occupy a significant portion of land. While the purpose of some of these buildings has not changed, the appearance and the proportion of materials used to construct them has over time. The visual appearance of these buildings serves to classify them and anecdotal sources have generalized them into three distinct generations of "early days", "interwar and post-war", and "contemporary" [43].

Remote sensing provides a framework for obtaining data for analysis by using satellite imagery amongst other items to gain insights for a region [44]. GIS software provides the perfect opportunity to use this data more appropriately and a variety of different platforms are available [45]. It has been used to monitor how surface temperatures can change as urbanization increases [46,47]. Using remote sensing and GIS insights can be drawn from the world that would otherwise require extensive man-hours and time spent on site. This is manageable for some projects but utterly infeasible for projects of a larger geographic area which can arise when considering a large geographic area [48].

As the development of cities changes, it is important to understand what the implications of that are. This can be used to help drive policy if the outcomes can highlight a clear picture of the positives that can arise from a particular decision [49]. The choice of construction used during urbanization also impacts the environment [50,51]. There is often a significant variation in the embodied quantities in the materials being used in the construction too. The choice of other materials can also have a significant effect and this often changes depending on the fashion of the time when the building has been constructed [52,53].

Parameters that drive different urbanization strategies are again varied [54]. In some areas, high-rise constructions are favored over the low-rise as environmental factors can be better adapted to higher populations using the space [55]. Population density is a key metric when this metric is being considered. Typically, compact regions have a higher population density vs sprawl region. Whilst optimum models have been developed for space planning [54]. Energy use in sprawl areas is shown to be increasing based on current models [56]. This energy is typically involved in HVAC systems and lifecycle energy trends. By modeling the embodied environmental attributes, a level can be added to further assist in policy regarding urban development.

3. Research Objectives

Although there are many studies that study the relationship between carbon and building structures, few studies have focused on the regional disparity in assessing the carbon and energy savings of buildings [57–60]. Embodied carbon and energy calculations have typically focused on very defined building types, whereas water footprint analysis has been able to consider larger areas both spatially and by industry [13]. Every building uses a differing proportion of structural materials to achieve its objectives, which change depending on what society needs at a particular juncture. This can lead to a broad spectrum of construction types, especially with areas that have had a long history of development. This research aims to bridge the gaps in the knowledge about the embodied carbon, energy, and water of the buildings by analyzing the consumptions in construction of metropolitan and growth regions of Melbourne. The research addresses the significant differences between growth region and metropolitan construction within Victoria.

The objective of this research can be summarized as to identify the construction category that can help in accommodating the urbanization of growing Victoria with minimum embodied energy, carbon, and water. The task is accomplished by comparing construction types in a metropolitan and growth region to assess the environmental impact of the predominant materials used. For this purpose, two areas, each 5 km × 5 km in the metropolitan and western growing area, are chosen. These areas are chosen in a way to avoid unnecessary concentration of a particular land use and being representative of the majority of land use types. This research provides an indication of how embodied energy, water, and carbon change as these developments occur. Various aspects are taken into consideration to find the difference between metropolitan and growth region construction. Some of these factors include identification of the purpose of construction, categories of constructions, type and utilization of construction materials, and difference between land-use in metropolitan and growth region areas. By addressing these aspects, it is possible to consider how environmental factors can be better integrated into the construction industry.

Various research has been conducted on embodied energy for typical Victorian homes, high-rise buildings, and commercial buildings [38,41,61]. The existing research focuses on the cost of materials for the constructions being considered, provided by engineering and architectural companies. This research is significant as it utilizes a broad spatial system to document embodied energy, water, and carbon without a specific cost of materials. By considering urbanization categories, links between embodied energy and the choice of method can also be explored, showing relative merits of each. This approach can also show how these embodied quantities are distributed amongst building subtype, per capita, and by unit area. These criteria can then be used for determining the relative merits of each construction and region.

4. Methodology

The methodology designed to achieve the research objectives consists of a selection of representative study areas, spatial analysis, material analysis, and eventually environmental analysis to identify the embodied attributes. The flowchart of the methodology is shown in Figure 1. Further detail of each step is explained in the following sections.

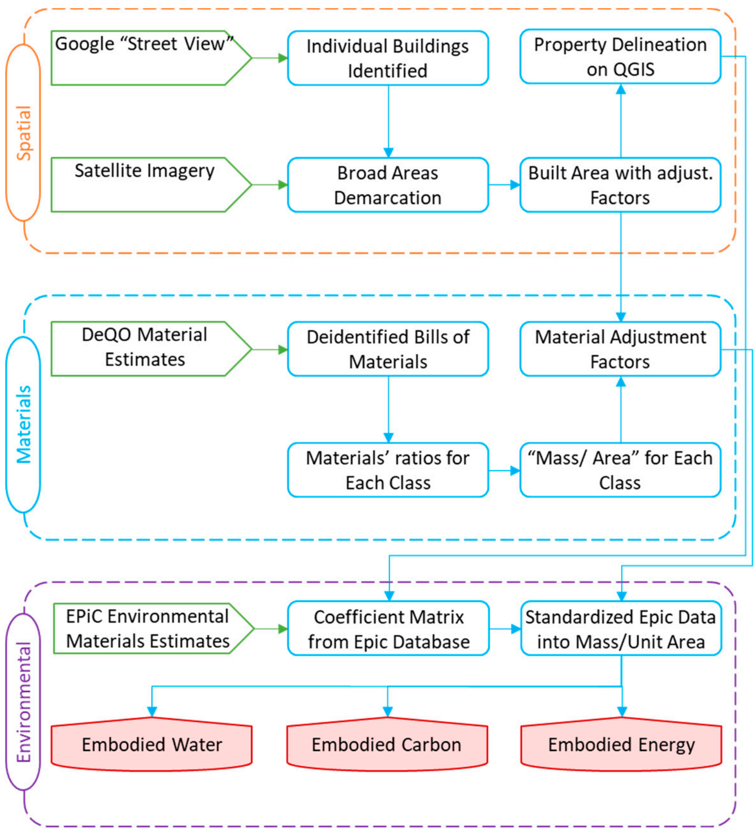

Figure 1. Flowchart showing the methodology adopted in the study. Three main technical sub-categories are prominent including Spatial, Material, and Environmental analysis. Three colors (orange, blue, and purple) are used to show the Spatial, Materials, and Environmental parts of the modeling, while the individual boxes and arrows have three colors showing input data (green), internal processes (blue), and the final output (red).

This research evaluates the embodied carbon, water, and energy for the 25 km^2 region of Victoria. These regions have been chosen as they offer a variety of different land for differing societal needs and can be considered a typical representation of a metropolitan and growing region in Victoria. Both regions are experiencing notable change as older constructions are demolished and new developments arise.

4.1. Spatial Analysis

The methodology heavily relies on the open-source satellite imagery obtained from Google Earth (TruEarth 15-m-per-pixel imagery) to build a spatial dataset in QGIS [60]. Google Street-View is used to identify the individual construction type. Photographs provided are from the remote survey performed or from various online sources. They are featured to illustrate the identifiers used for classification (refer to Appendix A). GIS spatial data are gathered for both the metropolitan and the growth region with key geometries logged in GIS. Once the spatial data is gathered and stored in QGIS, it is possible to utilize the "Database of Embodied Quantity Outputs (DEQO): Lowering Material Impacts Through Engineering" and generate coefficients based on building mass and the program which can be multiplied by the total building area of each category [23].

Outputs (DEQO) are linked to the classifications derived in this research. With this link, it is possible to make assumptions on the mass per unit area of each building classification with a maximum, minimum, mean, upper, and lower quartile reference point. The connection between the Building Code, DEQO program type, and all 28 selected building classifications identified in this research is shown in Table 1.

Table 1. Classification Matrix between Building Codes, DEQO program, and classification used in this research.

Code	Program	DEQO Classification
HCN	High-rise Commercial	Office
HRN	High-rise Residential	Multi Family High-rise (>15)
HR2	High-rise Residential 2nd Generation	Multi Family High-rise (>15)
MC1	Medium-rise Commercial 1st Generation	Residential/Office/Retail
MC2	Medium-rise Commercial 2nd Generation	Residential/Office/Retail
MC3	Medium-rise Commercial 3rd Generation	Residential/Office/Retail
MR2	Medium-rise Residential 2nd Generation	Multifamily-Medium-rise 6–15
MLR1	Medium-rise Residential 1st Generation	Multifamily Low-rise (<5)
MLR2	Medium-rise Residential 2nd Generation	Multifamily Low-rise (<5)
MLR3	Medium-rise Residential 3rd Generation	Multifamily Low-rise (<5)
LC1	Low-rise Commercial 1st Generation	Factories and Plants
LC2	Low-rise Commercial 2nd Generation	Factories and Plants
LC3	Low-rise Commercial 3rd Generation	Factories and Plants
LR1	Low-rise Residential 1st Generation	Single Family
LR2	Low-rise Residential 2nd Generation	Single Family
LR3	Low-rise Residential 3rd Generation	Single Family
SCT	Special Purpose Control Tower	Other
SE3	Special Purpose Educational 3rd Generation	Educational
SEV	Special Purpose Educational Victorian	Educational
SSN	Special Purpose Grain Silo	Other
SIN	Special Purpose Ice Rink	Civic Building

Table 1. *Cont.*

Code	Program	DEQO Classification
SPN	Special Purpose Multistorey Carpark	Other
MIN	Mixed Purpose Industrial	Factories and Plants
SR1	Special Purpose Religious Establishment 1st Generation	Cultural/Institutional
SRE	Special Purpose Religious Establishment	Cultural/Institutional
SSN	Special Purpose Stadium	Stadium
SSL	Special Purpose Stadium Local	Civic Building
NR3	Townhouse 3rd Generation	Single Family

During the remote survey, 1463 buildings for Metropolitan and 940 construction types in the growing region are identified and categorized. The program types are stated on the Database of Embodied Quantities.

Tables 2 and 3 provide the details of perimeters, boundary wall areas, land-use area, and the number of storeys for Metropolitan as well as for the growth area.

Table 2. Summary of building parameters for Metropolitan.

	Sum of Perimeter [m]	Sum of Wall Area [m^2]	Sum of Area [m^2]	Number of Storeys
HCN	2654	134,583	36,685	16.73
HRN	11,037	579,201	130,701	17.26
HR2	309	13,389	2938	14.50
MC1	19,491	19,491	236,579	1.00
MC2	29,877	119,508	506,733	1.00
MC3	19,018	76,072	232,080	1.00
MR2	29,043	141,738	351,980	1.57
MLR1	2001	9708	12,325	1.67
MLR2	46,562	71,113	385,642	1.53
MLR3	1997	19,378	22,547	3.00
LC1	6537	140,406	105,546	6.17
LC2	1750	18,535	17,038	2.92
LC3	6445	119,658	38,611	6.27
LR1	3346	37,704	31,901	3.74
LR2	131	1572	756	4.00
LR3	45	540	124	4.00
SCT	75	2250	333	10.00
SE3	2302	19,857	28,179	2.73
SEV	486	2916	6485	2.00
SSN	89	1602	490	6.00
SIN	421	3789	6997	3.00
SPN	2011	29,211	26,589	5.13
MIN	56,359	322,233	1,119,508	1.98
SR1	363	3993	2101	3.00
SRE	5964	47,607	147,786	3.00
SSN	1628	29,823	53,285	3.67
SSL	791	5385	17,356	2.50
NR3	15,284	115,047	97,134	2.51

Table 3. The summary of spatial data for the growth region.

	Sum of Wall Area [m^2]	Sum of Perimeter [m]	Sum of the Area [m^2]	Number of Storeys
LC2	28,600	4281	52,058	1.59
LC3	76,011	16,945	200,009	1.50
LR1	1,619,442	365,692	8,036,689	1.50
LR2	308,382	72,095	1,171,977	1.44
LR3	888	148	794	2.00
MR2	6288	524	4718	4.00
MC3	1632	272	1289	2.00
SE3	93,939	10,160	223,650	2.96
NR3	1320	220	1325	2.00

To calculate the total material mass for each building classification, along with the breakdown at the material level, the areas are multiplied to the mass densities of each construction material. Figures 2 and 3 show snapshots of how land is used in these regions. Please refer to Appendix A for further information regarding construction type definition and key identifiers.

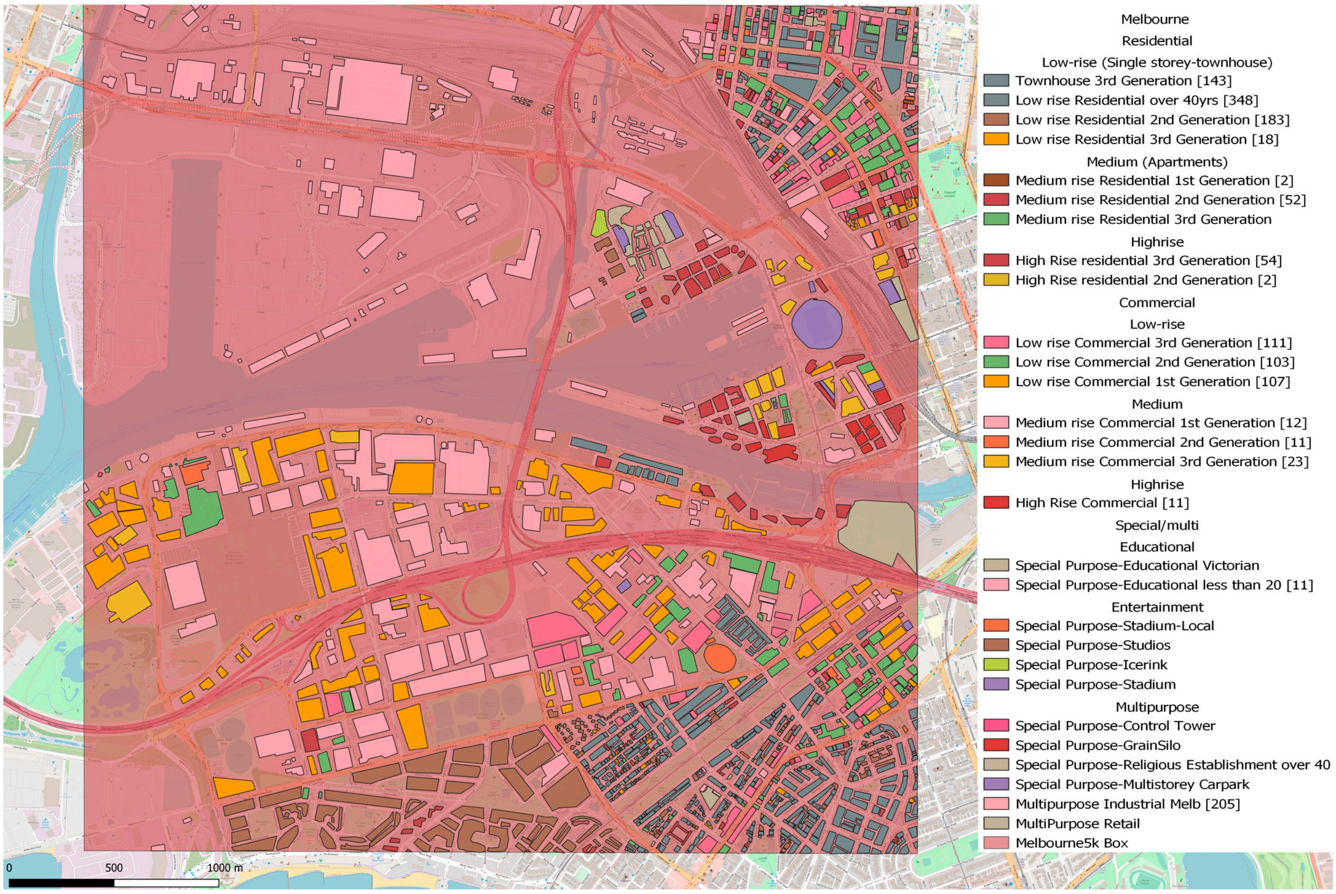

Figure 2. Map showing development, their numbers, and classification in metropolitan Melbourne.

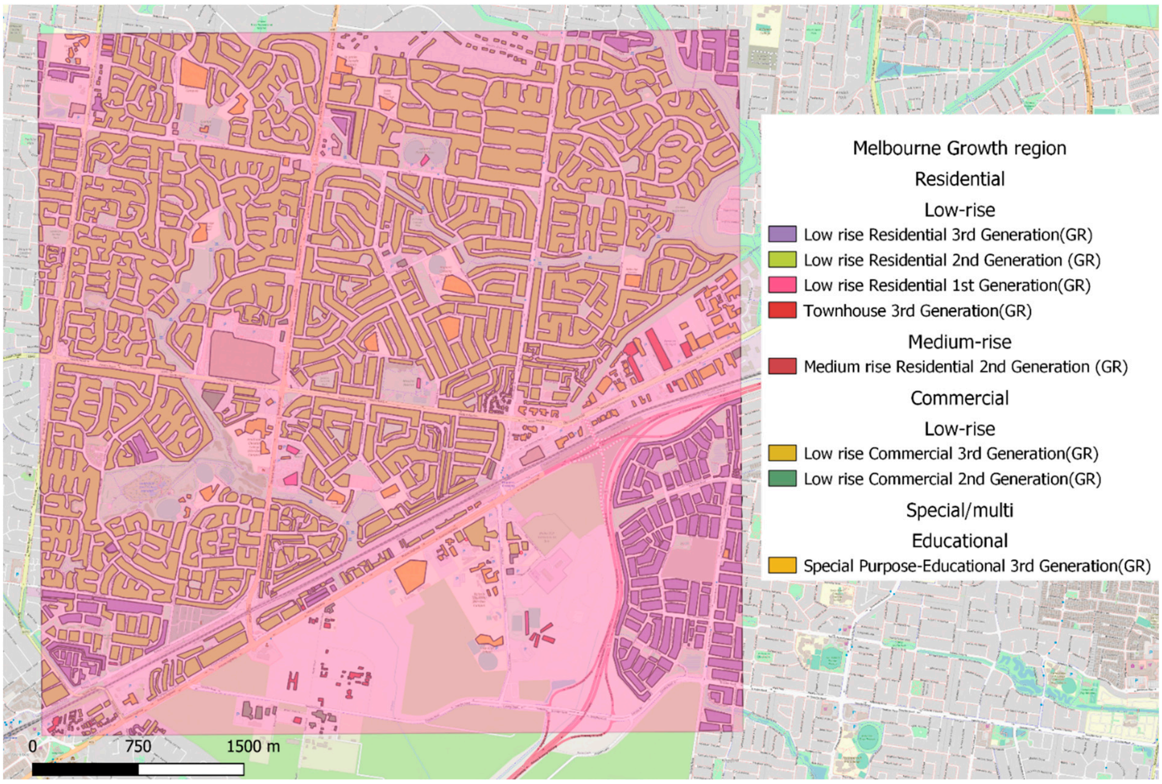

Figure 3. Map showing development and classification in the growth region.

4.2. Material Analysis

It is possible to deidentify the DEQO to find the mass per unit area for structural elements and the overall mass per unit area for different program types (please refer to Figure 4).

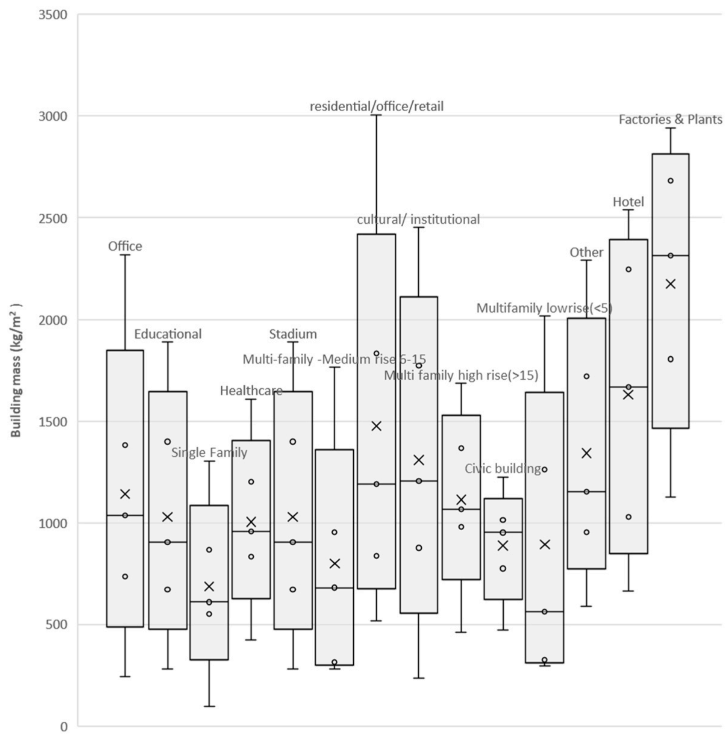

Figure 4. Mass per unit area per program type, where ◦ represents inner points and × shows the mean value (Data source: DEQO [23]).

The same data are used further to find the exact structural components for the buildings. The approach taken in this research is to firstly find the proportions of structural quantities and derive percentages from these. The masses of different materials are obtained in kg per m^2 (please refer to Figure 5).

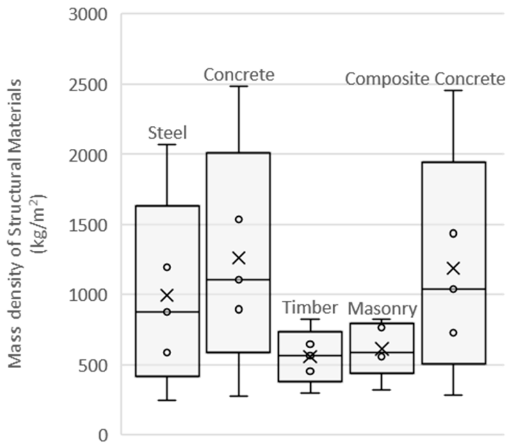

Figure 5. The box-and-whisker diagram is taken from the DEQO, showing the mass per unit area for different structural materials, where ◦ represents inner points and × shows the mean value (Data source: DEQO [23]).

The box-and-whisker plot is converted into percentages based on the summation of corresponding summary statistical points. This is presented in Appendix C.

4.3. Environmrntal Analysis

The visual identification of the constructions in the regions of concern enables to draw conclusions as to their generational identity and materials used in their construction. When identifying each building subtype and using prior assumptions of typical construction, a table of coefficients derived from the Environmental Performance in Construction (EPiC) Database can be built [21]. These assumptions are based on the embodied energy of building materials in houses [38].

The environmental performance in the construction database provides the embodied environmental coefficients required to determine the quantities and composition for both regions. It is an extensive database; however, some of the units are for unit volume or length and are required to be converted into mass units. In addition to this, the breadth of buildings classifications and the array of choice of materials to be used was made based on material research into typical buildings [6,38,42]. From this, it is possible to build a matrix of energy, water, and carbon coefficients which are subsequently multiplied by the calculated mass of each building and their corresponding percentages. One typical example of a high-rise commercial building is shown in Table 4.

4.4. Assumptions and Limitations

This research focuses on the structural components of construction and does not consider the internal fit-out. This has been decided as the internal configuration of a building can vary tremendously, and a one-size-fits-all approach would not be appropriate for the large areas and limited building types being considered.

It has been noted that the DEQO database analysis suggests that there is a considerable proportion by mass of materials that have not been used at the high concentrations as indicated. A modification coefficient has been used to adjust this to reflect the diminished use of composite concrete in low-rise residential construction and timber in high-rise construction.

Table 4. Table showing an excerpt of material assumptions for a high-rise commercial building.

Material Assumptions	Steel	Rebar	Concrete	Timber	Masonry	Composite Concrete
	Hot-Rolled Structural Steel	**Steel ReinForcement Bar —12 mm dia.**	**Concrete 50 MPa**	**Hardwood**	**Concrete Block**	**Concrete 32 MPa**
Embodied Energy (MJ)	38.8	34.5	1.66	15.85	2.6	1.31
Embodied Water (L)	37.1	32.9	1.81	22.22	3.7	1.87
Embodied Greenhouse Gas Emissions (kg CO_2)	2.9	2.6	0.25	1.09	0.24	0.18

Often, with low-rise residential construction and for mixed-purpose industrial construction regions, the built area deviates from the amount of land captured in the remote survey. To overcome this area reduction, factors are found based on a sample of sites measured and ratios calculated for this relationship. These coefficients are shown in Appendix B.

The size of the buildings found in the remote survey has governed the choice of the building mass per unit area that has been used. The DEQO database features buildings over 100 storeys tall, whereas the tallest featured in the survey is 25. Because of this, the mass values chosen are not the maximum values for the material obtained. The assumed mass/unit area used for each building type is shown in Appendix C.

Using the above-stated assumptions and the input data from the remote survey, DEQO and EPiC database embodied environmental attributes for construction are found.

5. Results

The calculations are performed to identify the environmental attributes for spatial distribution of total, material wise, and at building classification levels.

5.1. Spatial Distribution

Despite similar areas of land being used for both study areas, it has been observed that Metropolitan has a broader range of building types compared to the growth region. Based on the building classifications, the constructed land-use area of Metropolitan is 3.6 km^2 and the growth area is 9.7 km^2 after applying the reduction factors. Green areas, roads, water bodies, parks, and all green areas are excluded from the area calculations. The data show that 1st generation low-rise residential (LR1) makes 77% followed by 2nd generation low-rise residential (LR2) making 13% in the growth region. Whereas 26% of land in the Metropolitan survey consists of mixed purpose industrial (MIN), followed by low-rise residential 3rd generation (LR3), low-rise commercial 3rd generation buildings (LC3), and low-rise residential 1st generation (LR1) (refer to Figure 6). During the survey, it is noted that buildings in the metropolitan as well as in growth regions are being redeveloped at a greater rate as the current structures are at the limit of their service life or not suited to the current market needs.

5.2. Embodied Materials

When considering the embodied materials (structural steel, rebars, concrete, composite concrete, masonry concrete, and timber) across each region based on each structural component, it is found that Metropolitan has greater embodied quantities for all components except for timber (refer to Figure 7). This is expected due to the higher quantity of timber used in residential construction compared to the large and dense constructions in the metropolitan region.

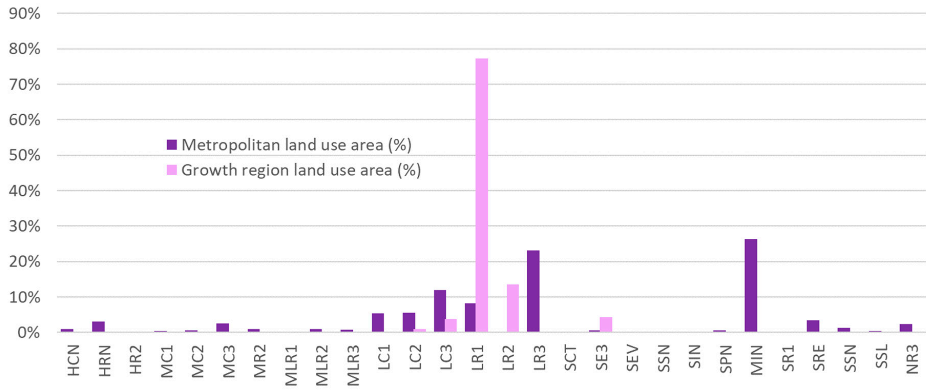

Figure 6. Land-use percentages and building categories in Metropolitan and growth region.

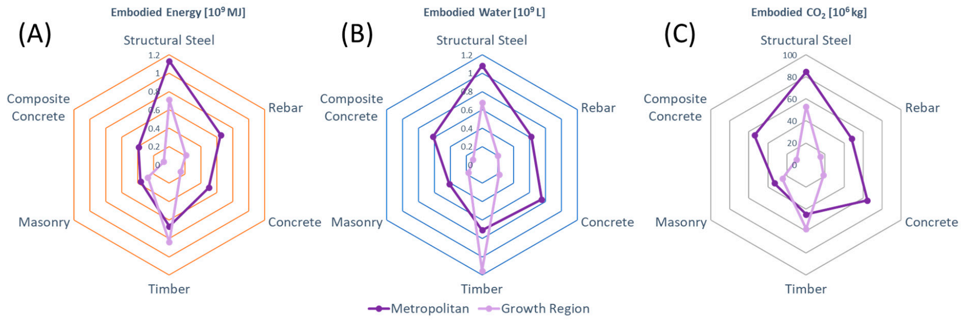

Figure 7. Breakdown of embodied: (**A**) Energy (MJ), (**B**) Water (L), and (**C**) Green gas emission (kg CO_2) by building materials in metropolitan and growth region.

To further analyze the contribution of each building class, an analysis into the embodied quantities by building classification was performed. Based on the DEQO and EPiC database, it is observed that the embodied environmental attributes for the commercial construction classes along with high-rise residential are exceptionally high in the metropolitan region (refer to Figure 8). Additional details are provided in Tables A6 and A7.

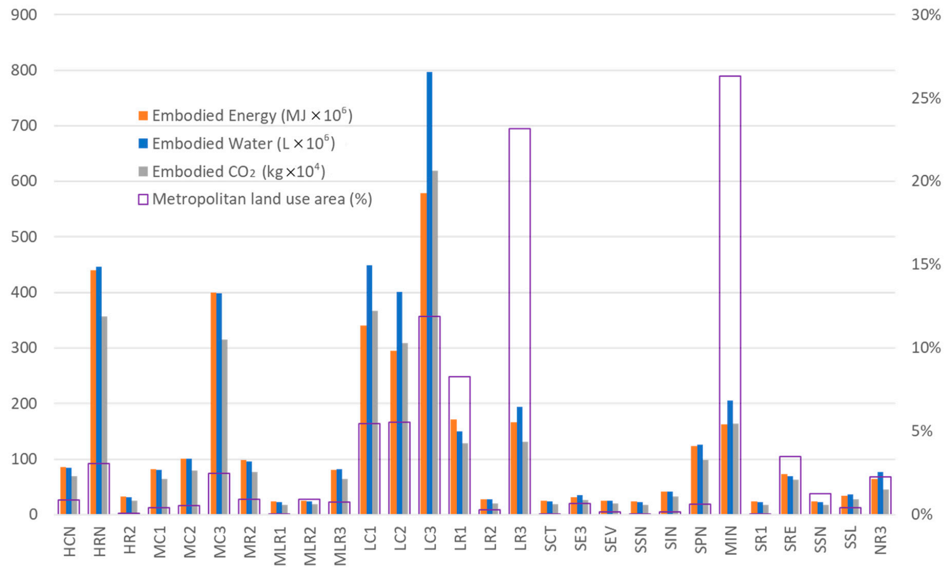

Figure 8. Embodied quantities for each construction subtype with relation to land-use area in Metropolitan.

The regional area shows a balance of residential and commercial construction sharing the environmental attributes, although 77% of the area consists of 1st generation low-rise residential construction (refer to Figure 9).

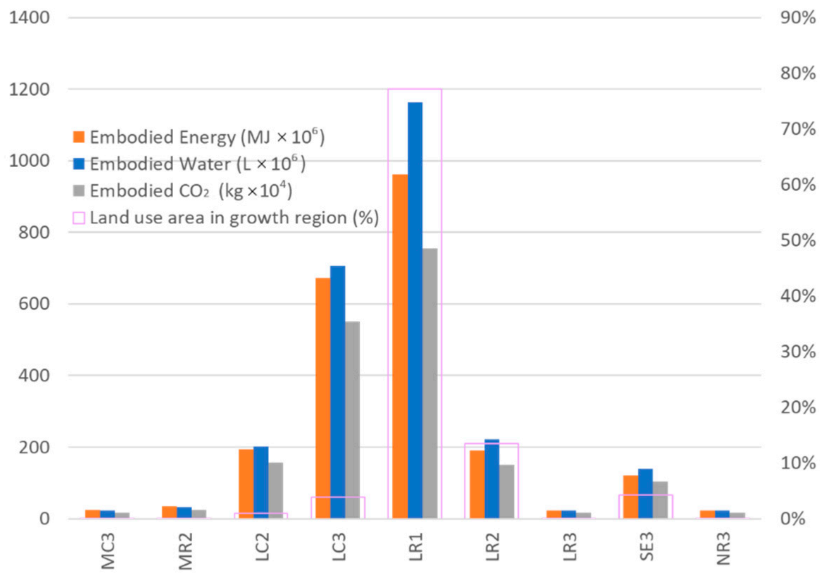

Figure 9. Embodied quantities for each construction subtype with relation to the land-use area in the growth region.

5.3. Densities of Attributes

It is important to investigate the concentrations of environmental attributes over the unfolded area to identify the consumptions per area in both regions. To identify the efficiencies in terms of area-wise, the embodied attributes are divided by the unfolded areas (of multistory buildings). Based on the remote survey, the number of storeys for various building types in both study areas are estimated and shown Figure 10.

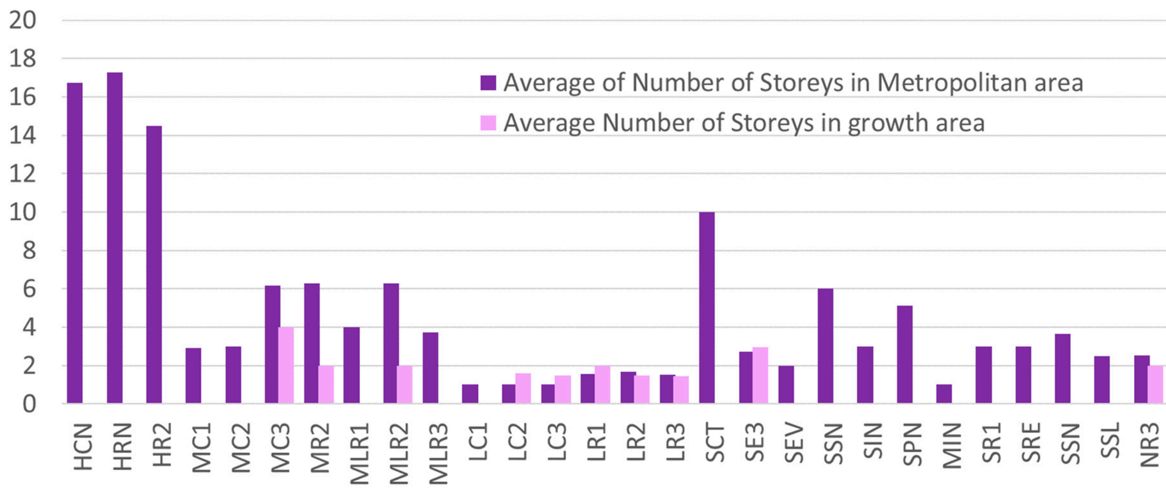

Figure 10. Average number of storeys for different construction classifications in both study areas.

After incorporating the number of storeys for each building class, the unfolded area of Metropolitan is 8.7 km^2 and growth area is 14.8 km^2. The Metropolitan unfolded area increased more than twice due to high-rise residential and commercial areas (HRN and HCN). The unfolded area of Hhgh-rise commercial (HCN) and high-rise residential (HRN) increased multiple times in the Metropolitan area and became among the top four largest unfolded areas. However, the unfolded area in the regional area did not bring differences in proportions of the building classification except a slight increase in ration of special purpose educational 3rd generation (SE3) and slight decrease in 2nd generation low-rise residential (LR2) is hardly noticeable. The resulting areas for each building classification are shown in Figure 11.

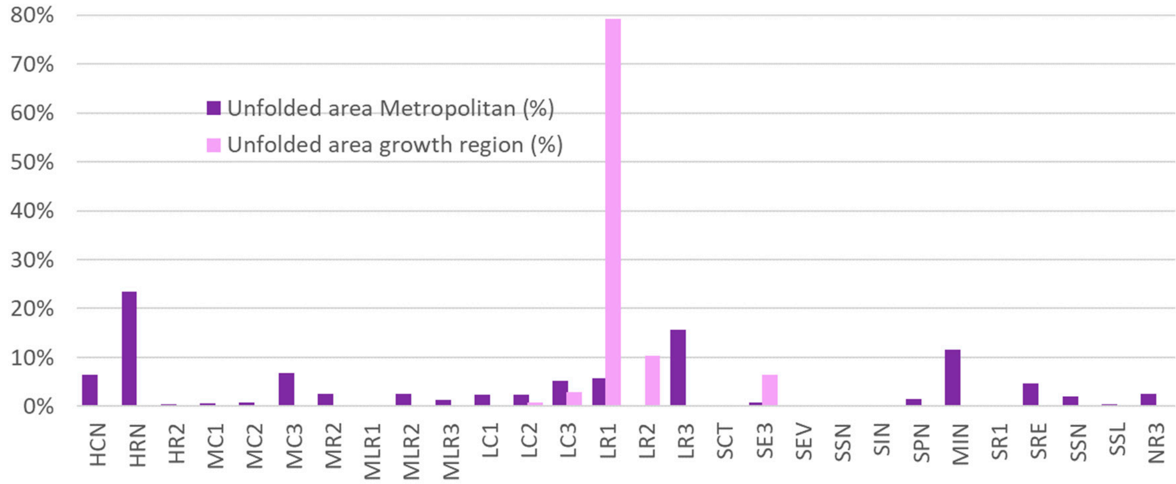

Figure 11. The box-and-whisker diagram is taken from the DEQO, showing the mass per unit area for different structural materials.

Figure 12 indicates that Metropolitan has higher quantities/concentrations for each material compared to the growth region. This shows higher attributes compared to land-use concentrations (refer to Figure 7). This indicates that the range of construction types in Metropolitan has inferior performance than the growth region.

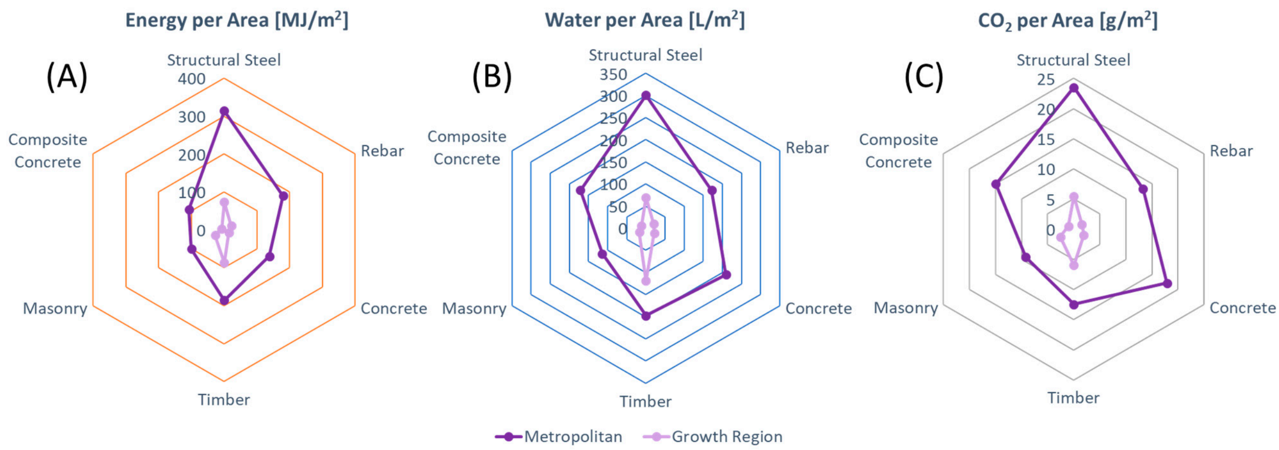

Figure 12. Comparison of (**A**) Embodied Energy (MJ), (**B**) Embodied Water (L), and (**C**) Embodied Greenhouse Gas Emission (kg CO_2) for meteropolitan and growing regions per unit area for the basic construction materials including Structural Steel, Rebar, Structural Concrete, Composite Concrete, Timber, and Masonary.

The outcome shows that high-rise residential properties (HRN) in Metropolitan and 1st generation low-rise residential construction (LR1) in the growth region have the highest embodied attributes (refer to Figures 13 and 14).

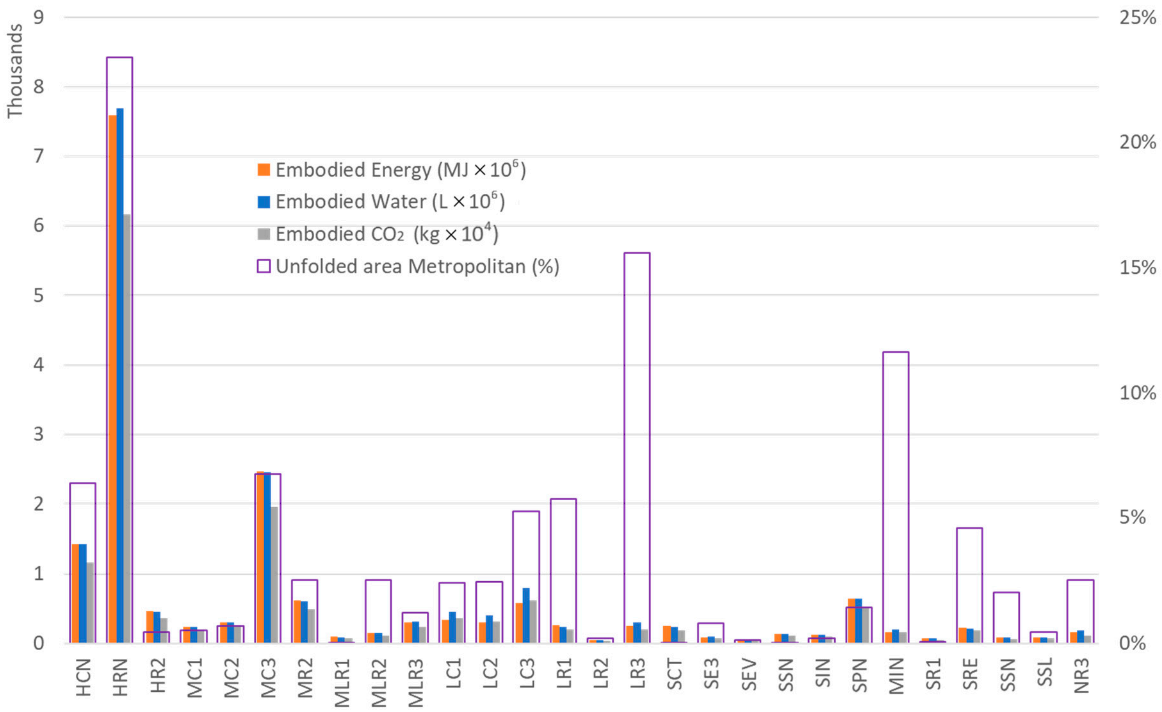

Figure 13. Embodied quantities for each construction subtype and their percentage area in Metropolitan.

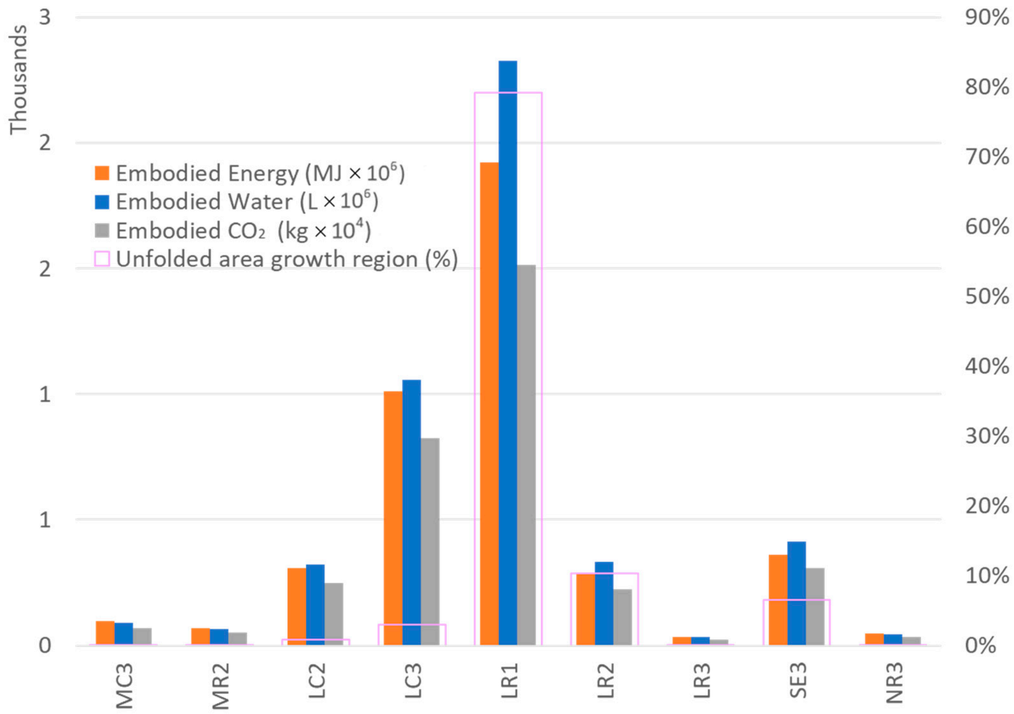

Figure 14. Embodied quantities for each construction subtype and their percentage area in the growth region.

Population data are available from the recent census. To develop a connection between land-use, embodied quantity, and population, the 2016 census is used. Data on population density can provide the connection between the embodied attributes and apparent utility per head. By linking these sources of data relating to the spatial, material, and embodied quantities, it is possible to develop a broad area estimate of the environmental impact of construction in the metropolitan and growth region. The total embodied quantities in each area have been calculated. However, it is also worth noting that the population densities are quite different in both study areas. Based on the 2016 census (the latest available at the time of analysis), the density in the metropolitan area is 3258 capita/km^2 and 1561 capita/km^2 in the growth region [62]. When compared with the population density in each region, the growth region has higher quantities of structural steel, masonry, and timber per head (refer to Figure 15). The population density is taken for the average density in the area, but in actual, the constructed area in Metropolitan is much less compared to the growth area. Therefore, the calculated attributes for the Metropolitan area are on a higher side but are still adequate to provide the general trends of environmental attributes.

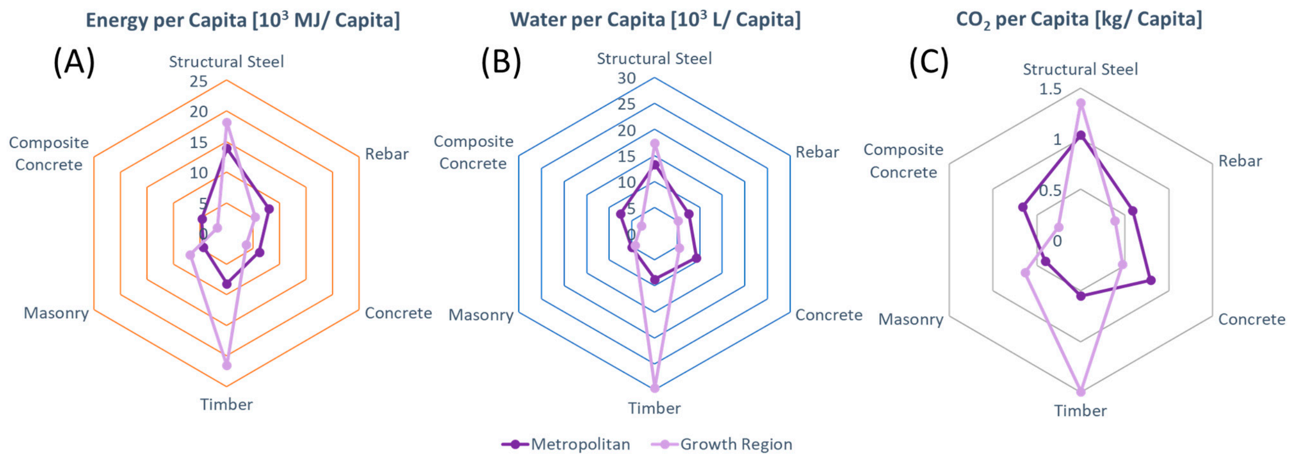

Figure 15. Comparison of (**A**) Embodied Energy (thousands MJ/capita), (**B**) Embodied Water (thousand L/capita), and (**C**) Embodied Greenhouse Gas Emission (kg CO_2/capita) for both regions per person for the basic construction materials including Structural Steel, Rebar, Structural Concrete, Composite Concrete, Timber, and Masonary.

6. Discussion

The utilization of a broad spatial system enables to document embodied energy, water, and carbon, ignoring the costs of materials. This helped to investigate the embodied quantities and their distribution amongst building subtypes and per capita. These criteria are also used for determining the relative merits of each construction in both regions.

The analysis shows that 1st generation low-rise residential (LR1) makes up 77% of the land-use in the growth region and 22% in the Metropolitan region, which is the second highest after mixed industrial which accounts for 30% of land. The residential construction in Metropolitan is dominated by high-rise residential, which covers only 2.6% of the land use but is found to be around 23% of the unfolded built area accommodating most of the population due to its 17 average number of storeys construction style. As mentioned, the service life of most of the construction from 1st generations is reaching maturity, the other option of replacements is 3rd generation low-rise residential which does not have much different embodied environmental attributes.

It is found that mixed purpose industrial buildings (MIN), although accounting for 27% of the built area in the Metropolitan region, only has around 5% of the embodied elements. However, these regions are likely to become high-rise residential based on observations of the surroundings, which despite accounting for less than 5% of the land-use area, is using over 10% of the embodied quantities.

A similar analysis was performed for the growth region which indicates that 1st generation low-rise residential (LR1) accounts for 77% of the land-use and holds the majority of the embodied attributes. Given that these areas will be redeveloped (more likely into 3rd generation low-rise residential (LR3)), the environmental attribute values of LR3 still indicate higher land-use to embodied attribute ratios. This shows that there will be a disposal of embodied environmental attributes and the replacement structures will not pose as much harm as the replacement structures in the Metropolitan region if considered in terms of land-use area. But the same will be inefficient in terms of per capita efficiency.

The results identify some positive aspects of modern construction, especially high-rise residential and commercial buildings and provide some support for future planning of the urban expansion. Fantilli et. al. [63] supported the fact that the high strength concrete used for high-rise buildings in fact reduces the carbon footprints. Various studies have recommended the use of energy efficient designs as well as recycled and environmental friendly materials to overcome the increasing carbon footprints of building [64–68], whereas, our results show that the vertical expansion of urban and regional areas is another tool that has been ignored so far. Additionally, the study considers overall environmental attributes covering water, carbon, and energy. Hosseinian and Ghahari studied water footprints of various residential buildings and found that short buildings consumes less water [69]. Chang et al. [70] found that public/commercial buildings have higher water footprints compared to residential buildings.

7. Conclusions and Recommendations

This study finds that same size areas can have dramatically different embodied attributes. The values of embodied attributes are linked to the area of the construction, type of construction, the nature of the construction, and its purpose. Despite similar areas of land-used for the study, it has been observed that Metropolitan has a broader range of building types compared to the growth region. This analysis helps identifying the most efficient construction practices. Google Earth TruEarth 15-m resolution images supported with Google Street View are used to identify the classification of the different program. Only 1463 buildings for the Metropolitan and 940 construction types in the growing region are identified and categorized. Therefore, applying any auto classification along with built-in inaccuracy is not viable in our study. However, application of classification techniques to automatically classify study areas into different programs is recommended for larger study areas.

These analyses provide an indication of how footprints of embodied energy, water, and carbon change as these developments occur in Victorian construction. It covers the vast range of construction classification, development details, and an established regime of construction. The expected construction in growth regions can bypass the intensive attributed construction styles considering this research. The study has the intrinsic capability to provide pragmatic improvements to reduce the environmental attributes of local construction. Theory and practices of imported construction styles might not be suitable construction styles due to the climatic, market, and socio-cultural constraints of Victoria. The objective of the research is to identify best practices for land use planning for policy makers and urban planners. The research provides a broader investigation of different types of constructions for different purposes in different eras. The research enables the identification of efficient materials, construction types, and planning aspects for all three environmental attributes.

When considering the embodied energy, carbon, and water as a summation across each region, depending on each structural component, it is found that Metropolitan had greater embodied quantities for all components except timber. This is due to the higher land-use percentages of the construction class that has deficient performance. The other reason is higher densities of buildings and vertical development compared to the growth region. Growth regions evolve to cater for the growing population demands and need to develop a broader range of residential properties. The study finds that the current approach of low-rise residential and commercial construction in growth regions is inefficient in terms of embodied quantities per capita. The current performance per head in the growth region is considerably lower than that of Metropolitan. An approach of using diverse residential construction types could serve to mitigate this.

Metropolitan's mixed purpose industrial areas (MIN) are being redeveloped into a series of high-rise, office, and residential spaces. These will increase the embodied attributes as redevelopment has the potential to increase the unfolded built-up area for these constructions. If green space is incorporated into the new constructions, then the accommodating population relative to the increased construction material concentrations will lead to an improved per head relationship in this region. Alternatively, the shifting of vital offices from this region can help in reducing the environmental attribute's concentrations to the Metropolitan region. Such shifting to regional areas should be in shape of vertical developments, e.g., high-rise commercial and residential constructions (HCN and HRN).

Little can be done in terms of existing growth regions as the replacement of existing residential construction is dominant by 3rd generation residential buildings, unless there is a high demand for residences in a particular area which can be seen in the Metropolitan region. Such high demand is not expected in the growth region in any near future. It means that little can be done in existing growth areas in terms of reducing environmental attributes. As land-use change disposal of current materials becomes significant, as though a percentage of the former structural material can be reused, it would serve to offset the creation of additional embodied attributes. However, this does option does not seem practical as new and modern 3rd generation construction materials and construction are entirely different. However, if the new construction in planned growth areas is dominated by vertical planning of residential areas, that can help reduce embodied attributes per capita and will provide higher land-use area for green areas.

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Appendix A

Table A1. Construction type definition and key identifiers.

Description	Example	Visual Identifiers
High-rise commercial	 [70]	Predominantly glass and steel wall Large footprint Office precinct Built-in last 20 years Typically, high-rise construction over 15 storeys

Table A1. *Cont.*

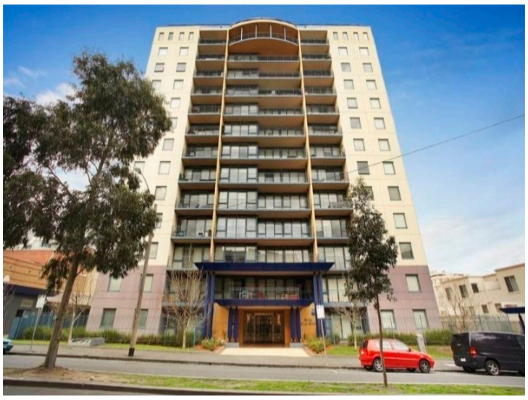
Description	Example	Visual Identifiers
High-rise residential		Predominantly glass and steel wall Large footprint Residential users High-rise construction over 15 storeys Built-in last 20 years
High-rise residential 2nd Generation		Primarily Concrete Wall Large footprint Residential users High-rise construction over 12 storeys Over 20 years old, less than 50
Low-rise commercial 1st Generation		Brick Finish 1–2 storeys tall Pre-war construction Inner Suburbs Location Commercial land-use
Low-rise commercial 2nd Generation		Over 20 years old, less than 50 Rendered wall finish Small window to wall ratio Low-rise, less than 2 storeys Small footprint Commercial land-use
Low-rise commercial 3rd Generation		Less than 20 years old Concrete wall Steel sheet roofing Small window to wall ratio Low-rise, less than 2 storeys Small footprint Commercial land-use

Table A1. *Cont.*

Description	Example	Visual Identifiers
Low-rise residential 1st Generation		Tin/Tile roof Inner Suburbs of Metropolitan Wrought ironwork Brick finish Pre-war construction was largely Victorian
Low-rise residential 2nd Generation		Tile roof Metropolitan, Port residential region, sth Williamstown road Central Werribee, Older constructions growth region, Variable footprint, Larger in Growth Region, more condensed, "workers" housing Port Metropolitan, Terraces vs Bungalow Not Townhouse as predominantly no incorporated garage
Low-rise residential 3rd Generation		Colourbond steel/Tile roof More frequent in growth regions A greater ratio of built area to green space versus old constructions Typically brick timber construction with masonry veneer
Medium-rise Commercial 1st Generation		Brick Finish 4 + Storeys tall Pre-war construction Inner Suburbs Location

Table A1. *Cont.*

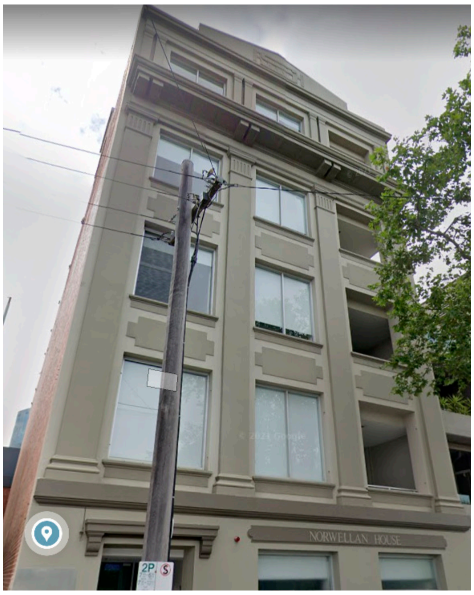
Description	Example	Visual Identifiers
Medium-rise Commercial 2nd Generation		Industrial location 4 + Storeys tall Concrete and steel are predominant materials
Medium-rise Commercial 3rd Generation		Industrial location 4 + Storeys tall Concrete and steel are predominant materials Increased mixed-use with included office space
Medium-rise residential 1st Generation		4–5 Storeys tall Masonry/Brick finish Inner Suburb location Residential use Some repurposed from different earlier use
Medium-rise residential 2nd Generation		4–5 Storeys tall Concrete Predominant feature Brickwork in addition in portions Larger balcony comparative to 1st generation Residential use

Table A1. *Cont.*

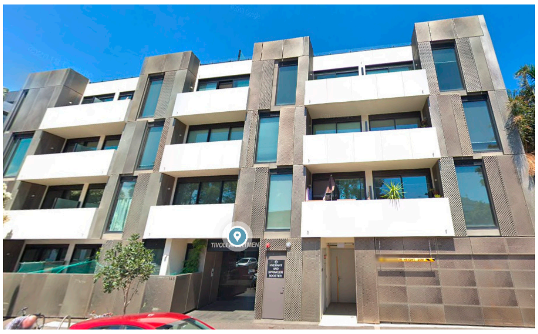
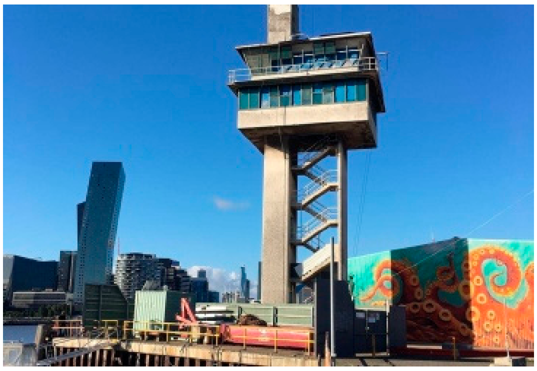
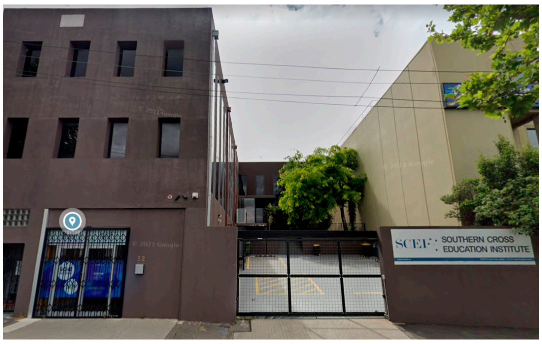
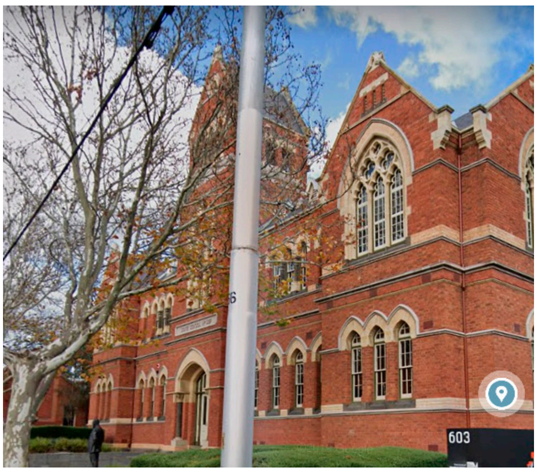
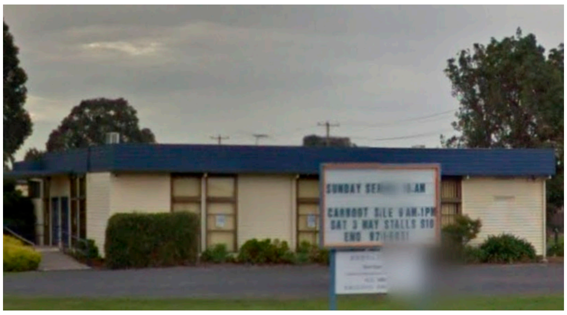
Description	Example	Visual Identifiers
Medium-rise residential 3rd Generation		4–5 Storeys tall Concrete Predominant feature Less than 20 years old Increased window: wall ratio
Special Purpose Control tower		Single land-use item Concrete construction A large amount of material for small footprint owing to high elevation
Special purpose educational 3rd Generation		Less than 20 years old Concrete and masonry wall Steel sheet roofing Small window to wall ratio Low-rise, typically 2 storeys Located amongst residential areas
Special purpose educational 1st Generation		4–5 Storeys tall Masonry/Brick finish Inner Suburb location Educational use Typically located near educational facilities

Table A1. *Cont.*

Description	Example	Visual Identifiers
Special purpose Grain Silo		Single land-use item Concrete construction A large amount of material for a small footprint owing to a size proportional to the built area
Special Purpose Ice-rink		Single land-use item Reinforced Concrete construction Steel sheet wall
Special Purpose Multistorey car park		Reinforced Concrete and composite concrete construction Exposed concrete walls Minimal use of Enclosed spaces
Mixed Purpose Industrial		2 Storeys tall Concrete, steel construction predominantly Mixed-use office and warehousing typically Located in industrial areas
Special Purpose Religious establishment 1st generation		4–5 Storeys tall Masonry/Brick finish Inner Suburb location Typically located near residential areas

Table A1. *Cont.*

Description	Example	Visual Identifiers
Special Purpose Religious establishment		Low-rise construction Lightweight construction Built post-war Typically located near residential areas
Special Purpose Stadium		Single land-use item Reinforced Concrete construction Heavyweight The broad range of materials used The high density of higher performance materials
Special Purpose Stadium Local		Low-rise construction Lightweight construction Typically timber and steel frame structures Typically located near residential areas
Townhouse 3rd Generation		Flat or Tile roof Typical of Knockdown rebuilds in inner Metropolitan suburbs Incorporated garage 2–3 Storeys Situated amongst 1st generation homes in inner suburbs

Appendix B. Reduction Coefficients

Table A2. Material reduction coefficients.

	Timber Reduction Coefficient	Masonry Reduction Coefficient	Composite Concrete Reduction Coefficient
High-rise commercial	10.00%	50.00%	100.00%
High-rise residential	10.00%	50.00%	100.00%
High-rise residential 2nd Generation	10.00%	10.00%	100.00%
Low-rise commercial 1st Generation	10.00%	70.00%	100.00%
Low-rise commercial 2nd Generation	10.00%	40.00%	100.00%
Low-rise commercial 3rd Generation	10.00%	30.00%	100.00%
Low-rise residential 1st Generation	80.00%	100.00%	20.00%
Low-rise residential 2nd Generation	80.00%	100.00%	20.00%
Low-rise residential 3rd Generation	80.00%	100.00%	20.00%
Medium-rise Commercial 1st Generation	10.00%	40.00%	100.00%
Medium-rise Commercial 2nd Generation	10.00%	50.00%	100.00%
Medium-rise Commercial 3rd Generation	20.00%	40.00%	100.00%
Medium-rise residential 1st Generation	10.00%	100.00%	100.00%
Medium-rise residential 1st Generation	10.00%	100.00%	100.00%
Medium-rise residential 2nd Generation	10.00%	80.00%	100.00%
Medium-rise residential 3rd Generation	10.00%	70.00%	100.00%
Special Purpose Control tower	10.00%	0.00%	100.00%
Special purpose educational 3rd Generation	10.00%	50.00%	100.00%
Special purpose educational Victorian	10.00%	100.00%	10.00%
Special purpose Grain Silo	10.00%	0.00%	100.00%
Special Purpose Ice-rink	10.00%	0.00%	100.00%
Special Purpose Multistorey carpark	10.00%	0.00%	100.00%
Mixed Purpose Industrial	10.00%	30.00%	100.00%
Special Purpose Religious establishment 1st Generation	10.00%	100.00%	20.00%
Special Purpose Religious establishment	10.00%	100.00%	20.00%
Special Purpose Stadium	10.00%	10.00%	100.00%
Special Purpose Stadium Local	20.00%	50.00%	100.00%
Townhouse 3rd Generation	100.00%	40.00%	20.00%

Table A3. Area modification coefficients.

Low-rise residential 1st Generation	0.4
Low-rise residential 2nd Generation	0.5
Low-rise residential 3rd Generation	0.6
Mixed Purpose Industrial	0.1

Appendix C. Box-and-Whisker Input Data

Table A4. Proportion of material in construction by overall mass of the building.

	Steel	Concrete	Timber	Masonry	Composite Concrete
Max	23.93%	28.71%	9.55%	9.49%	28.33%
Uq	21.45%	27.50%	11.61%	13.71%	25.73%
Mean	20.97%	26.47%	13.49%	14.11%	24.96%
Lq	18.19%	27.79%	14.16%	17.35%	22.51%
Min	17.16%	19.48%	20.82%	22.71%	19.83%

Table A5. Database of Embodied Quantity Outputs (DEQO) assumptions on the mass per unit area of each building classification with a maximum, minimum, mean, upper, and lower quartile reference point.

	Statistical Identifier	Mass per Unit is [kg/m^2]
High-rise commercial	Uq	244
High-rise residential	Uq	463
High-rise residential 2nd Generation	Uq	463
Low-rise commercial 1st Generation	Lq	1128
Low-rise commercial 2nd Generation	Lq	1128
Low-rise commercial 3rd Generation	Lq	1128
Low-rise residential 1st Generation	Min	98
Low-rise residential 2nd Generation	Min	98
Low-rise residential 3rd Generation	Min	98
Medium-rise Commercial 1st Generation	Mean	517
Medium-rise Commercial 2nd Generation	Mean	517
Medium-rise Commercial 3rd Generation	Mean	517
Medium-rise residential 1st Generation	Lq	296
Medium-rise residential 1st Generation	Lq	296
Medium-rise residential 2nd Generation	Mean	282
Medium-rise residential 3rd Generation	Lq	296
Mixed Purpose Industrial	Min	1128
Special Purpose Control Tower	Mean	589
Special purpose educational 3rd Generation	Lq	282
Special purpose educational Victorian	Min	282
Special purpose Grain Silo	Lq	589
Special Purpose Ice rink	Lq	472
Special Purpose Multistorey carpark	Mean	589
Special Purpose Religious establishment 1st Generation	Min	235
Special Purpose Religious establishment	Min	235
Special Purpose Stadium	Uq	282
Special Purpose Stadium Local	Mean	472
Townhouse 3rd Generation	Min	98

Table A6. Detailed embodied attributes for structural materials.

Material Assumptions		**Steel**	**Rebar**	**Concrete**	**Timber**	**Masonry**	**Composite Concrete**
Melbourne		**Mass [kg]**	**Mass [kg]**	**Mass [kg]**	**Mass [kg]**	**Mass [kg]**	**Mass [kg]**
High-rise commercial	1,919,819.849	1,329,106.05	590,713.7998	2,461,924.368	103,930.0971	613,476.2677	2,303,142.276
High-rise residential	12,979,023.81	8,985,478.026	3,993,545.789	16,643,944.49	702,623.8456	4,147,432.422	15,570,491.39
High-rise residential 2nd Generation	291,752.7178	201,982.6508	89,770.06701	374,135.6907	15,794.13209	18,645.85039	350,005.7667
Low-rise commercial 2nd Generation	48,550,329.6	0	48,550,329.6	74,151,100.66	3,777,977.866	18,525,347.61	60,066,534.06
Low-rise commercial 3rd Generation	103,990,862.1	0	103,990,862.1	158,825,634.1	8,092,121.693	29,759,842.28	128,657,636.6
Low-rise commercial 1st Generation	47,627,052.67	0	47,627,052.67	72,740,976.34	3,706,132.426	31,802,842.51	58,924,254.58
Low-rise residential 1st Generation	5,918,808.551	0	5,918,808.551	6,719,303.15	5,744,155.184	7,835,144.107	1,368,118.042
Low-rise residential 2nd Generation	207,254.1491	0	207,254.1491	235,284.4233	201,138.4529	274,356.9269	47,906.28692
Low-rise residential 3rd Generation	6,484,860.411	0	6,484,860.411	7,361,911.204	6,293,503.874	8,584,466.855	1,498,959.538
Medium-rise Commercial 2nd Generation	2,444,934.563	1,692,647.005	752,287.558	3,085,540.988	157,214.3278	822,437.9424	2,909,304.286
Medium-rise Commercial 3rd Generation	11,445,117.46	7,923,542.859	3,521,574.604	14,443,895.38	1,471,889.248	3,079,967.537	13,618,904.07
Medium-rise Commercial 1st Generation	1,847,553.781	1,279,075.694	568,478.0864	2,331,638.238	118,801.5131	497,190.6742	2,198,462.165
Medium-rise residential 2nd Generation	2,283,747.528	1,581,055.981	702,691.547	2,882,120.736	146,849.6694	1,229,147.411	2,717,502.779
Medium-rise residential 3rd Generation	1,717,919.856	1,189,329.131	528,590.7249	2,623,785.446	133,681.1355	1,147,136.586	2,125,412.791
Medium-rise residential 1st Generation	40,711.80876	28,185.09837	12,526.71039	62,179.29835	3168.017883	38,836.00869	50,368.70537
Medium-rise residential 1st Generation	6677.598261	4622.952643	2054.645619	10,198.72089	519.6219808	6369.927352	8261.533685
Special Purpose Control tower	41,138.40605	28,480.43496	12,657.97109	51,917.23326	2645.284233	0	48,951.87905
Special purpose educational 3rd Generation	1,445,711.303	0	1,445,711.303	2,208,040.301	112,499.0366	689,550.0158	1,788,635.998
Special purpose educational Victorian	313,797.384	0	313,797.384	356,237.1941	38,067.22363	415,395.7173	36,266.74684
Special purpose Grain Silo	52,507.12822	0	52,507.12822	80,194.33406	4085.87892	0	64,961.89072
Special Purpose Ice rink	600,842.665	415,967.9989	184,874.6662	917,669.258	46,754.99236	0	743,363.3654
Special Purpose Multistorey carpark	3,284,772.007	2,274,072.928	1,010,699.079	4,145,427.373	211,217.605	0	3,908,653.189
Mixed Purpose Industrial	21,668,384.38	0	21,668,384.38	24,598,944.56	2,628,623.679	8,605,190.353	25,042,968.83
Special Purpose Religious establish ment 1st Generation	84,719.64838	0	84,719.64838	48,088.81681	10,277.46554	112,149.3706	19,582.7384
Special Purpose Religious establishment	5,959,247.004	0	5,959,247.004	6,765,210.738	722,925.0464	7,888,675.338	1,377,465.291
Special Purpose Stadium	322,2821.159	2,231,183.88	991,637.2798	4,132,857.543	174,468.5139	205,969.7733	3,866,308.425
Special Purpose Stadium Local	1,718,223.174	0	1,718,223.174	2,168,421.237	220,970.5776	577,983.5392	2,044,567.622
Townhouse 3rd Generation	1,633,381.3	0	1,633,381.3	1,854,289.426	1,981,478.954	864,888.7865	377,552.0709
Growth Region							
Low-rise commercial 2nd Generation	6,837,281.235	3,418,640.617	3,418,640.617	10,442,605.3	532,047.823	2,608,901.167	8,459,093.678
Low-rise commercial 3rd Generation	26,269,118.72	13,134,559.36	13,134,559.36	40,120,923.65	2,044,149.853	7,517,630.051	32,500,189.55
Low-rise residential 2nd Generation	43,245,751.31	0	43,245,751.31	49,094,561.93	41,969,647.17	57,247,449.48	9,996,149.072
Low-rise residential 3rd Generation	7,567,747.247	0	7,567,747.247	8,591,254.047	7,344,436.672	10,017,960.49	1,749,266.167
Low-rise residential 1st Generation	3418.037108	0	3418.037108	3880.312619	3317.176997	4524.696664	790.0708726
Medium-rise Commercial 3rd Generation	327,428.4301	226,681.2208	100,747.2093	413,219.1744	42,108.64478	88,113.46311	389,617.3539
Medium-rise residential 2nd Generation	44,425.41501	8885.083003	35,540.33201	67,851.10314	3456.994752	33,902.80818	54,963.1841
Special purpose educational 3rd Generation	7,343,530.044	1,468,706.009	5,874,824.035	11,215,801.01	571,441.9283	3,502,588.135	9,085,425.396
Townhouse 3rd Generation	14,259.75809	0	14,259.75809	16,188.33193	17,298.72293	7550.65879	3296.108017

Table A7. Detailed estimation of environmental attributes for building components.

Material Assumptions	Steel			Rebar			Concrete			Timber			Masonry			Composite Concrete		
Melbourne	Embodied Energy (MJ)	Embodied Water (L)	Embodied Greenhouse Gas Emissions ($kgCO_2e$)	Embodied Energy (MJ)	Embodied Water (L)	Embodied Greenhouse Gas Emissions ($kgCO_2e$)	Embodied Energy (MJ)	Embodied Water (L)	Embodied Greenhouse Gas Emissions ($kgCO_2e$)	Embodied Energy (MJ)	Embodied Water (L)	Embodied Greenhouse Gas Emissions ($kgCO_2e$)	Embodied Energy (MJ)	Embodied Water (L)	Embodied Greenhouse Gas Emissions ($kgCO_2e$)	Embodied Energy (MJ)	Embodied Water (L)	Embodied Greenhouse Gas Emissions ($kgCO_2e$)
High-rise commercial	51,569,314.73	49,309,834.44	3,854,407.544	23,251,026.75	22,172,718.26	1,752,251.291	4,101,155.677	4,477,624.945	615,481.0921	1,647,652.373	2,309,759.158	114,097.9929	1,595,038.296	2,269,862.19	147,234.3042	3,019,119	4,305,874.689	416,568.3
High-rise residential	348,636,547.4	333,361,234.8	26,057,886.27	23,251,026.75	22,172,718.26	1,752,251.291	25,847,903.54	30,200,935.17	3,321,676.101	11,139,024	15,615,225.11	771,364.3381	10,783,324.3	15,345,499.96	995,383.7813	20,410,883	29,110,049.13	2,816,228
High-rise residential 2nd Generation	7,836,926.85	7,493,556.344	585,749.6873	23,251,026.75	22,172,718.26	1,752,251.291	507,452.1639	673,117.4873	64,044.18811	250,391.7531	351,011.3264	17,339.33501	48,479.211	68,989.64643	4475.004092	458,811.9	654,358.6073	63,305.39
Low-rise commercial 2nd Generation	0	0	0	23,200,481.04	22,139,021.12	1,668,008.441	81,862,815.13	133,999,277.9	10,348,198.05	72,590,066.72	65,041,666.95	4,873,591.447	48,165,903.78	68,543,786.15	4,446,083.426	68,598,108	111,521,759.7	9,594,699
Low-rise commercial 3rd Generation	0	0	0	23,200,481.04	22,139,021.12	1,668,008.441	175,343,500.1	287,015,568.1	22,164,999.61	155,482,026.2	139,313,967.1	10,438,836.98	77,375,589.93	110,111,416.4	7,142,362.147	1.47×10^8	238,870,550	20,551,065
Low-rise commercial 1st Generation	0	0	0	23,200,481.04	22,139,021.12	1,668,008.441	95,353,932.03	135,993,999.2	13,156,628.76	71,209,628.43	63,804,775.85	4,780,910.829	82,687,390.52	117,670,517.3	7,632,682.201	67,293,585	109,400,961.2	9,412,237
Low-rise residential 1st Generation	0	0	0	23,200,481.04	22,139,021.12	1,668,008.441	8,337,778.779	11,904,852.32	1,089,695.685	110,368,197.7	98,891,375.65	7,409,960.188	27,423,004.37	14,103,259.39	2,507,246.114	1,562,439	2,540,098.808	218,535.7
Low-rise residential 2nd Generation	0	0	0	23,200,481.04	22,139,021.12	1,668,008.441	291,957.2801	416,862.6196	38,156.99561	3,188,741.84	4,470,133.257	220,816.6298	960,249.244	493,842.4684	87,794.2166	54,710.68	88,944.59288	7652.287
Low-rise residential 3rd Generation	0	0	0	23,200,481.04	22,139,021.12	1,668,008.441	10,889,363.13	13,643,031.19	1,556,965.901	99,773,856.44	139,867,840.1	6,909,222.453	30,045,633.99	15,452,040.34	2,747,029.394	1,711,865	2,783,023.991	239,435.6
Medium-rise Commercial 2nd Generation	65,674,703.81	62,797,203.9	4,908,676.316	23,200,481.04	22,139,021.12	1,668,008.441	3,143,044.252	5,649,345.045	388,497.6608	3,020,716.094	2,706,601.867	202,806.4828	2,878,532.798	1,480,388.296	263,180.1416	3,322,528	5,401,522.471	464,716.3
Medium-rise Commercial 3rd Generation	307,433,462.9	293,963,440.1	22,978,274.29	23,200,481.04	22,139,021.12	1,668,008.441	14,713,077.07	26,445,459.36	1,818,617.736	28,280,880.01	25,340,045.3	1,898,737.13	10,779,886.38	5,543,941.566	985,589.6118	15,553,271	25,285,363.49	2,175,409
Medium-rise Commercial 1st Generation	49,628,136.94	47,453,708.26	3,709,319.513	23,200,481.04	22,139,021.12	1,668,008.441	2,662,813.404	4,329,006.215	372,443.0991	2,282,652.273	2,045,286.85	153,253.9519	1,740,167.36	894,943.2135	159,101.0157	2,510,722	4,081,746.568	351,170.3
Medium-rise residential 2nd Generation	61,344,972.05	58,657,176.88	4,585,062.344	23,200,481.04	22,139,021.12	1,668,008.441	3,291,483.902	5,351,052.481	460,374.1529	2,821,569.548	2,528,163.908	189,436.0735	4,302,015.938	2,212,465.339	393,327.1715	3,103,484	5,045,416.664	434,079
Medium-rise residential 3rd Generation	46,145,970.28	44,124,110.76	3,449,054.48	23,251,026.75	22,172,718.26	1,752,251.291	3,558,723.84	4,720,522.286	449,137.0719	2,119,309.481	2,970,951.011	146,759.6941	2,982,555.125	4,244,405.37	275,312.7807	2,786,139	3,973,597.827	384,422.5
Medium-rise residential 1st Generation	1,093,581.817	1,045,667.149	81,736.78527	23,183,632.47	22,105,323.98	1,725,293.579	63,338.09437	113,844.6426	7828.938929	57,642.08537	78,295.58196	3463.039548	135,926.0304	69,904.81565	12,427.52278	57,522.84	93,516.4105	8045.621
Medium-rise residential 1st Generation	179,370.5625	171,511.543	13,406.56266	23,183,632.47	22,105,323.98	1,725,293.579	10,945.41296	18,913.16366	1493.384131	9454.52194	12,842.13249	568.0117777	22,294.74573	11,465.86923	2038.376753	9434.964	15,338.67051	1319.652
Special Purpose Control tower	1,105,040.876	1,056,624.137	82,593.26137	23,251,026.75	22,172,718.26	1,752,251.291	55,718.31641	96,278.6549	7602.166299	41,936.92649	58,789.22134	2904.082938	0	0	0	55,904.78	90,885.87809	7819.305
Special purpose educational 3rd Generation	0	0	0	23,183,632.47	22,105,323.98	1,725,293.579	2,437,676.492	3,990,174.162	308,144.2909	1,783,499.772	2,500,196.644	123,505.2659	1,792,830.041	2,551,335.059	165,492.0038	2,042,686	3,320,848.074	285,706.9
Special purpose educational Victorian	0	0	0	23,183,632.47	22,105,323.98	1,725,293.579	442,043.8921	631,159.3765	57,772.37974	603,497.4764	846,012.0873	41,791.49191	1,080,028.865	1,536,964.154	99,694.97215	47,540.97	67,803.04843	6559.551
Special purpose Grain Silo	0	0	0	23,183,632.47	22,105,323.98	1,725,293.579	105,124.3118	149,928.5376	14,504.71433	64,775.34692	90,805.22885	4485.616747	0	0	0	85,156.57	121,450.4913	11,749.63
Special Purpose Ice rink	16,139,558.36	15,432,412.76	1,206,307.197	23,183,632.47	22,105,323.98	1,725,293.579	1,048,010.776	1,703,778.852	146,583.4523	741,228.732	1,039,090.454	51,329.2197	0	0	0	848,947.3	1,380,156.054	118,740.8
Special Purpose Multistorey carpark	88,234,029.61	84,368,105.63	6,594,811.491	23,183,632.47	22,105,323.98	1,725,293.579	4,734,224.801	7,696,554.538	662,167.8237	3,348,531.347	4,694,133.952	231,881.8656	0	0	0	446,3820	7,256,950.789	624,346.8
Mixed Purpose Industrial	0	0	0	23,251,026.75	22,172,718.26	1,752,251.291	41,786,533.29	45,661,131	5,194,283.572	4,1672,798.94	58,418,954.5	2,885,792.415	22,373,494.92	31,839,204.31	2,065,245.685	32,828,066	46,819,463.47	4,529,511
Special Purpose Religious establish ment 1st Generation	0	0	0	23,183,632.47	22,105,323.98	1,725,293.579	63,038.16638	89,905.17925	8697.803388	162,933.4616	228,408.0436	11,282.95098	291,588.3636	414,952.6712	26,915.84895	22,364.18	36,358.03996	3128.039

Table A7. *Cont.*

Material Assumptions	Steel			Rebar			Concrete			Timber			Masonry			Composite Concrete		
Melbourne	**Embodied Energy (MJ)**	**Embodied Water (L)**	**Embodied Greenhouse Gas Emissions ($kgCO_2e$)**	**Embodied Energy (MJ)**	**Embodied Water (L)**	**Embodied Greenhouse Gas Emissions ($kgCO_2e$)**	**Embodied Energy (MJ)**	**Embodied Water (L)**	**Embodied Greenhouse Gas Emissions ($kgCO_2e$)**	**Embodied Energy (MJ)**	**Embodied Water (L)**	**Embodied Greenhouse Gas Emissions ($kgCO_2e$)**	**Embodied Energy (MJ)**	**Embodied Water (L)**	**Embodied Greenhouse Gas Emissions ($kgCO_2e$)**	**Embodied Energy (MJ)**	**Embodied Water (L)**	**Embodied Greenhouse Gas Emissions ($kgCO_2e$)**
Special Purpose Religious establishment	0	0	0	23,183,632.47	22,105,323.98	1,725,293.579	7,260,520.81	12,545,841.7	990,620.1438	13,153,621.22	17,866,640.69	790,247.4414	27,610,363.68	14,199,615.61	2,524,376.108	1,573,114	2,557,453.257	220,028.7
Special Purpose Stadium	86,569,934.52	82,776,921.93	6,470,433.251	23,183,632.47	22,105,323.98	1,725,293.579	4,435,441.756	7,664,236.712	605,168.426	3,174,454.61	4,311,880.278	190,715.8942	720,894.2067	370,745.592	65,910.32747	4,415,461	7,178,331.925	617,582.9
Special Purpose Stadium Local	0	0	0	23,183,632.47	22,105,323.98	1,725,293.579	2,327,180.649	4,021,259.741	317,518.824	4,020,559.659	5,461,149.718	241,548.4626	2,022,942.387	1,040,370.371	184,954.7326	2,334,969	3,796,020.239	326,588
Townhouse 3rd Generation	0	0	0	23,183,632.47	22,105,323.98	1,725,293.579	1,990,049.902	3,438,713.516	271,520.9517	36,053,009.56	48,971,013.91	2,166,004.181	3,027,110.753	1,556,799.816	276,764.4117	431,177.8	700,977.2077	60,308.1
Growth																		
Low-rise commercial 2nd Generation	132,643,256	126,831,566.9	9,914,057.79	23,200,481.04	22,139,021.12	1,668,008.441	11,528,636.25	18,870,948.06	1,457,323.584	10,222,766.87	9,159,735.321	686,341.6917	6,783,143.035	9,652,934.319	626,136.2802	9,660,584	15,705,467.73	1,351,209
Low-rise commercial 3rd Generation	509,620,903.2	487,292,152.3	38,090,222.15	23,200,481.04	22,139,021.12	1,668,008.441	44,293,499.71	72,502,966.91	5,599,097.789	39,276,295.27	35,192,083.87	2,636,953.31	19,545,838.13	27,815,231.19	1,804,231.212	37,116,367	60,341,059.88	5,191,402
Low-rise residential 2nd Generation	0	0	0	23,200,481.04	22,139,021.12	1,668,008.441	60,919,947.72	86,982,756.47	7,961,857.218	665,364,419.5	932,740,174.3	46,075,705.11	200,366,073.2	103,045,409.1	18,319,183.83	11,415,956	18,559,221.91	1,596,730
Low-rise residential 3rd Generation	0	0	0	23,200,481.04	22,139,021.12	1,668,008.441	12,707,744.28	15,921,238.88	1,816,958.835	116,434,785	163,223,939.3	8,062,972.198	35,062,861.73	18,032,328.89	3,205,747.358	1,997,724	3,247,752.582	279,418.2
Low-rise residential 1st Generation	0	0	0	23,200,481.04	22,139,021.12	1,668,008.441	4814.961832	6874.901705	629.2854812	63,736.23882	57,108.51918	4279.158326	15,836.43832	8144.453995	1447.902932	902.2889	1466.874947	126.2016
Medium-rise Commercial 3rd Generation	8,795,231.368	8,409,873.293	657,375.5404	23,200,481.04	22,139,021.12	1,668,008.441	420,920.0771	756,566.7429	52,028.05059	809,075.5009	724,942.4286	54,320.15177	308,397.1209	158,604.2336	28,196.30819	444,956.8	723,378.0606	62,,235.34
Medium-rise residential 2nd Generation	344,741.2205	329,636.5794	25,766.74071	23,200,481.04	22,139,021.12	1,668,008.441	77,488.36159	125,974.88	10,838.16293	66,422.69716	59,515.62165	4459.52323	118,659.8286	61,025.05473	10,848.89862	62,769.9	102,046.6905	8779.517
Special purpose educational 3rd Generation	56,985,793.14	54,488,992.93	4,259,247.426	23,200,481.04	22,139,021.12	1,668,008.441	12,382,244.31	20,268,198.62	1,565,227.34	9,059,335.796	12,699,817.13	627,348.3708	9,106,729.152	12,959,576.1	840,621.1525	10,375,877	16,868,338.48	1,451,256
Townhouse 3rd Generation	0	0	0	23,200,481.04	22,139,021.12	1,668,008.441	17,373.54909	30,020.6834	2370.434318	314,750.2636	427,527.1254	18,909.6665	26,427.30577	13,591.18582	2416.210813	3764.272	6119.676654	526.5022

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