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Embodied carbon of New Zealand office and residential building services

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Preface

This report provides an embodied carbon footprint assessment of building services for a selection of case study New Zealand dwellings and offices. The assessment includes a comparison with other building elements and a hotspot analysis of the key contributors to the services embodied carbon footprint as well as a comparison with published international benchmarks.

A discussion about data quality underlying the calculations is provided. On the whole, services carbon footprint data quality was assessed as being poor due to the lack of New Zealand-specific data in many cases.

Acknowledgements

We would like to thank the following contributors to the report:

- Beca, in particular, Alex Manktelow, Nick Baty and Shaan Cory, for provision of services quantities data for the office building case studies and input to the design of the study from its inception.
- Ortus International Ltd, in particular, Matt Simpson and David Grenfell, for provision of services quantities data for the stand-alone residential, medium-density and apartment buildings.

Amendment

Note that the services contribution to total carbon footprint for a stand-alone house has been corrected (from 17% as orginally published) in Table 4.

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BRANZ Study Report SR479

Authors

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Reference

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Abstract

BRANZ's previous research on carbon footprinting of buildings has excluded the embodied carbon of building services, focusing primarily on the structure and thermal envelope. This study focuses on the embodied carbon contribution that building services (primarily HVAC, electrical and plumbing) can make to the carbon footprint of New Zealand residential and office buildings. It is based on an assessment of several case study buildings in New Zealand. The embodied carbon footprint assessment was carried out assuming a 50-year building service life and included within scope Modules A1–A3, A4–A5, B1 (for refrigerant loss), B2, B4, C1–C4 and D. Biogenic carbon was negligible due to the lack of bio-based materials used. Module D was calculated and reported separately. Materials embodied carbon data was drawn from several international sources and was assessed as being of generally poor quality as they rarely represented the specific services items used in the assessed buildings.

Results for the residential buildings (stand-alone housing, medium-density housing and apartments) suggest that the embodied carbon of the building services can add up to an additional 20% to the embodied carbon of dwellings. For offices, this contribution increased to 30–40% (although with one of the four assessed buildings showing a much higher contribution of 54%). In residential buildings, heat pumps and LED lighting make the most significant contributions. In offices, HVAC is the most significant contributor – in particular, fugitive emissions of refrigerants, which are small in mass terms but potentially significant due to their high global warming potentials. The amount of refrigerant lost due to fugitive emissions annually (which can vary depending on the type of HVAC system installed) was a significant source of uncertainty. Other parts of the HVAC system such as pipework, ductwork and fan coil units also appeared important due to the high embodied carbon of manufacture. As with results for residential buildings, lighting was also found to be important.

Keywords

Building services, carbon footprint, case studies, embodied carbon, offices, residential.

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1. Introduction

1.1 Background

The carbon footprint of a building consists of both operational and embodied carbon. The life cycle of a building can be divided into different stages and modules as defined in BS EN 15978:2011 *Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method* and summarised in Figure 1. Traditionally, efforts to reduce the carbon footprint of buildings have been focused on operational emissions (Modules B6 and B7) with an emphasis on reducing operational energy use. However, more recently, greater focus has been directed towards the role of the embodied carbon footprint or the greenhouse gas emissions associated with the building itself.

For the purposes of this study, embodied emissions are defined as emissions associated with Modules A1–A5, B1 (refrigerants only), B2, B4 and C1–C4. Benefits and loads associated with Module D are also estimated but reported separately.

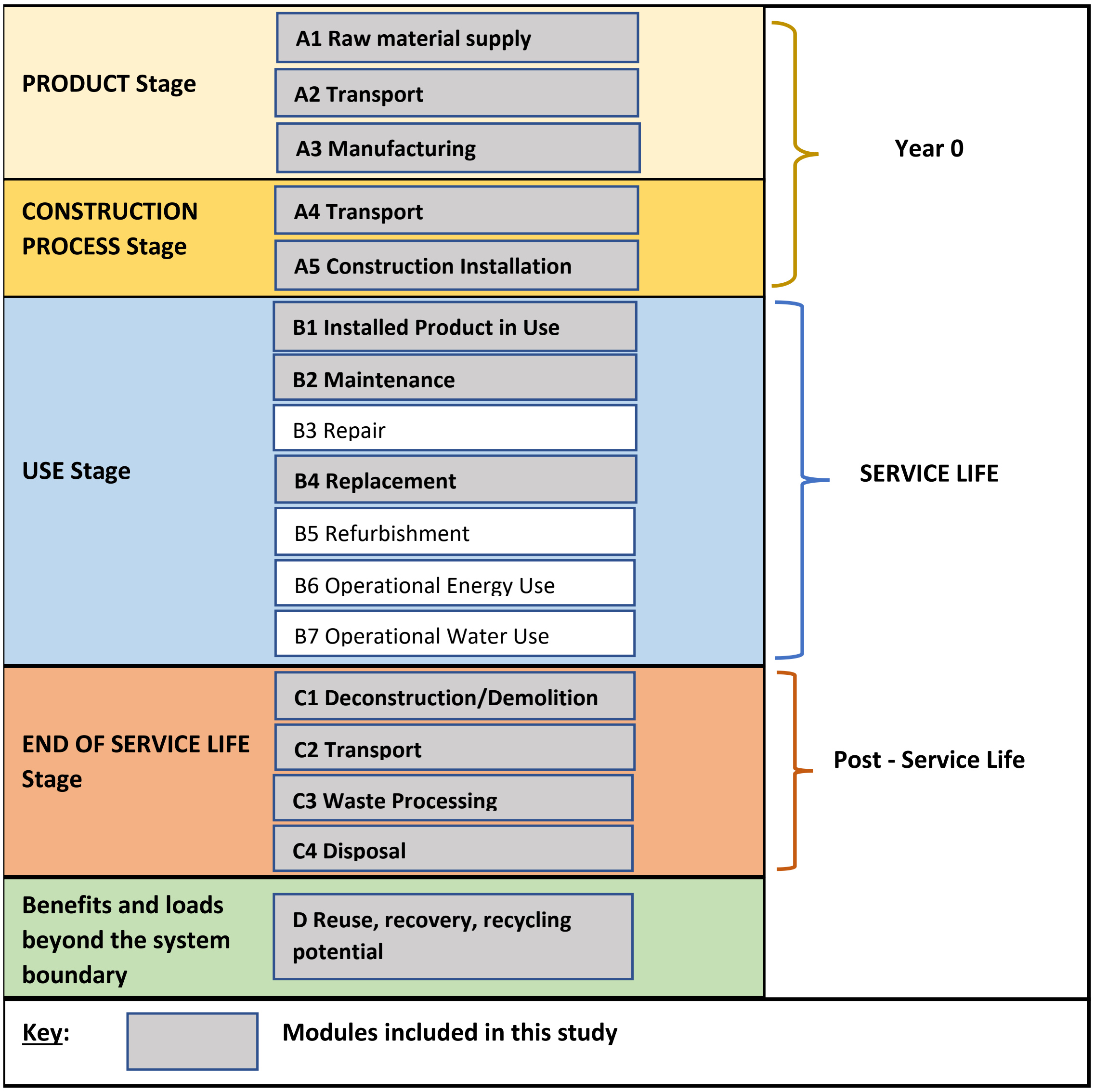

Figure 1. Building life cycle stages (adapted from BS EN 15978:2011).

BRANZ's previous research carbon footprinting buildings (Berg et al. 2016; Dowdell et al., 2020) has excluded building services, focusing primarily on the structure and thermal envelope. Recent studies carried out overseas have focused on building services (and fit-out):

- The Carbon Leadership Forum (2019) calculated the carbon footprint of mechanical, electrical and plumbing (MEP) services and tenant improvements (fit-out) for office buildings. They found that the contributions to embodied carbon from MEP and tenant improvements are significant, especially when the full life cycle of the building is considered due to repeated replacements of MEP and tenant improvement elements over the lifetime of a building.
- The Chartered Institution of Building Services Engineers (CIBSE, 2021) has also identified the importance of embodied carbon of building services to the whole-of-life emissions of a building and has recently released guidance on calculating the embodied carbon associated with building services (see section 2.2.2).

This report presents the results of two related studies to quantify the contribution from building services to the carbon footprint of New Zealand office and residential buildings. These studies represent case studies only.

1.2 Purpose

The purposes of this project are to:

- estimate the contribution of building services to the life cycle carbon footprint of reference New Zealand residential buildings including stand-alone houses, medium-density housing (MDH) and an apartment;
- estimate the contribution of building services to the life cycle carbon footprint of reference New Zealand office buildings.

2. Methodology

2.1 Introduction

The methodology used in this study involved quantifying the carbon footprint of installed services (mechanical, electrical and plumbing) at a building level based on case study reference buildings. The carbon footprint of building services over a 50-year building reference service life is estimated based on quantified schedules of services installed in four reference office buildings, two stand-alone houses, one MDH and one apartment building.

The greenhouse gas emissions were estimated for product, construction, use and end-of-life stages (see Figure 1). Benefits and loads outside the building life cycle were also calculated and are reported separately. The specific life cycle modules included are described in section 2.5.3.

The office and residential assessments were both undertaken excluding the benefits of carbon sequestration in bio-based materials. However, for the assessed buildings in this study, there were minimal bio-based products included and therefore biogenic carbon benefits were negligible.

The methodologies used to quantify the embodied carbon emissions of office and residential buildings were similar but with some minor differences. The specific methodologies adopted are described in sections 2.3 to 2.5, but in summary, the main differences between the methods used for residential and office buildings were as follows:

- The carbon footprint of the installed mechanical services, including refrigerants associated with heating, ventilation and cooling (HVAC) as well as electrical and plumbing services, was calculated for office buildings. Transport, including elevators and escalators, were not included in the study.
- The carbon footprint of the installed electrical and plumbing services was calculated for residential buildings, but data was not available on installed HVAC services in the reference buildings. An indicative carbon footprint associated with residential HVAC was estimated by assuming that a single air-source heat pump (5–6.5 kW) was installed in stand-alone houses and individual units in the MDH and apartment buildings.
- The carbon footprint associated with maintenance (Module B2) was assessed for office buildings (primarily due to manufacture of refrigerant to top up fugitive losses in use) where relevant. Replacement of lost refrigerant was not considered in the residential assessment. The impact is likely to be small in comparison with the impact of fugitive losses themselves, and any losses from systems in use are less likely to be topped up.

2.2 Comparison with other methodologies

This study takes a building-level approach to estimate the embodied carbon footprint of building services based on the estimated service life of the different services elements. The following sections provide a brief comparison of the method used in this study with two other recent methodologies used to estimate the carbon footprint of building services.

2.2.1 Carbon Leadership Forum (CLF)

The Carbon Leadership Forum (2019) estimated the carbon footprint of building services based on eight hypothetical office buildings in the Pacific Northwest of the USA in consultation with local mechanical and electrical engineers and contractors. These hypothetical buildings covered four size categories and two energy performance categories. In contrast, the current study is based on material quantity take-offs of actual office buildings located in New Zealand main centres.

The CLF study compiled embodied carbon footprint data for services products based on embodied carbon databases and product-specific environmental product declarations (EPDs). The Germany-based ÖKOBAUDAT database[1] is used as the main data source, followed by the USA-based Quartz Project database.[2] The CLF study uses EPDs or French-based product environmental profiles (PEPs) only for MEP items that are not listed under the ÖKOBAUDAT database. The current study uses similar information sources as well as data from the BRANZ LCAQuick database. (See section 2.5.1 for more detail on these information sources.)

The primary difference between the current study and the CLF study is the life cycle stages considered. The CLF study only calculates the product stage carbon footprint (Modules A1–A3) whereas the current study considers product, construction, use and end-of-life stages. The CLF study also estimates a lifetime carbon footprint based on a mid-range product phase carbon footprint and an assumption that all building services are replaced every 15 years (the initial installation plus three replacements of all services over a 50-year building service life). The CLF study also assessed the impact of refrigerants separately whereas the current study incorporates the impact of refrigerant manufacture and use into the main assessment.

2.2.2 Chartered Institution of Building Services Engineers (CIBSE)

The CIBSE methodology is a product-level methodology for MEP products used for heating, cooling, ventilation, lighting, electrical and public health, which was published following completion of much of this study.

The CIBSE methodology provides two levels of calculation to estimate the carbon footprint of a MEP product where a product-specific EPD is not available. Both the basic and mid-level CIBSE methodologies require some level of product-specific manufacturer information, with the basic method using several scale-up factors to estimate missing information. The CIBSE calculation methods provide the lifetime carbon footprint at the product level but not at the building level and therefore do not include calculation of Module B4 (replacement).

In common with the method used in this study and the CLF methodology, the CIBSE calculation methodologies are only concerned with embodied impacts and therefore do not include Module B6 (operational energy use) or B7 (operational water use).

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[1] www.oekobaudat.de/no_cache/en/database/search.html –a standardised database for ecological evaluations of buildings provided by the German Federal Ministry for Housing, Urban Development and Building. It includes an online database with life cycle assessment datasets on building materials, construction, transport, energy and disposal processes.
[2] https://pharosproject.net/common-products – the Quartz Project was a database of life cycle impacts of common building projects that has now been integrated into the Pharos database.

2.2.3 Ministry of Business, Innovation and Employment (MBIE)

MBIE published its *Whole-of-life embodied carbon assessment: Technical methodology* as part of its Building for Climate Change programme in 2022. In addition to requiring a building service life of 50 years as the basis for assessment, it also sets out mandatory and voluntary elements for inclusion in the building carbon footprint.

With respect to services, HVAC is included as mandatory, with other services products considered as voluntary (water, drainage, electrical services and other building systems such as fire and security systems).

2.3 Reference buildings

2.3.1 Residential

The reference residential case study buildings in this study include two detached houses, one MDH and an apartment (see Table 1).

Table 1. Details of residential reference buildings.

Residential building	Gross floor area (GFA)	Number of bedrooms	Number of storeys
Detached house 1	160 m²	4	2
Detached house 2	242 m²	5	2
MDH	154 m² per unit 616 m² total – 4 units	3	3
Apartment	2,629 m² total Apartment levels 2–8 Ground floor retail, Level 1 commercial 3,895 m² total including circulation space and ground floor	Standard – 1 Penthouse – 3	9 (whole building)

2.3.2 Office

Four case study office buildings located in New Zealand main centres were used in this study (see Table 2).

Table 2. Details of office reference buildings.

Office building	Location	GFA (m²) (rounded)	Storeys	HVAC and plumbing system components
Office 1	Christchurch	8,000	6	4 pipe (water) fan coil unit (FCU) air conditioning, air handling units (AHU), artesian water source heat pump for central heating and cooling water, domestic hot water (DHW) heat pump
Office 2	Wellington	5,000	11	Variable refrigerant flow (VRF) air conditioning, gas boiler hydronic radiators, natural ventilation with small mechanical systems for internal area and extract zones, electric cylinder DHW
Office 3	Christchurch	25,000	5	AHU, VRF air conditioning, DX (direct exchange) split system heat pumps, electric cylinder DHW
Office 4	Christchurch	1,700	5	4 pipe (water) FCU air conditioning, AHU, reversible air source heat pump for central heating & cooling water, electric cylinder DHW

2.4 Estimating services

2.4.1 Residential

Ortus International Ltd provided a schedule of services items for each of the case study residential buildings, focusing on electrical and plumbing items. The identity of the buildings themselves was not provided. Measurements and estimates were made from drawings for each building using standard measurement protocols, as defined by the New Zealand Institute of Quantity Surveyors.

Information on HVAC services in the reference residential buildings was not available – in particular, whether owners have heat pumps installed post-occupation. HVAC services (interpreted here as heat pumps) were anticipated to be a potentially significant contributor to the services carbon footprint. Therefore, to provide an estimate of the role of HVAC services in residential buildings, it was assumed that a single heat pump (5–6.5 kW) was installed in each dwelling. This size of heat pump is typical of domestic heat pumps used in New Zealand houses but may represent an underestimate for heating services in a multi-bedroom detached house and an overestimate for the one-bedroom apartments included in this study. The results presented for residential HVAC services are therefore considered indicative only.

2.4.2 Offices

Beca analysed the 3D Revit design models used to produce construction drawings for case study buildings 1, 3 and 4 and the as-built drawings for case study building 2 to derive estimated quantities of services systems components. As with the dwellings, the identities of the buildings remained confidential. Supporting specific product information was additionally provided as well as estimated service lives and any assumptions or estimates.

A mass threshold of 1% was adopted for the first case study building, meaning that service items within the scope of the study and contributing 1% or more of the total mass of included services were in the final schedule. For the remaining three office buildings, a 3% mass threshold was used (excluding refrigerants, which were included irrespective of mass threshold), meaning that fewer items were included in the final schedule.

Services elements associated with HVAC, electrical and plumbing were calculated for all four office building case studies based on the schedules developed by Beca. Fire protection elements were only included for Office 3 and Office 4. Details on the fire protection design were not available for Office 1 and therefore could not be quantified. Office 2 is not sprinkler protected, and the remaining fire protection elements (smoke detectors/alarm points, wiring, alarm panel and hose reels/hydrants) were considered to be minor contributors and were not quantified.

Exclusions to the scope of office building services were:

- gas services elements were generally not quantified except for Office 3 where the gas pipework associated with the retail tenancies within the building were included
- retail tenancy fit-outs
- vertical transport services.

2.5 Calculating the carbon footprint

2.5.1 Information sources

The following information sources on the carbon footprint of building services products have been utilised for this study:

- **Environmental product declarations (EPDs)**[3] are independently verified and registered documents that communicate transparent data and other relevant environmental information about the life cycle environmental impact of products. EPDs are specific to a particular product or group of products.
- **PEP ecopassport** is the international reference programme for environmental declarations of products (PEPs) from electric, electronic and heating and cooling industries. The programme is based in France, and most products contained within the database are of European origin.
- **LCAQuick**[4] is a New Zealand-based free tool developed by BRANZ that evaluates the carbon footprint and other environmental impacts of a building design utilising data from EPDs, modelling using the proprietary database Ecoinvent and other data sources. A limited number of building services products were already available within the LCAQuick database but with most missing as services have largely been outside the scope of the tool. However, where relevant, data within LCAQuick was also utilised to approximate the impacts of some building services products based on the material composition of the products.
- **Ecoinvent**[5] is a global life cycle inventory database covering a wide range of activities, materials and industries.
- **Published life cycle assessment literature** was utilised for a limited number of product types or materials.

Where available, EPDs representing specific products manufactured or imported into New Zealand have been utilised as the highest-quality data source. However, EPDs for building services products are limited and EPDs for New Zealand-produced products extremely so. This required the use of proxy data representing similar products or an assessment based on the main materials making up a product.

This proxy data was predominantly used to represent the product stage carbon footprint of a product (Modules A1–A3) with the remaining modules calculated based on New Zealand conditions:

- Transport distances associated with import to New Zealand and transport to the building site (Module A4) or to end-of-service-life destination (Module C2) were estimated using Ecoinvent data for land and sea transport and standardised BRANZ LCAQuick assumptions regarding transport distances.
- Wastage rates of materials such as wiring and piping during installation (Module A5) were estimated based on wastage rates within LCAQuick. A zero-wastage rate was assumed for products supplied as whole units (such as heat pumps, LED lights).
- HVAC refrigerant leakage rates associated with products in use (Module B1) were estimated based on standard leakage rate assumptions in CIBSE (2021), which vary between 2–6% per year depending on the type of HVAC system used.

[3] https://epd-australasia.com/
[4] https://www.branz.co.nz/environment-zero-carbon-research/framework/lcaquick/
[5] https://ecoinvent.org/

- The anticipated service life and replacement frequency of products (Module B4) for office building services was estimated by Beca based on industry expertise and CIBSE (2019) guidance. The service life of residential services was estimated based on the estimates in relevant EPDs or PEPs or for materials in LCAQuick.
- End-of-life disposal routes (Modules C1–C4) were based on the assumptions within LCAQuick where available. Where no information was available, a conservative approach of 100% landfill was generally adopted.

Refer to Appendix A for a list of data sources used. A small number of building services elements were excluded from the assessment due to a lack of relevant data. These items are considered likely to represent an insignificant contribution to the overall carbon footprint.

2.5.2 Data quality

The quality of the data used to estimate the carbon footprint of the office and residential services products was assessed using the data quality descriptors within CO_2NSTRUCT[6] and ranked from good quality (A) to poorer quality (G). A summary of these descriptors and the number of different products that were considered to fall in each quality level are contained in Table 3.

Table 3: Summary of carbon footprint data quality for office and residential services.

Data quality level	Description of data quality level	Residential services elements	Offices services elements
A	EN 15804-compliant EPD, specific product, geographical scope includes manufacture in New Zealand or manufacture of product overseas, which may be imported to New Zealand. Product – specific.	4	3
B	EN 15804-compliant EPD, sector average, manufacture in New Zealand or manufacture of product overseas, which may be imported to New Zealand. Product – average.	1	2
C	EN 15804-compliant EPD, specific product or sector average, geographical scope excludes New Zealand but data used as a proxy for product used in New Zealand. Product – proxy.	-	1
D	EPD, compliant with another standard (e.g. ISO 21930), specific product or sector average, geographical scope includes manufacture in New Zealand or manufacture of product overseas, which may be imported to New Zealand. Data may be used as a proxy for New Zealand product. Product – proxy.	2	-
E	Other form of published product or sector average carbon footprint or LCA (e.g. PAS 2050). Product – proxy.	5	9
F	Unpublished or published data based on modelling taking into account local conditions using a mix of primary data and generic data (e.g. from EPDs, AusLCI, Ecoinvent). May include data gaps. Product – generic.	1	33
G	Unpublished or published result based on modelling/assumptions that do not take account of local conditions. May include data gaps. Product – generic.	-	-

[6] https://www.branz.co.nz/environment-zero-carbon-research/framework/branz-co2nstruct/

The quality of the product-level embodied carbon footprint data is relatively evenly spread for the residential services although there is more data of a lower quality level than a high level. The office services are predominantly at the lower levels of data quality with the majority assessed as quality levels E or F. This reflects the low number of EPDs that are available for commercial services elements particularly for the specific products used in New Zealand buildings.

2.5.3 Life cycle modules assessed in this study

These life cycle modules and stages were assessed in relation to services within dwellings:

- Modules A1–A3: Product stage.
- Modules A4–A5: Construction process stage.
- Module B1: Use stage – installed product in use (refrigerant loss).
- Module B4: Use stage – replacement only.
- Modules C1–C4: End-of-service-life stage.

These life cycle modules were assessed in relation to services within office buildings:

- Modules A1–A3: Product stage.
- Modules A4–A5: Construction process stage.
- Module B1: Use stage – installed product in use (refrigerant loss).
- Modules B2 and B4: Use stage – maintenance and replacement only.
- Modules C1–C4: End-of-service-life stage.

Module B1 emissions associated with HVAC refrigerant losses are included in the assessment as refrigerant losses over the lifetime of HVAC products. These were expected to be a significant contributor to the embodied carbon footprint (CIBSE, 2021; Carbon Leadership Forum, 2019). It was assumed that any refrigerant loss was recharged each year (offices only).

Module B2 (maintenance) emissions were included for office buildings where data was available but are generally considered to be insignificant and were therefore not assessed in relation to residential buildings.

Module D (benefits and loads beyond the system boundary) were calculated where recycling or reuse of materials was assumed at end of life. However, this value is reported separately to the modules within the system boundary in section 3. It was assumed all services materials used in dwellings were landfilled except for the metal components of heat pumps.

This study is only concerned with the embodied carbon footprint of building services and therefore emissions associated with Module B6 (operational energy use) and Module B7 (operational water use) were not included.

3. Results

3.1 Dwellings

3.1.1 Embodied carbon footprint summary

Figure 2 summarises the calculated life cycle carbon footprints (excluding Module D) of each of the case study dwellings assessed in this study divided into the contribution from mechanical, electrical and plumbing services. The values in Figure 2 are presented normalised per m² GFA over a 50-year building service life in line with the MBIE embodied carbon technical methodology (MBIE, 2022).

The results for the apartment building are presented for both the areas of the building used as apartments (AP) and for the whole building including apartments, circulation spaces, retail and commercial areas (AP-building). Mechanical services, represented by a heat pump in each separate dwelling, dominate the carbon footprint for all housing typologies, accounting for 55–86% of the total services carbon footprint.

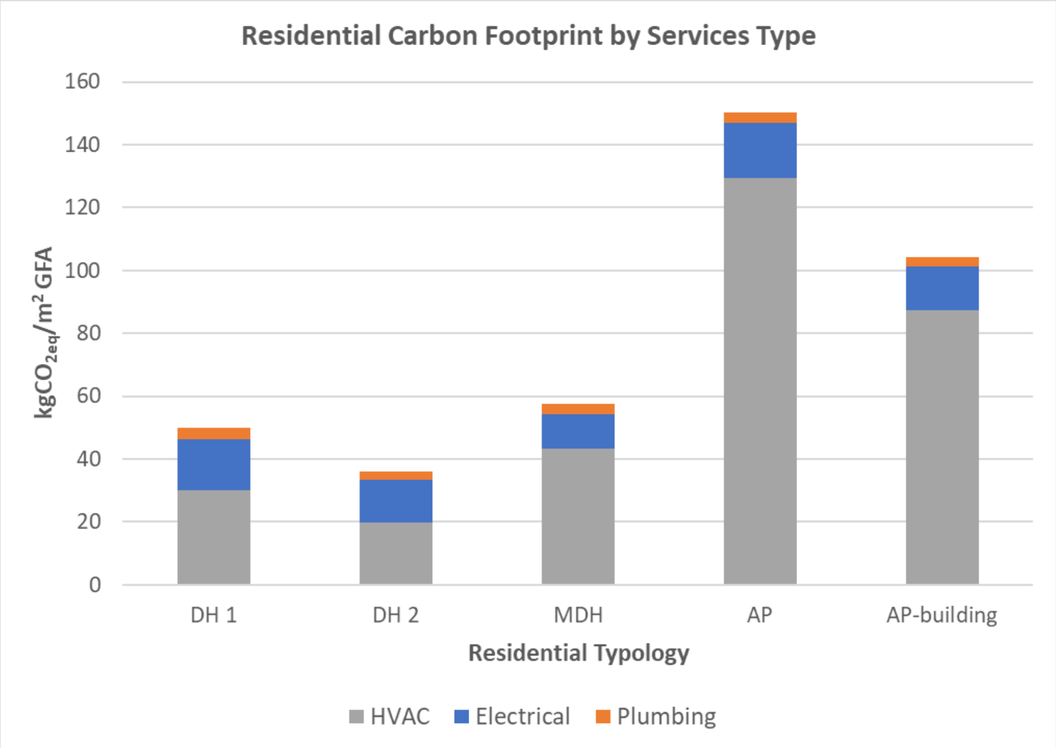

Figure 2. Carbon footprint of dwellings by services type.

Figure 3 provides the services carbon footprint of each of the dwellings split by the contribution from the different life cycle modules. This shows that most of the carbon footprint is due to Module B4 (50–59%), followed by Module B1 (21–23%) and Modules A1–A3 (11–22%). Therefore, the majority (71–82%) of greenhouse gas emissions from residential services appear to occur in the future.

A more detailed summary of the carbon footprint results for each dwelling is provided in Appendix B.

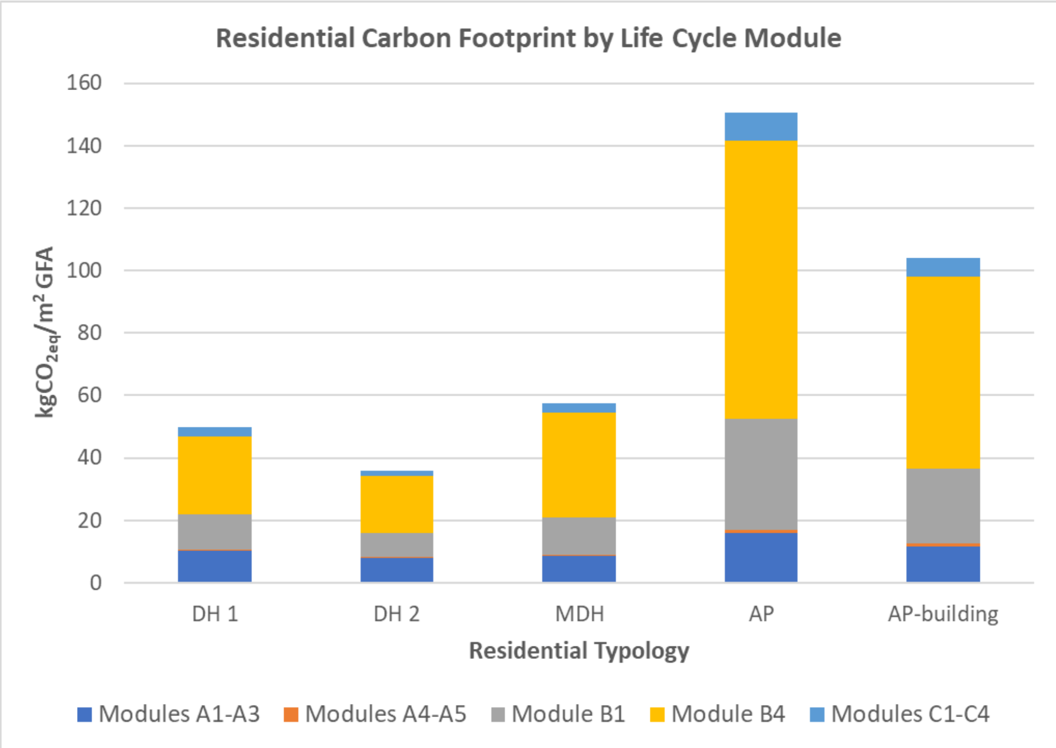

Figure 3. Carbon footprint of residential buildings by life cycle module.

3.1.2 Dwelling carbon footprint – MBIE methodology

This section presents the results of the case study dwellings according to MBIE (2022). The MBIE methodology recommends reporting emissions that occur in the present separately to future emissions and differentiating between carbon emissions and removals. Figure 4 to Figure 6 show the services embodied carbon footprint for each of the different dwelling typologies presented using the MBIE methodology.

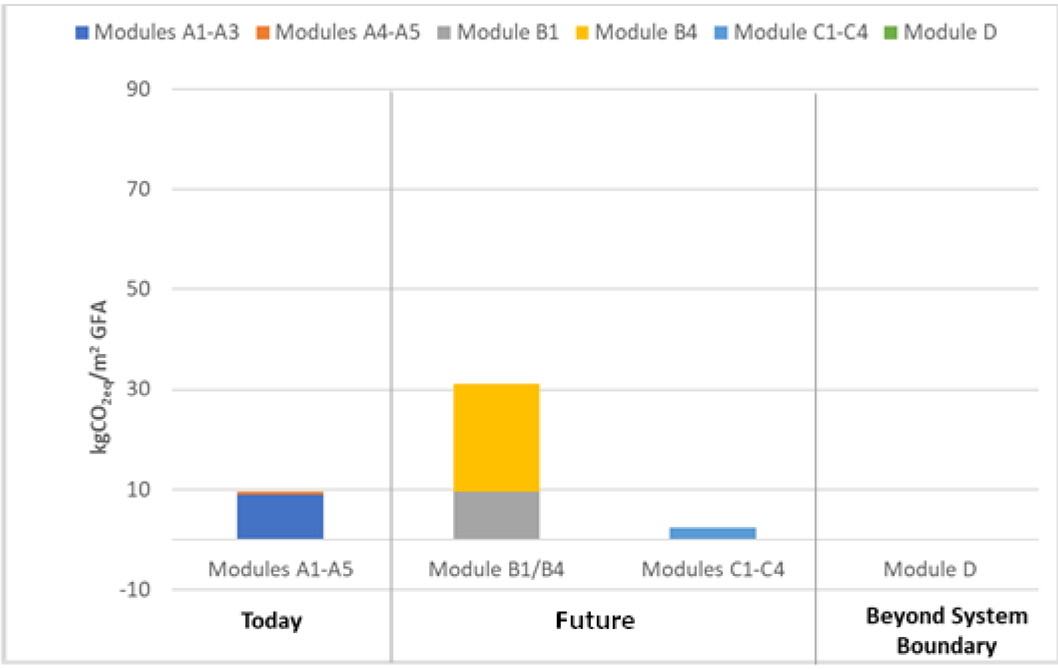

Figure 4. Carbon footprint of services for average of the two stand-alone houses – MBIE methodology.

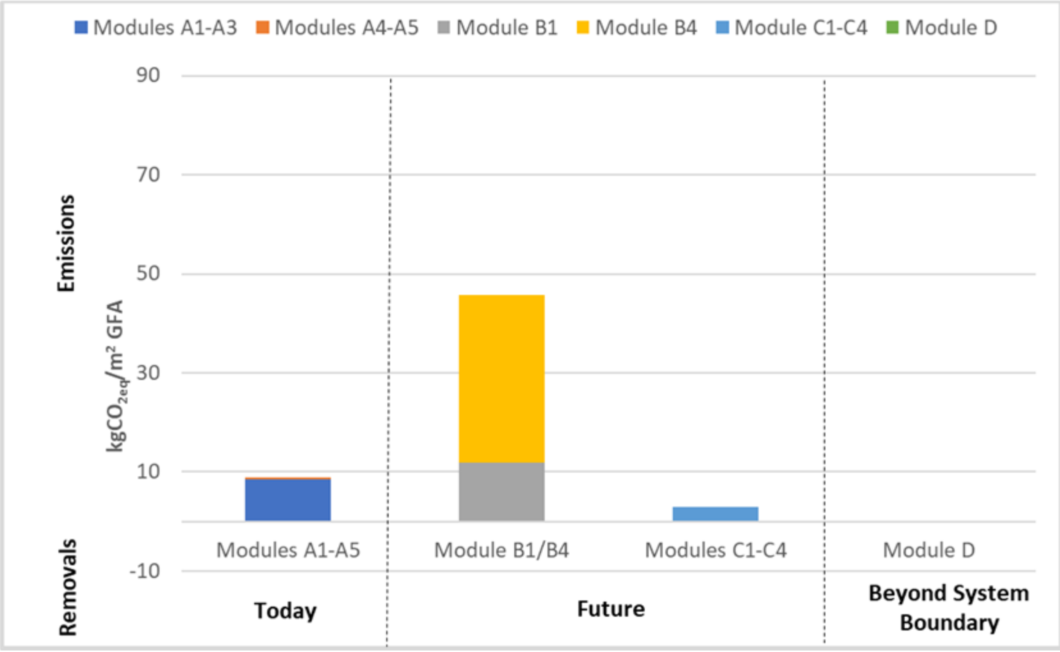

Figure 5. Carbon footprint of MDH services – MBIE methodology.

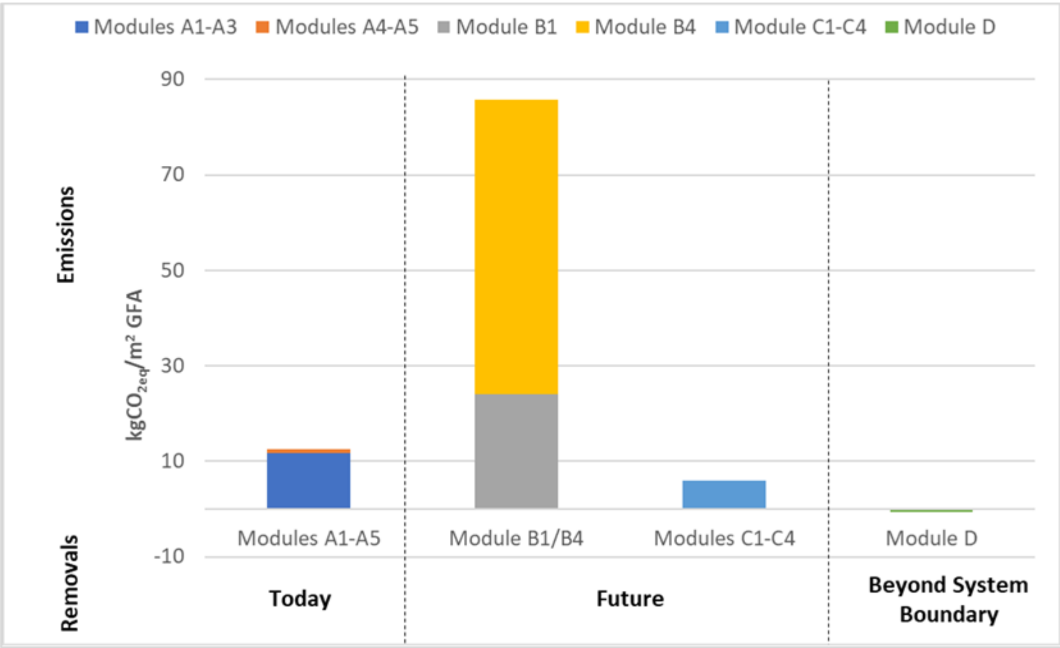

Figure 6. Carbon footprint of apartment building services – MBIE methodology.

Carbon removals in this study are minimal as there are no timber or other bio-based products included in the assessment (i.e. no removals due to biogenic carbon sequestration) and all services elements except metals within heat pumps are assumed to be landfilled at end of life (i.e. minimal benefits due to recycling under Module D). It is also noted that the MBIE methodology requires the mandatory reporting of HVAC elements under building services but water, drainage and electrical services as voluntary items. Using the MBIE methodology, the proportion of the services carbon footprint (excluding Module D) that occurs today is 22% for detached houses, 15% for MDH and 12% for the apartment building.

3.1.3 Services in comparison with the rest of the building

The carbon footprint of the other elements of the case study buildings was not available for this study. However, BRANZ has calculated carbon footprints for several residential typologies, including stand-alone houses, MDH and an apartment building. These carbon footprints included the structure, enclosure and interiors in scope but excluded building services (see Dowdell et al. (2020) for further details on these buildings).

Table 4 compares the carbon footprint of the dwellings (excluding services) on a per m² GFA basis (over 50 years) for these previously carbon footprinted dwellings and compares to the services carbon footprint calculated in this study also on a per m² GFA basis over a 50-year building service life.

The carbon footprints comprise Modules A1–A3, A4–A5, B1 (refrigerants only), B2 (excluding services), B4 and C1–C4.

Table 4. Comparison of residential building embodied carbon footprints and services carbon footprints.

Residential typology	Embodied carbon footprint – dwelling	Embodied carbon footprint – services	Total embodied carbon footprint – dwelling and services	Services contribution to total carbon footprint
	kgCO₂eq/m² GFA			
Stand-alone house[7]	254	43	297	14%[8]
MDH	296	58	354	16%
Apartment[9]	605	150	755	20%

Table 4 suggests that residential building services can contribute up to an additional 20% to the total dwelling carbon footprint irrespective of typology.

3.1.4 Residential services hotspots

This section assesses which services elements contribute the most to the services carbon footprint in dwellings (hotspots). Table 5 summarises the percentage contribution made by the most significant services elements to the total services carbon footprint for both the product stage (Modules A1–A3) and for all modules assessed in this study (all embodied) excluding Module D.

Heat pumps account for most of the embodied services impact over the service life of the building for all dwelling typologies and also account for the greatest proportion of the carbon footprint associated with the product stage for MDH and apartments.

The greatest contributor to the product stage carbon footprint for detached houses are LED lights, particularly interior LED lights, followed by PVC pipes, particularly exterior pipes. LED lights and PVC pipes are also important contributors to the product stage carbon footprint for MDH and apartments.

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[7] Average of two reference detached houses for services and four reference Code-compliant detached houses for the building.
[8] Note that this figure has been corrected (from 17% as orginally published).
[9] Based on residential parts of building only.

Table 5. Contribution to services carbon footprint (hotspots) – residential buildings.

	Stand-alone houses[1]		MDH		Apartments	
Category	**Modules A1–A3**	**Life cycle embodied**	**Modules A1–A3**	**Life cycle embodied**	**Modules A1–A3**	**Life cycle embodied**
Heat pump	17%	58%	23%	75%	33%	84%
LED lights (interior)	24%	21%	19%	11%	22%	10%
LED lights (exterior)	9%	8%	5%	3%	0%	0%
Wiring/cables	11%	3%	8%	2%	16%	2%
PVC pipes (outside)	23%	5%	19%	3%	4%	0%
PVC pipes (inside)	9%	2%	17%	3%	16%	2%
Other[2]	7%	3%	9%	3%	9%	2%

Notes:
1. Average of the two stand-alone houses.
2. Items within the other category account for <5% of total impact each and include switchboard, meter, pendant lighting, switches and plug outlets (for example).

3.2 Office buildings

3.2.1 Office building services embodied carbon footprint summary

Figure 7 provides a summary of the services carbon footprint of each of the office building case studies assessed in this study, divided into the contribution from mechanical, electrical, plumbing, gas and fire services (noting the limitations for gas and fire services in section 2.4.2). The values in Figure 7 represent the embodied carbon per m² GFA over a 50-year building service life for all life cycle modules (excluding Module D) assessed in this study.

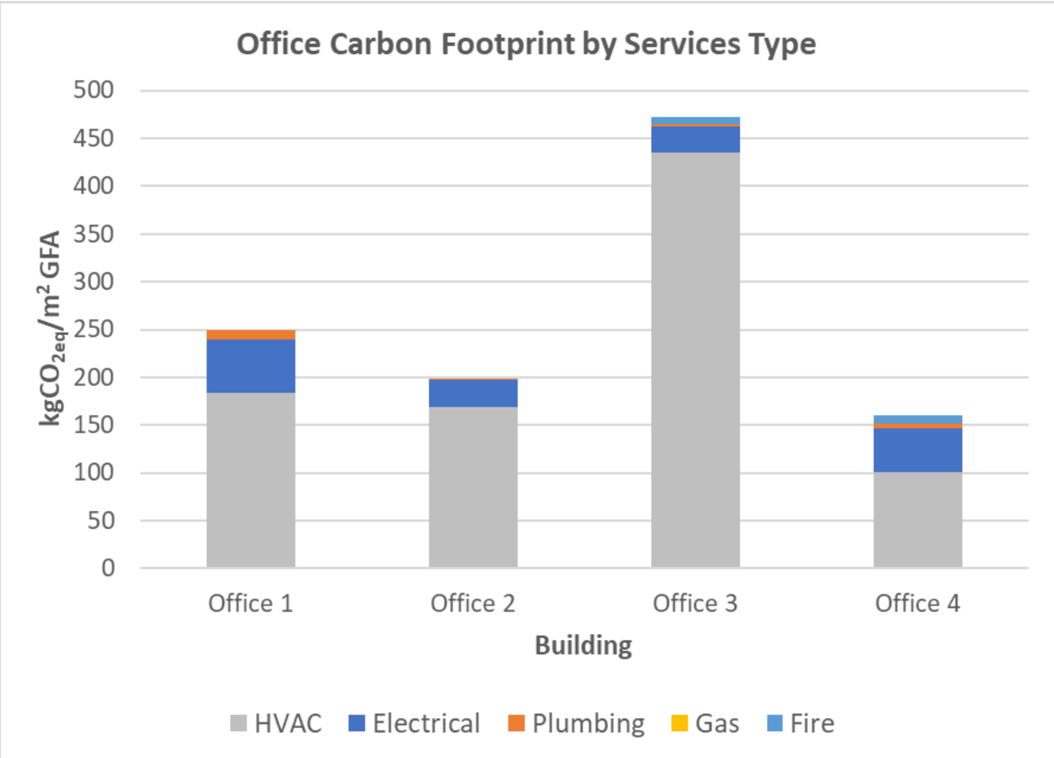

Figure 7. Carbon footprint of office buildings by services type.

Figure 8 provides the carbon footprint of each of the case study office buildings divided into the different life cycle modules. In Office 2 and Office 3, most of the services carbon footprint is due to Module B1 (60% and 82% respectively), followed by Modules B2 and B4 (24% and 11% respectively) and Modules A1–A3 (14% and 7% respectively).

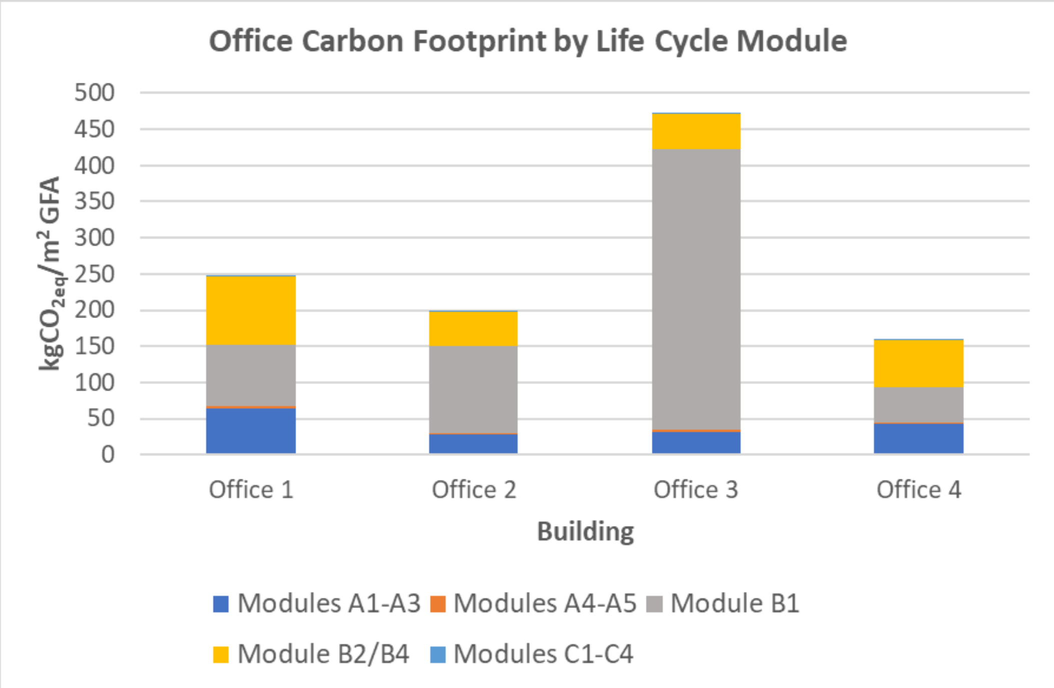

Figure 8. Carbon footprint of office buildings by life cycle module.

Module B1 is due to the annual loss of refrigerants during the use phase of the buildings. The high module B1 values in Office 2 and 3 appear to reflect the use of variable refrigerant flow/volume (VRF) HVAC systems in these buildings, which require greater quantities of refrigerants and for these refrigerants to be circulated around the building. The refrigerant distribution system can be prone to damage, which, along with the higher charge, results in a higher annual loss rate of refrigerant. A 6% annual loss of refrigerant was applied for VRF systems as recommended in CIBSE (2021). This compares to 2% recommended leakage rate for systems that do not require reticulation of refrigerant.

In Office 1 and Office 4, the contributions from Modules A1–A3, Module B1 and Modules B2 and B4 are more evenly spread, with the greatest contribution from Modules B2 and B4 (38% and 42% respectively) followed by Module B1 (34% and 30% respectively) and Modules A1–A3 (26% and 27% respectively).

A more detailed summary of the services carbon footprint results for each office building is provided in Appendix C.

3.2.2 Office carbon footprint – MBIE methodology

Figure 9 to Figure 12 show the services carbon footprint for each of the four office buildings presented using the MBIE methodology (see section 3.1.2).

Using the MBIE methodology, the proportion of the carbon footprint that occurs today (excluding Module D) varies between 7% for Office 3 and 28% for Office 4.

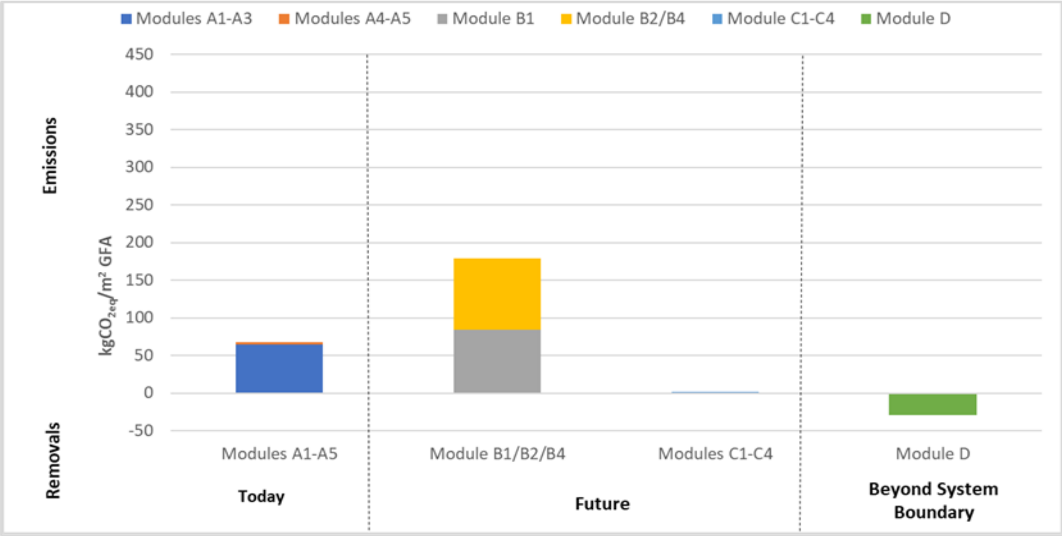

Figure 9. Carbon footprint of services for Office 1 – MBIE methodology.

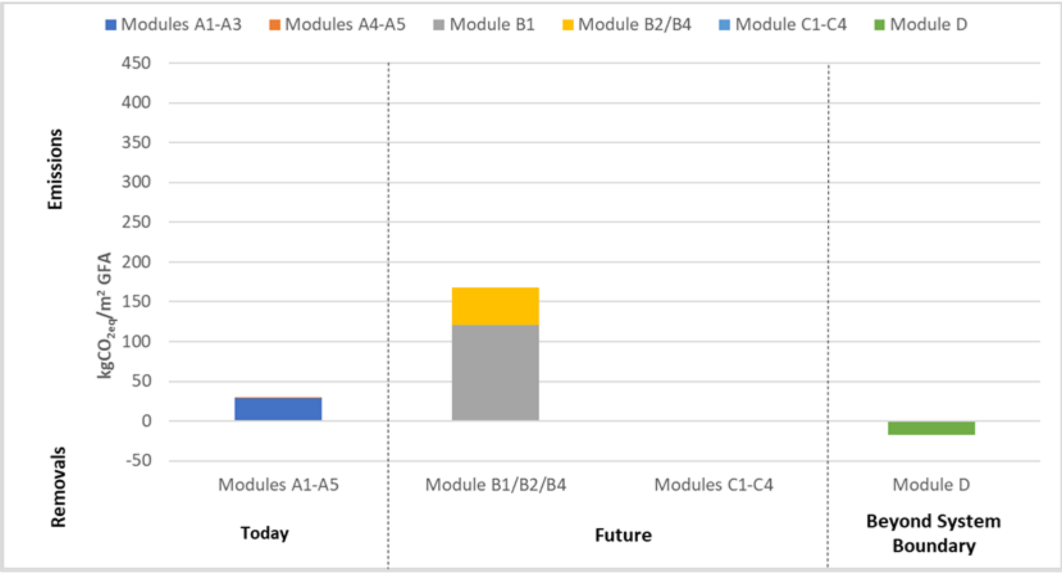

Figure 10. Carbon footprint of services for Office 2 – MBIE methodology.

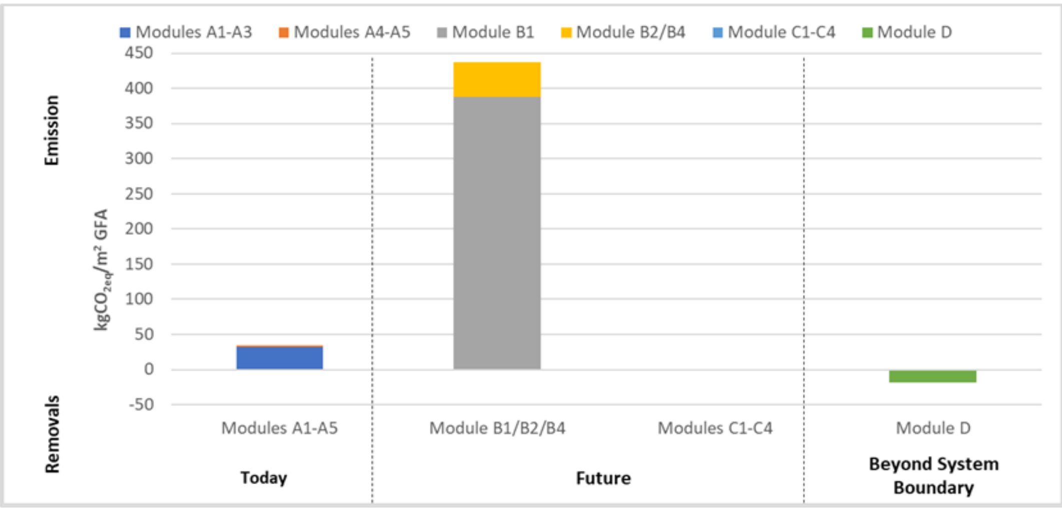

Figure 11. Carbon footprint of services for Office 3 – MBIE methodology.

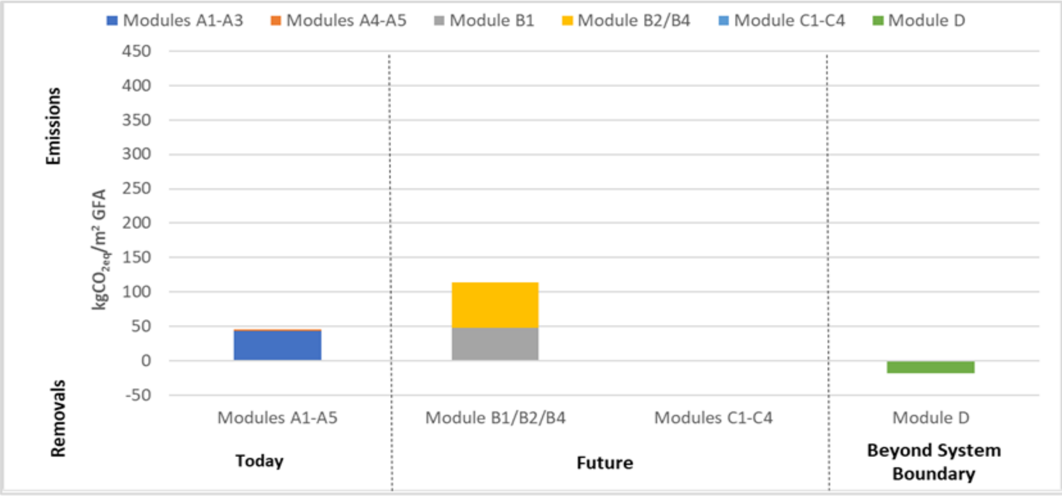

Figure 12. Carbon footprint of services for Office 4 – MBIE methodology

3.2.3 Services in comparison with the rest of the building

The building carbon footprint was not available for the case study office buildings used in this assessment. However, the carbon footprint of some office buildings (structure and enclosure but excluding fit-out) has previously been calculated by BRANZ for other reference office buildings of various sizes (Berg et al., 2016). Table 6 compares the services carbon footprint on a per m² GFA basis over a 50-year service life with the carbon footprint of office buildings (excluding services and fit-out) also on a per m² GFA basis.[10] These normalised metrics provide a basis for comparison that can provide an indication of the additional contribution services can make to an office building carbon footprint. The lifetime carbon footprint is based on Modules A1–A3, A4–A5, B1 (refrigerants only), B2, B4 and C1–C4. The structure and envelope carbon footprint values are based on buildings of a similar size range to the buildings in this study.

Table 6. Comparison of office building embodied carbon footprints (excluding fit-out) and services carbon footprints.

Office building	Embodied carbon footprint – building (excl. fit-out)	Embodied carbon footprint – services	Embodied carbon footprint – building (excl. fit-out) and services	Services contribution to total embodied carbon footprint
	kgCO₂eq/m² GFA			
Office 1	435	249	684	36%
Office 2	435	199	634	31%
Office 3	409	472	881	54%
Office 4	349	160	509	31%

Beca's own carbon footprinting of mid-rise and low-rise case study office buildings (comprising frame, foundations, upper floors and envelope) provides a modules A1–A5 carbon footprint in the range 500–550 kg CO_2eq/m² (personal communication). Based on this, the services contribution would be lower than shown in Table 6.

[10] Note that transport (elevators, escalators etc.) was excluded from the study.

3.2.4 Office building services hotspots

An assessment of the services elements contributing to the carbon footprint in office buildings (hotspots) was undertaken. Table 7 to Table 10 show the percentage contribution to the total assessed services carbon footprint from the most significant services elements for both the product stage (Modules A1–A3) and for all embodied modules assessed in this study excluding Module D for each of the office buildings.

Table 7. Contribution to carbon footprint (hotspots) – Office 1.

Category	Modules A1-A3	All Embodied
HVAC water pipework	16%	9%
Sheet metal ductwork	9%	5%
Fan coil units	9%	7%
Air terminals	5%	3%
Chiller refrigerant	0%	32%
Cable trays	6%	3%
UPS batteries	1%	5%
Generator	5%	3%
Lighting	8%	6%
Copper pipework	7%	2%
Other	35%	26%

Table 8. Contribution to carbon footprint (hotspots) – Office 2.

Category	Modules A1-A3	All Embodied
HVAC water pipework	8%	3%
Sheet metal ductwork	9%	3%
VRF heat pump split systems	13%	8%
VRF refrigerant	0%	61%
Louvres	8%	2%
Perimeter radiators	12%	5%
Cable trays	8%	2%
Lighting	20%	9%
Other	22%	7%

Table 9. Contribution to carbon footprint (hotspots) – Office 3.

Category	Modules A1-A3	All Embodied
Sheet metal ductwork	14%	2%
Air terminals	5%	1%
Air handling units	8%	2%
VRF system	14%	3%
VRF refrigerant	1%	82%
Cable trays	7%	1%
Lighting	15%	3%
Sprinkler pipework	11%	2%
Other	25%	4%

Table 10. Contribution to carbon footprint (hotspots) – Office 4.

Category	Modules A1-A3	All Embodied
Chiller/heat pump	8%	7%
Sheet metal ductwork	7%	4%
Fan coil units	10%	8%
Air terminals	6%	3%
Chiller/heat pump refrigerant	0%	28%
Cable trays	7%	4%
Lighting	21%	17%
Electrical boards	6%	4%
Sprinkler pipework	10%	6%
Other	24%	18%

Items within the Other category for each building commonly included pumps, fans, equipment restraints, cabling, flexible ductwork and polypropylene pipework. The larger contribution of the Other category for building 1 may be due, in part, to the lower materiality threshold employed for that building – 1% by mass of services instead of 3% used for buildings 2–4. In other words, a proportion of this may be due to the cumulative carbon impact of components that individually comprise less than 3% by mass but more than 1% by mass of the services in the building.

Refrigerants account for most of the embodied services impact over the service life of all four office buildings but are negligible contributors to the product stage, reflecting the significant carbon footprint associated with the estimated fugitive annual loss of refrigerants during use.

The greatest contributors to the services product stage carbon footprint varies between the different offices. Those elements accounting for more than 10% of the product stage carbon footprint include lighting (Offices 2, 3 and 4), HVAC water pipework (Office 1), VRF systems (Offices 2 and 3), sheet metal ductwork (Office 3), perimeter radiators (Office 2) and sprinkler pipework (Office 3). These hotspots demonstrate the importance of both the components of HVAC systems (other than refrigerants) and metal-based materials to the product stage carbon footprint of office services.

4. Discussion and conclusions

4.1 Discussion

4.1.1 Hotspots

HVAC systems and refrigerants

The annual loss of refrigerants from HVAC systems was a clear hotspot for both residential and office building services. The other components of HVAC systems (residential heat pumps, VRF systems, pipework and radiators) were also important contributors to the product stage carbon footprint for both residential and office building services. This finding is consistent with similar studies investigating the carbon footprint of building services (see section 4.1.2).

These findings are dependent on some important assumptions in relation to HVAC systems. The most significant assumption in relation to the office buildings is the percentage loss of refrigerant per year during the use stage. A 2% per year loss rate was used for Office 1 and 4 as these buildings use heat pump/chiller systems with minimal refrigerant handling on site. In contrast, a 6% per year loss rate was used for Offices 2 and 3 as these buildings use VRF HVAC systems, which involve a large amount of refrigerant pipework that needs to be refilled on site. These loss rates reflect the recommended default annual leakage rates for refrigerants in CIBSE (2021). The significance of refrigerant losses to the overall services carbon footprint means that adopting different assumptions can result in significantly different results. It should also be noted that information on the quantity of refrigerant installed in some of the HVAC systems was difficult to obtain and is based on best estimates in some cases (such as Office 3).

Whilst the quantity of refrigerants used may be small in relation to other services products, the high global warming potential (GWP) of many refrigerants used in HVAC systems means that their contribution can be significant.

Specific information on the HVAC systems in the residential reference buildings were not available. To provide an indicative contribution from HVAC systems, it was assumed that a single 5–6.5 kW heat pump was installed in each dwelling. This assumption may be an underestimate in some cases, particularly for the detached houses. On the other hand, a 5–6.5 kW heat pump may be an overestimate of the heating capacity required in the mostly one-bedroom apartment units.

Other hotspots

Lighting is another important component of the carbon footprint of services in both residential and office buildings. One of the factors contributing to the importance of lighting over the lifetime of a building is the relatively high replacement frequency of lighting with a reference service life of 15 years, which is based on the stated service life in the relevant LED light EPDs and the default service life used for LEDs in LCAQuick.

In residential buildings, PVC piping was also an important contributor to the product stage carbon footprint in residential buildings but was less significant over the lifetime of the building due to the long service life of PVC pipe (>50 years), which means that these pipes are not replaced during the 50-year service life of the building.

In office buildings, the other important contributors to the services carbon footprint tended to be metal-based elements (steel and aluminium), which reflects the relatively high embodied carbon of these materials.

4.1.2 Benchmarking

There are a limited number of studies that quantify the embodied carbon footprint of building services. A study by the Carbon Leadership Forum (2019) quantified a carbon footprint range for mechanical, electrical and plumbing (MEP) building services based on theoretical commercial building models in the Pacific Northwest of the USA. The methodology used in the CLF study differed to the approach taken in this study (see section 2.2.1) but provides a useful benchmark against which to compare results. The CLF study found a services carbon footprint range of 40–75 $kgCO_2eq/m^2$ for the product stage (Modules A1–A3). The range of product stage emissions for the four office buildings included in this study was lower at 29–64 $kgCO_2eq/m^2$.

To provide an estimate of the contribution of MEP services over the lifetime of a building, the CLF took a medium estimate of product stage MEP emission of 60 $kgCO_2eq/m^2$ and assumed that the MEP elements were fully replaced every 15 years, resulting in an embodied carbon footprint of 240 $kgCO_2eq/m^2$ over a 50-year building service life. In the current study, if refrigerant emissions are excluded as they were in the CLF study, the range of services lifetime emissions for the four office buildings is 78–164 $kgCO_2eq/m^2$, which is significantly lower than the CLF estimate. This difference reflects the lower range of Module A1–A3 carbon footprints found in the current study compared to the CLF study and the different approach to replacement of services elements. The replacement frequency in this study is based on the anticipated service life of the individual elements.

Replacement frequency is a complex aspect of a building's service life to model particularly for elements associated with commercial building fit-out. Forsythe and Wilkinson (2015) and Forsythe (2017) have highlighted the role of tenancy changes on the embodied energy of commercial buildings in Australia. The frequent change of tenants in commercial buildings combined with 'make good' tenancy clauses that require the outgoing tenant to return a building to its condition at the start of the tenancy mean that elements associated with office building fit-out, including services, can often be replaced on a much shorter frequency than would be suggested from the expected service life of individual elements. The frequency of tenant changeover in a New Zealand context was not within the scope of this project, but Forsythe (2017) estimated a fit-out churn rate[11] of 8.2 years for prime office buildings in the central business district of Sydney. A similar churn rate combined with the removal and replacement of the associated building services could result in a higher carbon footprint over a building's service life than indicated by the approach taken in this study.

The role of refrigerants was examined separately in the CLF study as most impacts associated with refrigerants do not occur during the product stage. However, refrigerants were identified as a high impact item within the CLF study as well as air handling units and other large, heavy units, galvanised sheet metal for ductwork, light fixtures and cast-iron piping for wastewater and ventilation. These items are similar to the hotspots found in this study (section 4.1.1).

[11] The frequency of a new interior fit-out in a building due to a change of tenant or update by existing tenant.

The CLF also investigated the role of tenant improvements on the carbon footprint of office buildings, and Rodriguez et al. (2020) concluded that, with recurrent installation over the lifetime of a building, the combined carbon footprint of MEP and tenant improvement elements can equal that of the building structure and envelope elements. The current study did not include tenant improvements but supports this conclusion as building services (including refrigerant losses) were estimated to account for 30-40% of the total carbon footprint of a building over its service life (with one building showing a value of up to 54%). In residential buildings, services were a smaller but still significant contributor to the overall carbon footprint of the building at 16–20% of the total lifetime carbon footprint.

4.1.3 Study limitations

The main limitation of this study is the lack of relevant EPDs or other good-quality carbon footprint data for the specific products used in both the residential and office buildings. Less than 40% of the services elements in the residential buildings and only 10% in the office buildings were represented by product-specific or product-average EPDs for items produced or imported into New Zealand. The product stage carbon footprint for the remaining elements was generally estimated using overseas EPDs or PEPs produced for similar products or based on the material composition of a product with assumptions made regarding transport, installation and replacement frequency. The accuracy of resulting carbon footprint values compared to the specific products used is difficult to determine.

Another limitation of the study is the incomplete nature of the schedule of quantities. As noted previously, there was no information available on HVAC systems in the residential buildings and assumptions were made regarding a single heat pump in each building to provide an estimate for this service category.

A detailed schedule of quantities was developed for most office building elements, but there were some information gaps (such as a fire protection system in Office 1) or instances where estimates were made based on the best available data (such as refrigerant volumes in Office 3). In addition, a more detailed assessment was undertaken for Office 1 compared to the other office buildings. The schedule of quantities for Office 1 was based on inclusion of all elements that comprised 1% or more of the total building services by mass. In Offices 2–4, this level was increased to 3% or more by mass. Refrigerants were included for all four office buildings regardless of mass due to their anticipated significance.

The combined effect of the limitations in both carbon footprint data and the schedule of quantities for the services within the buildings is that the results presented in this report should be considered indicative rather than definitive. The results can be used to indicate the general areas of importance and to provide a guide as to where the biggest improvements are likely to be made as well as important areas for further study.

4.1.4 Next steps

This study has identified several areas where further study or better data is required to fully understand the role of the embodied carbon of building services to the whole-of-life carbon footprint of buildings.

There is clearly a need for more EPDs for the specific systems, products and materials used within New Zealand building services. A large proportion of the carbon footprint calculations used in this study were based on overseas products, which may not accurately reflect the embodied carbon of products used in New Zealand buildings.

This study has indicated that refrigerant loss during the use stage of building services is a very important contributor to a building's carbon footprint. However, this conclusion is based on several assumptions regarding refrigerant volumes, number and size of HVAC systems and refrigerant loss rates. Obtaining New Zealand-specific data to better quantify and understand the role of refrigerant loss would provide a more robust understanding of this issue.

The approach used in this study has potentially underestimated the contribution of services replacement in office buildings due to frequent changes in tenancy. Assessment of the frequency of tenancy churn in New Zealand office buildings and the typical extent of replacement of services elements due to tenancy changes would provide valuable information to further refine the estimates provided by this study.

This study has identified several areas for potential focus on reducing the embodied carbon of building services. Further investigation is required to identify the potential for reductions in these areas and any consequent implications for operational energy use.

These high-impact items are priorities for further assessment of reduction opportunities:

- **Use of low GWP refrigerants:** Different refrigerants can have very different GWPs. The role of refrigerant loss was particularly significant in office building systems where R410a was used or assumed to be used. R410a has a GWP of 2088. Refrigerant loss was still important but less dominant in residential buildings where R32 refrigerant, with a lower GWP of 675, was assumed. R32 is typically used in modern domestic heat pumps available in New Zealand. Prioritising the identification and use of lower GWP refrigerants in commercial HVAC systems could lead to significant reductions in the carbon footprint of office services.
- **Assessing the role of VRF HVAC systems:** The impact of refrigerant losses was very marked in Office 2 and Office 3 due to the use of VRF HVAC systems for which a higher annual refrigerant loss rate of 6% was used (based on CIBSE, 2021) together with a higher volume of refrigerant used in these systems and the need for on-site refilling. Refrigerant loss is not well researched in New Zealand, and there is merit in a study to evaluate this more closely. Consideration of HVAC systems needs to include the efficiency of the system and source(s) of energy, which contribute to the operational carbon footprint (not considered in this study). Based on the CIBSE methodology, VRF systems can be more energy efficient but may not necessarily be more carbon efficient. This highlights the need to consider both embodied and operational carbon, primarily because of refrigerant loss.
- **LED lighting:** LED lighting was an important contributor to the embodied carbon of services particularly in residential buildings. Reducing the use of LED lighting could potentially reduce embodied carbon but this needs to be balanced with potential implications for occupant wellbeing (need for adequate lighting) and energy use as LED lights are a very energy-efficient form of lighting.
- **Use of low embodied carbon materials:** Metal-based products or equipment were important contributors to the carbon footprint of services. Minimising the weight of high embodied carbon materials used or using alternative materials is a potential means to minimise the embodied carbon of services. Where these materials are used, they should be recycled when they reach their end of life.

4.2 Conclusions

The embodied carbon associated with building services is an important contributor to the embodied carbon footprint of both residential and office buildings. This study estimated that the embodied carbon footprint of services accounts for 16–20% of the total embodied carbon footprint in residential buildings. In office buildings, the services component was estimated to be 30-40% of the total.

HVAC systems were the most important contributors to the embodied carbon of services in both residential and office buildings and refrigerant losses were a significant component of this impact particularly in office buildings. HVAC is the only mandatory services element in the MBIE (2022) methodology.

Other important contributors to the carbon footprint of services were LED lighting, PVC piping (residential buildings) and metal-based products (office buildings) such as sheet metal ductwork, fan coil units, cable trays, pipework and radiators. Transport services (such as elevators and escalators) were excluded from the study.

These results are consistent with but lower than the results obtained in a similar study by the Carbon Leadership Forum (2019).

This study has identified several areas where further investigation or better New Zealand-specific data would enable a more robust analysis of the importance of building services to the embodied carbon footprint of residential and office buildings. This includes a need for more EPDs specific to New Zealand building services products, better data on both residential and office HVAC systems, including refrigerant loss rates, and a better understanding of the role of tenancy turnover on the replacement frequency of office building services.

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Appendix A: Data sources

PEP ecopassport

- Atlantic (2016). Air handling unit (PEP-PCR-ed 3-FR-2015 04 02).
- Eaton (2019). UltraLED – Planete 45. (EATO-00005-V01.01-FR).
- Hager (2017). Movement detectors 360°. (HAGE-00127-V01.01-EN).
- JA Solar (2018). JAP60 poly-crystalline silicon 60 cells PV panel. (JASO-00002-V01.01-EN).
- Legrand (2019). AF series raised floor boxes. (LGRP-01145-V01.01-EN).
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- Legrand (2020). Mosaic two-way switch – 10 AX. (LGRP-01210-V01-01-EN).
- Legrand (2021). DLPlus mini-trunking system. (LGRP-01349-V01.01-EN).
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Environmental product declarations (EPDs)

- EPD Australasia (2015). iPlex Pipelines PVC non-pressure pipes for building applications. (S-P-00713)
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- IBU (2018). Grundfos MAGNA3 circulator pumps 25-40/60/80/100/120 (Cast iron). (EPD-GRU-20180144-CCC1-EN)
- IBU (2018). Thorn Wall/Ceiling mounted LED luminaire NOVALINE LED1800-830 HF WH (ECO-ZGR-96642694-Office-EU-2018-02-07)
- IBU (2018). Wildeboer Fire damper FK90. (EPD-WWB-20180133-ICC1-DE)
- IBU (2018). Wildeboer Fire damper FK90K. (EPD-WWB-20180150-ICC1-DE)
- IBU (2018). Wildeboer Fire damper FR90. (EPD-WWB-20180132-ICC1-DE)
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- IBU (2021). Thorn Wall mounted luminaire AVENUE W300 II LED 12L35 730 CL2 (ECO-ZGR-96258554-Amenity-EU-2021-06-10)
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LCA studies

- Prastawa, H. & Hartini, S. (2019). *The influence of product design on environmental impacts using life cycle assessment*. AIP Conference Proceedings 2114, 030015. https://doi.org/10.1063/1.5112419 (LCA of fans)

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Other

- LCAQuick database.
- Ecoinvent database.

Appendix B: Residential building results

Table 11. Residential services carbon footprint summary (kgCO₂eq per m² GFA)

	DH 1	DH 2	DH avg	MDH	AP	AP-building
Electrical						
Modules A1–A3	4.94	4.07	4.50	3.45	6.66	5.13
Modules A4–A5	0.40	0.34	0.37	0.28	0.85	0.62
Module B1	0.00	0.00	0.00	0.00	0.00	0.00
Module B4	10.85	8.93	9.89	7.31	9.95	8.26
Modules C1–C4	0.03	0.02	0.02	0.02	0.04	0.03
Electrical	**16.21**	**13.36**	**14.79**	**11.06**	**17.51**	**14.05**
Module D	0.00	0.00	0.00	0.00	0.00	0.00
Plumbing						
Modules A1–A3	3.36	2.64	3.00	3.18	3.46	2.68
Modules A4–A5	0.02	0.02	0.02	0.02	0.03	0.03
Module B1	0.00	0.00	0.00	0.00	0.00	0.00
Module B4	0.00	0.00	0.00	0.00	0.00	0.00
Modules C1–C4	0.06	0.05	0.06	0.06	0.07	0.05
Plumbing	**3.45**	**2.71**	**3.08**	**3.25**	**3.57**	**2.76**
Module D	0.00	0.00	0.00	0.00	0.00	0.00
HVAC (heat pump)						
Modules A1–A3	1.86	1.23	1.55	1.94	5.78	3.90
Modules A4–A5	0.06	0.04	0.05	0.06	0.18	0.12
Module B1	11.44	7.57	9.50	11.89	35.52	23.97
Module B4	14.09	9.32	11.70	26.53	79.25	53.49
Modules C1–C4	2.78	1.84	2.31	2.88	8.62	5.82
HVAC	**30.23**	**19.99**	**25.11**	**43.30**	**129.34**	**87.30**
Module D	-0.28	-0.18	-0.23	-0.29	-0.85	-0.58
All services						
Modules A1–A3	10.16	7.94	9.05	8.56	15.91	11.72
Modules A4–A5	0.48	0.39	0.43	0.35	1.06	0.77
Module B1	11.44	7.57	9.50	11.89	35.52	23.97
Module B4	24.94	18.24	21.59	33.84	89.20	61.75
Modules C1–C4	2.87	1.91	2.39	2.97	8.73	5.90
All services	**49.89**	**36.05**	**42.97**	**57.61**	**150.42**	**104.11**
Module D	-0.28	-0.18	-0.23	-0.29	-0.85	-0.58

Appendix C: Office building results

Table 12. Office building services carbon footprint summary (kgCO₂eq per m² GFA)

	Office 1	Office 2	Office 3	Office 4	Average
HVAC					
Modules A1–A3	38.08	17.16	16.82	19.62	22.92
Modules A4–A5	1.98	0.66	1.09	1.02	1.19
Module B1	83.37	120.12	387.61	47.48	159.64
Module B2/B4	59.26	30.70	29.19	32.49	37.91
Modules C1–C4	1.04	0.45	0.41	0.39	0.57
HVAC	**183.73**	**169.09**	**435.11**	**101.00**	**222.23**
Module D	-23.19	-14.10	-13.38	-10.24	-15.23
Electrical					
Modules A1–A3	19.24	10.75	10.69	16.74	14.36
Modules A4–A5	1.30	0.54	0.89	0.93	0.91
Module B1	0.00	0.00	0.00	0.00	0.00
Module B2/B4	34.39	17.20	15.71	27.71	23.75
Modules C1–C4	0.51	0.13	0.12	0.21	0.24
Electrical	**55.44**	**28.62**	**27.41**	**45.59**	**39.26**
Module D	-6.10	-3.09	-2.48	-4.29	-3.99
Plumbing					
Modules A1–A3	6.77	0.61	0.98	2.48	2.71
Modules A4–A5	0.32	0.01	0.02	0.05	0.10
Module B1	0.83	0.00	0.00	0.00	0.21
Module B2/B4	1.30	0.38	0.77	1.82	1.07
Modules C1–C4	0.45	0.01	0.02	0.04	0.13
Plumbing	**9.66**	**1.01**	**1.79**	**4.39**	**4.21**
Module D	-0.36	-0.09	-0.10	-0.20	-0.19
Gas					
Modules A1–A3	0.00	0.00	0.10	0.00	0.03
Modules A4–A5	0.00	0.00	0.01	0.00	0.00
Module B1			0.00		0.00
Module B2/B4	0.00	0.00	0.00	0.00	0.00
Modules C1–C4	0.00	0.00	0.01	0.00	0.00
Gas	**0.00**	**0.00**	**0.12**	**0.00**	**0.03**
Module D	0.00	0.00	-0.04	0.00	-0.01
Fire					
Modules A1–A3	0.00	0.00	3.60	4.08	1.92
Modules A4–A5	0.00	0.00	0.21	0.24	0.11
Module B1			0.00	0.00	0.00
Module B2/B4	0.00	0.00	3.99	4.52	2.13
Modules C1–C4	0.00	0.00	0.17	0.20	0.09
Fire	**0.00**	**0.00**	**7.97**	**9.04**	**4.25**
Module D	0.00	0.00	-2.72	-3.08	-1.45
All services					
Modules A1–A3	64.09	28.52	32.19	42.92	41.93
Modules A4–A5	3.59	1.21	2.22	2.24	2.32
Module B1	84.20	120.12	387.61	47.48	159.85
Module B2/B4	94.96	48.27	49.66	66.54	64.86
Modules C1–C4	2.00	0.59	0.72	0.83	1.03
All services	**248.83**	**198.72**	**472.40**	**160.02**	**269.99**
Module D	-29.64	-17.27	-18.73	-17.82	-20.87