

**Embodied Carbon of Heating, Ventilation, Air Conditioning and Refrigerants (HVAC+R)
Systems**

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Abstract

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This dissertation expands on preliminary studies of embodied carbon in building systems in commercial office buildings and aims to advance the understanding of the role that heating, ventilation, air conditioning, and refrigeration (HVAC+R) systems play in whole building life carbon. Previous studies on embodied carbon in buildings using Whole Building Life Cycle Assessment (WBLCA) have developed the understanding of this topic over the last years. However, these studies have focused primarily on estimating the embodied carbon of manufacturing (life cycle stage A), rarely including maintenance, energy use, or end-of-life impacts. In addition, most of these studies have focused solely on estimating carbon embodied in the structural system of the building, seldom considering mechanical, electrical, and plumbing (MEP) systems, tenant improvements, or site development impacts. Thus, this dissertation aims to fill in the gap regarding the estimation the HVAC+R component of MEP across the whole building life cycle.

This dissertation seeks to answer the following research question: What is the contribution of individual equipment and distribution material types in typical HVAC+R systems for commercial office buildings of the Pacific Northwest (PNW) relative to total embodied carbon and in relation to the impact of the use phase (replacement and maintenance). In order to answer this question, an observational study design using a mixed methods triangulation approach was completed. The first study involved the development of a systematic framework to assess embodied carbon in HVAC+R. This exploratory qualitative research stage included a systematic literature review of existing WBLCA methods and participation of an advisory committee to assess the embodied carbon of HVAC+R systems in 16 hypothetically representative office buildings and 20 existing high-performance buildings registered under LEED v3 2009 in Washington State. Finally, a third study assessed the embodied carbon of HVAC+R in one “in depth” case study using an alternative method to assess material quantities .

Three contributions of this dissertation to the literature of the field are: a) development of a systematic framework to estimate embodied carbon of HVAC+R systems in buildings, b) a database of embodied carbon of HVAC+R systems and their equipment, c) and a typical range of embodied carbon of HVAC+R systems, including refrigerants, in commercial office buildings in the PNW.

TABLE OF CONTENTS

1. Introduction	1
1.1 The global warming potential of heating, ventilation and air conditioning systems and refrigerants (HVAC+R)	4
1.2 The importance of simplified Life Cycle Assessment Methods for widespread use in the building industry.....	8
2. Review of existing WBLCA methods and a taxonomy for the definition of Goal and Scope.....	13
2.1 Introduction.....	13
2.2 Literature review	14
2.2.1 Life Cycle Assessment (LCA) in Practice, Barriers and Harmonization efforts.....	14
2.2.3 WBLCA tools and inconsistencies.....	15
2.2.4 Taxonomies and classification systems in the AEC industry.....	16
2.3 Methods.....	17
2.3.1 Stage 1: Selection of LCA tools for AEC	17
2.3.2 Stage 2: Parameter Analysis.....	20
2.3.3 Stage 3 New Taxonomy for the definition of G&S Stage.....	20
2.4. Results.....	21
2.4.1 Background information on the LCA tools included in the sample.....	21
2.4.2 Details a summary and a frequency analysis for the total parameters coded by source in the sample.....	21
2.4.3 Analysis of parameters by topic and subtopics	23
2.4.4 Final proposed taxonomy	24
2.5 Discussion	27
2.6 Conclusion	28
3. Embodied Carbon Coefficients (ECC) for Heating, Ventilation, Air Conditioning and Refrigerants (HVAC+R) Systems in the context of office buildings: A review of published articles, EPD and open databases	29
3.1 Introduction.....	29
3.1.1 LCA methods for the building industry.....	30
3.1.2 LCA data in environmental product declarations (EPD) and product specific LCA databases	30
3.2 Methodology	35
3.2.1 Stage 1: Selection of HVAC+R systems and components.....	35
3.2.2 Stage 2: Selection of the data sample: EPD, Open Databases and published articles.....	35
3.3 Results.....	38

3.3.1	Studies in HVAC+R: Components vs Systems.....	38
3.3.2	Goal and Scope Stage.....	39
3.3.3	Inventory Analysis	45
3.3.4	Impact Assessment Stage.....	45
3.4	Discussion	48
3.5	Conclusion	49
4.	Embodied Carbon in Heating, Ventilation and Air Conditioning (HVAC+R): A simplified method for standard and high-performance buildings.....	51
4.1	Introduction.....	51
4.2	Methodology	52
4.2.1	Stage 1: Embodied Carbon in Hypothetical Building Models	52
4.2.2	Stage 2: Development of a simplified LCA method for HVAC+R	53
4.2.3	Stage 3: Analyzing the Data Using Two-way ANOVA Test.....	55
4.3	Results and discussion.....	56
4.3.1	Stage 1: Embodied Carbon in Hypothetical Building Models	56
4.3.2	Stage 2: Development of a simplified LCA method for HVAC	62
4.3.3	Stage 3: Two-way ANOVA test.....	64
4.4	Conclusions and recommendations.....	67
5.	Embodied and Operational Carbon of Typical Heating, Ventilation and Air Conditioning (HVAC) Systems in Office Buildings in Washington State: A study of buildings registered under LEED v3 200968	
5.1	Introduction.....	68
5.1.1	Whole Building Carbon: Operational Energy and CO ₂ e of Buildings and HVAC+R.....	68
5.1.2	LEED Rating System and Building Regulation in Washington State.....	70
5.1.3	New HVAC+R Technologies and Reduction of Operational Energy and CO ₂ e in Office Buildings	72
5.2	Method	73
5.2.3	Data Gathering Process	74
5.2.4	Analyzing the Data Using Two-way ANOVA Test.....	76
5.3	Results and Discussion.....	77
5.3.1	HVAC+R Systems descriptions per type of Building Size Category	78
5.3.2	Performance Results per type of HVAC+R System and Building Size Category (EUI and total CO ₂ e).....	78
5.4	Discussion and conclusion	86
6.	Case study of a VAV w PFP terminals: Understanding mechanical material quantities using an in depth analysis.....	88
6.1	Introduction: Goal and Scope.....	88
6.2	Methodology	89

6.2.1 Case study and description of the HVAC+R system.....	89
6.2.2 Stage 1: Gathering Material Quantities	89
3. Simplify and combine similar QTO items.....	90
4. Collect LCA data for QTO items	91
5. Apply LCA data to QTO items / make assumptions	92
6.3 Results.....	93
6.3.1 Results of the original study.....	93
6.3.2 HVAC +R GWP detailed contribution analysis.....	94
6.4 Discussion	94
6.4.1 Refrigerants	94
6.5 Conclusion	96
7. Conclusion, summary of findings and future research.....	97
7.1 Contributions of this dissertation	97
7.2 Results and estimation of impacts.....	99
7.2.1 A taxonomy for WBLCA and review of methods.....	100
7.2.2 Embodied Carbon Coefficients (ECC) for HVAC+R equipment and distribution material types.	100
7.1.3 HVAC+R systems in existing and new commercial office buildings	101
7.1.4 Mechanical material quantity estimates (QTOs) in typical HVAC+R Systems	102
7.1.5 Embodied Carbon (EC) in typical HVAC+R Systems.....	103
7.1.5 Embodied Carbon (EC) vs Operational Carbon in HVAC+R Systems	104
8.2 Limitations of the study	107
8.2.1 Limitations on compiling LCA data for HVAC+R equipment and distribution components..	107
8.3 Identifying knowledge gaps in the simplified method proposed	107
8.3.2 Knowledge gaps on calculating material quantities of typical HVAC+R systems	107
8.3.3 Knowledge gaps on compiling LCA data of typical HVAC+R systems	108
8.4 Future development and future research questions	108
8.4.1 Validating the results of this study: Material quantities estimates	108
8.4.2 LCA data for HVAC+R equipment and distribution components.	109
8.4.3 Accurate estimations of refrigerant charge overtime in HVAC+R in commercial buildings. .	109
8. References	110
Appendix A WBLCA Method matrix comparison.....	121
Appendix B HVAC+R Systems Descriptions	121
Appendix C Lifespan of typical HVAC+R equipment and distribution types	121

LIST OF FIGURES

Figure 1.1 Overview of research project.....	10
Figure 2.1 Methodological stages for the development of a taxonomy to describe the Goal and Scope (G&S) stage of a WBLCA	17
Figure 3.1 HVAC+R distribution material types and equipment types for different ducted and ductless systems. Highlighted in orange are distribution material and equipment types for which there is data available in LCA studies	34
Figure 3.2 Typical lifespan for HVAC+R equipment.....	44
Figure 3.3 Embodied Carbon Coefficient of distribution material types per kg.....	46
Figure 3.4 Embodied energy per distribution material type	46
Figure 3.5 Embodied carbon for each equipment type	47
Figure 3.6 Embodied carbon for each equipment type per item	47
Figure 4.1 Material Quantities for Equipment Types of HVAC+R systems in Standard and High Performance Buildings (kg/m ²)	60
Figure 4.2 Material Quantities for Material Types of HVAC+R systems in Standard and High Performance Buildings (kg/m ²)	61
Figure 4.3 Global Warming Potential (GWP) for equipment types in HVAC+R systems Standard Buildings and High Performance Buildings (kg CO ₂ eq/m ²).....	63
Figure 4.4 Global Warming Potential (GWP) for HVAC+R System Types in Standard Buildings and High Performance Buildings (kg CO ₂ eq/m ²).....	64
Figure 4.5 Interaction between building size category and HVAC+R item type	66
Figure 5.1 Cooling capacity [TONS] according to each building size category.....	79
Figure 5.2 Site Energy Use Intensity (EUI) [kWh/m ² -year] according to each building size category	79
Figure 5.3 Operational Carbon Intensity [CO ₂ e/m ² -year] according to each building size category.....	79
Figure 5.4 HVAC+R Total Carbon Intensity [CO ₂ e/m ² -year -] according to each building size category	80
Figure 5.5 HVAC+R Embodied Carbon Intensity [CO ₂ e/m ²] in 15 years according to each building size category	80
Figure 5.6 Total Material Quantities (kgm/m ²) of HVAC+R systems in ducted and ductless systems	81
Figure 5.7 Mechanical Material Quantities (kgm/m ²) of HVAC+R per equipment types.....	82

Figure 5.8 Total Refrigerant charge according to total cooling tons, per type of equipment	83
Figure 5.9 Total LCGWP per m ² according to service life of each type equipment.....	83
Figure 5.10 Total EC (kgCO ₂ e/m ²) of HVAC+R systems in ducted and ductless systems HPB .	84
Figure 5.11 Interaction between system category and item type HVAC+R item type.....	86
Figure 6.1. Contribution of cost estimate categories to overall results of the detailed LCA (M. Huang, Rodriguez, and Simonen 2019).....	93
Figure 6.2 Embodied Carbon of HVAC+R	94
Figure 7.1 HVAC+R Total Carbon Intensity [CO ₂ e/m ² -year] according to each building size category	105
Figure 7.2 HVAC+R Embodied Carbon Intensity [CO ₂ e/m ²] in 15 years according to each building size category	105
Figure 7.3 Embodied Carbon (EC) vs Operational Carbon in HVAC+R Systems a high impact worst-case scenario (no refrigerant management).....	106

LIST OF TABLES

Table 1.1 Data gathering method for the material quantities in each study.....	10
Table 2.1 WBLCA tools included in the sample	19
Table 2.2 Number and Names of Unique Parameters.....	22
Table 2.3 Number of parameters types categorized by tool.....	22
Table 2.4 Number of parameters according to G&S topic.....	23
Table 2.5 Parameters names listed under “Area Characteristics” for “Functional Unit”.....	23
Table 2.6 Proposed taxonomy for the definition of the WBLCA goal	25
Table 2.7 Proposed taxonomy for the definition of the WBLCA scope.....	26
Table 3.1 Number of Published Studies for HVAC+R Equipment and materials published in Journals, EPD programs and Open Databases (as of May 2019)	35
Table 3.2 Published Studies for HVAC+R Equipment in Scientific Journals and other	35
Table 3.3 Existing LCA data for HVAC+R distribution	36
Table 3.4 Existing LCA data for HVAC+R equipment.....	37
Table 3.5 Reference standards used by type of source	39
Table 3.6 Life Cycle Boundaries according to ISO 21930	40
Table 3.7 Functional Units and Reference Flows for HVAC+R distribution.....	41
Table 3.8 Functional Units and Reference Flows for HVAC+R equipment	42
Table 3.9 Functional Units and Reference Flows for equipment types	43
Table 4.1 Sixteen HVAC+R Systems according to four building size categories for Commercial Office SP and HP Buildings in the Pacific Northwest (PNW)	56
Table 4.2 Descriptive Statistics for Building size and HVAC+R item type.....	64
Table 4.3 Two Way ANOVA Table for dependent variable material quantity estimate (calculated) [kg/m ²].....	65
Table 5.1 Outcome based targets of the City of Seattle Energy Code for office buildings	71
Table 5.2 Categorical and numerical HVAC+R variables used in the study.....	74
Table 5.3 Twenty sample buildings classified according to LEED Certification types and the three building size categories	76
Table 5.4 Descriptive Statistics.....	84
Table 5.5 Two Way ANOVA Table for dependent variable material quantity estimate (calculated) [kg/m ²].....	85

Table 6.1. Categories evaluated in detailed LCA, organized by cost estimate categories, CSI categories, and source of material quantity data.....	90
Table 6.2. Consolidation of original QTO items into simplified QTO items, for TI.....	90
Table 6.3. LCA data selections for QTO items. Data source's marked with a * were characterized per CML, not TRACI 2.1.....	92
Table 6.4. Calculation assumptions for simplified QTO items.....	92
Table 6.5. Total detailed LCA results, life cycle stages A and C.....	93
Table 7.1 Comparison between the total material quantity results [kg/m ²] without refrigerants for the three exercises in this study.....	103
Table 7.2 Comparison between the material quantity results [kg/m ²] in HPB for equipment, distribution and refrigerant for the three exercises in this study.....	103
Table 7.3 Comparison between the total embodied carbon results [CO ₂ e kg/m ²] stage A without refrigerants for the three exercises.....	104
Table 7.4 Comparison between the embodied carbon results [CO ₂ e kg/m ²] stage A for equipment, distribution and refrigerant in HPB in three exercises.....	104

Dedication

To Rafael, José Manuel and their generation

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NOMENCLATURE

AHRI	Air-conditioning, Heating, and Refrigeration Institute
AHU	Air Handling Units
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
CDD	Cooling degree days
CFCs	Chlorofluorocarbons
CO₂e	Carbon dioxide equivalent
COP	Coefficient of performance
DOAS	Dedicated outdoor air system
EN	European Standard
EC	Embodied carbon
ECC	Embodied carbon coefficient
EPD	Environmental product declaration
ERV	Energy recovery ventilator
EUI	Energy use intensity
GBRS	Green building rating systems
GHG	Greenhouse gas emissions
GWP	Global warming potential
G&S	Goal and scope
HCFCs	Hydrochlorofluorocarbons
HDD	Heating degree days
HFCs	Hydrofluorocarbons
HPB	High-performance building
HVAC+R	Heating, ventilation, air conditioning and refrigerants
HPVAV	High performance variable air volume
HPAS	High performance air systems
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
kg	kilograms
kg/m²	kilogram per square meter (material quantities)
kWh	kilowatt-hour
kWh/ m²	kilowatt-hour per square meter (EUI)
LCA	Life cycle assessment
LCI	Life cycle inventory
LEED	Leadership in energy efficient design
Lr	Refrigerant leakage rate
MEP	Mechanical, electrical, plumbing
MJ	Megajoules
m²	Square meter
Mr	End of life refrigerant loss
MZVAV	Multi zone variable air volume
NZB	Net zero building
NZC	Net zero carbon

NZE	Net zero energy
OC	Operational Carbon
ODS	Ozone depleting substances
PFP	Parallel fan powered
PNW	Pacific northwest
PTAC	Packaged terminal air conditioner
PTAHP	Packaged terminal heat pump
Q unit	Gross AHRI rated cooling capacity of an individual HVAC or refrigeration unit (tons)
Q total	Total gross AHRI rated cooling capacity of all HVAC or refrigeration
Rc	Refrigerant charge
ReqSL	Required service life
RTU	Rooftop unit
RSP	Reference study period
R-value	Thermal resistance
SPB	Standard performance building
U-factor	Thermal transmittance (for windows including frames)
U-value	Thermal transmittance (for walls)
UHI	Urban heat island effect
UK	United Kingdom
US	United States
USGBC	United States Green Building Council
VAV	Variable air volume
VRF	Variable refrigerant flow
WBLC	Whole building life cycle carbon
WBLCA	Whole building life cycle assessment
WSEC	Washington State Energy Code
WSHP	Water source heat pump

1. Introduction

Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, a number likely to rise to 1.5°C between 2030 and 2052 if emissions caused by anthropogenic action continue to increase at the current rate (IPCC 2018). According to the Fourth National Climate Assessment, currently one of the most comprehensive and up-to-date studies, if the goal is to have a 66% chance of preventing an increase of 2°C, then cumulative global CO₂ emissions must remain below ~800GtC. Assuming global emissions follow the lower RCP4.5 scenario, this limit allows for approximately 20 years' worth of emissions before hitting the limit (USGRP 2017). Nevertheless, the observed increase in global CO₂e emissions over the past 15 years has been consistent with higher impact scenarios (Knutti et al. 2016). The recent SPE 1.5C report indicates that the window of time to prevent widespread impact of climate change caused by anthropogenic activities is closing fast, revealing the urgent need for near-term, high-impact strategies to reduce emissions of all climate pollutants (IPCC 2018).

The construction sector is the largest global consumer of materials, and buildings comprise the sector with the largest single energy use worldwide (Giesekam et al., 2015). According to United Nations Environment Programme, the building sector is responsible for 40% of global energy consumption and one third of global GHG emissions(UNEP 2009). Recent reports show that nearly 50% of all energy consumption and greenhouse gas emissions in the US and 30–40% of total carbon emissions in the UK are attributable to the built environment (Al-Sallal 2016). Unprecedented global population and urbanization growth rates will inevitably require the development of large number of buildings¹. Consequently, buildings offer the greatest abatement opportunities for reducing greenhouse gas (GHG) emissions in the short term (IPCC, 2014).

In order to transition toward a complete zero carbon-built environment, the design community has responded with increased development of net zero buildings (NZB), typically under the name of net zero energy (NZE) and net zero carbon buildings (NZC). NZE, “a term subject to ambiguity, is used to describe a building with characteristics such as equal energy generation to usage, significantly reduced energy demands, energy costs equaling zero or net zero GHG emissions” (Wells, Rismanchi, and Aye 2018). An NZC building is “a highly energy efficient building that produces on-site, or procures, enough carbon-free renewable energy to meet building operations energy consumption annually”(Architecture 2030 2016) . It is estimated that in order to reach the Paris Agreement targets, all new buildings must

¹ Between now and 2030, cities will house an additional one billion people, which will entail building one new city of 1.5 million inhabitants, roughly the population of Manhattan, each week for the next 12 years (D’Amico and Pomponi 2019) .

operate at net zero carbon from 2030 and 100% of buildings must operate at net zero carbon by 2050 (WGBC 2017).

The design and assessment of NZB commonly focuses exclusively on the operational phase, ignoring the embodied environmental impacts over the building's life cycle (Lützkendorf, Balouktsi, and Frischknecht 2016). Whole life carbon or whole lifecycle carbon (WLC) emissions of buildings are often divided into operational carbon versus embodied carbon. Operational carbon (OC) consists of the GHG emissions generated from the burning of fossil fuels to heat, cool and power a building during its service life (Zizzo, Kyriazis, and Goodland 2017), while embodied carbon (EC) encompasses the GHG equivalent to producing, procuring, and installing the materials and components that make up a structure (Cabeza et al. 2014). The latter also includes the lifetime emissions from maintenance, repair, replacement, and ultimately demolition and disposal (RICS 2017). Both EC and OC are typically expressed as GWP or CO₂e. In brief, embodied carbon can represent between 2 and 80% of carbon emissions of the total building life cycle, depending on building use, location, material palette, and assumptions about the service life and future energy supply (Zabalza Bribiá, Usó, and Scarpellini 2009). Consequently, total embodied carbon amounts in buildings vary widely, ranging from 350 to 950 kg CO₂ eq/m², depending on the construction type, number of stories, location, and methodology used for the study (Al-Ghamdi & Belic, 2015; De Wolf, 2014).

The embodied GHG emissions due to construction industries amount to approximately 5 to 10% of the entire energy consumption in developed countries and 10 to 30% in developing countries (Seo, Passer, and Balouktsi 2016). However, analysis of the operational carbon emission has dominated building energy research for many years when compared to analysis on the embodied carbon (L. Huang et al. 2017). For the most part, embodied carbon has remained unexamined (Pomponi and Moncaster 2016b).

In recent years, though, as more stringent energy codes aim to reduce OC, EC is gaining attention. During the last two decades, OC has reduced, while EC is not being addressed. According to data from the U.S. Energy Information Administration, energy efficiency and power sector decarbonization have reduced U.S. building sector CO₂ emissions by 20.2% below 2005 levels, despite adding approximately 30 billion square feet to our building stock during the last 12 years (Architecture 2030, 2018). It is expected that by 2050 embodied carbon will account for 50% of total emissions. According to the IEA's latest report on materials, the carbon footprint in materials of new and renovated buildings is massive, representing 11% of total global CO₂ emissions, with steel and cement contributing the main share (IEA 2019).

Currently, one of the most important barriers to understanding and developing effective policy to reduce embodied carbon in buildings is the limited use of a life cycle perspective to assess emissions in

the building sector. Life Cycle Assessment (LCA) provides a methodology to estimate and evaluate the environmental impact throughout the product life cycle from cradle to grave, encompassing a comprehensive evaluation of the sustainability of products and processes. LCA is used to evaluate the resource consumption and environmental impacts of products and processes (goods and services) during their entire life cycle in order to compare building assemblies and their ability to meet project goals (Cabeza et al., 2014; Initiative, G. B., 2013). Whole building life cycle assessment (WBLCA) is an LCA exercise wherein the entire building project is considered holistically to help building designers align their efforts in light of a reduced footprint (Athena, 2014). In recent years, interest has grown in including LCA in Green Building Rating Systems GBRS and metrics (Al-Ghamdi & Bilec, 2015; Collinge et al., 2015; Olander, 2012; Olinzock et al., 2015)(Al-Ghamdi and Bilec 2015). LCA offers a quantitative comparison of materials across a range of environmental impact performance metrics, rather than relying on the imperfect prescriptive or qualitative measures common in green building assessment programs up to now (Lucuik, 2014). WBLCA appears in Green Building Rating Systems (GBRS) and standards as a compliance path or an opportunity to earn points when designers use LCA to measure environmental performance during design, leading to design refinements that reflect best LCA performance of the whole building (Athena, 2014). During the project's design phase, the assessment can inform decision-making processes by allowing the environmental performance of different design options to be compared and identifying opportunities to improve environmental performance throughout the life cycle (DGNB, 2014). Understanding full lifecycle performance and impacts has also become critical for architects focused on conserving existing and historic buildings and places (AIA, 2015).

WBLCA is considered the prominent method to assess embodied and operational emissions. However, the incompleteness of most LCA studies has been widely demonstrated. A recent study indicates that over 90% of LCA studies reviewed look at the manufacturing stage only, whereas just over 50% extend consideration to the end of the construction stage (Pomponi and Moncaster 2016b). Another recent review of WBLCA studies indicated that one major gap in the literature is accounting for overlapping effects on carbon emissions in different phases of the building life cycle. For example, a focus on selection of materials with low cradle to grave embodied carbon might overlook the effects that such low-carbon materials may have on the carbon emissions of the construction, operation, and end-of-life phases (Akbarnezhad and Xiao 2017).

Another critical barrier to better understanding embodied carbon in buildings is the broad array of methodologies used in previous studies (Wolff, Duffy, and Hammond 2012). It has been documented that all decisions made during the LCA (functional unit choice, LCA system boundaries, inventory data, choice of the impact assessment method, etc.) greatly influence LCA results (Hammond & Jones, 2008; Van Den Heede & De Belie, 2012)(Hammond and Jones 2008).

Some of the common methodological challenges of the application in LCA in the building industry include the following: the variety of methodological approaches used (Buyle, Braet, and Audenaert 2013); lack of consistency of functional units and system boundaries across studies during the goal and scope stage; missing data and uncertainty in data collection methods; and comparison of LCA impacts results in LCA during the impact assessment stage (Anand and Amor 2017).

1.1 The global warming potential of heating, ventilation and air conditioning systems and refrigerants (HVAC+R)

Most WBLCA studies do not include impacts from mechanical, electrical, and plumbing (MEP) or other service equipment or their maintenance (Basbagill et al. 2013a) Simonen, K. et al., 2017). Mechanical and electrical equipment systems are frequently omitted from analyses due to their complexity, which is considered significant, relative to their overall share of the building impact, which is estimated to be small (Zizzo, Kyriazis, and Goodland 2017). However, considering that most MEP systems have to be maintained, repaired, and replaced over a 15 to 25 year lifespan (Grondzik 2016), this omission seems to pose a serious oversight when gauging the impact of a building and all materials associated with its construction and operation (Cheshire 2014).

HVAC+R, also called “mechanical systems” or the “mechanical component” of MEP, represents a significant contribution to global CO_{2e} emissions. However, as is the case with most building systems, only OC has been tracked and incorporated into policies. In developed countries, HVAC systems account for almost half of the total energy use in commercial buildings (Yu et al. 2016). Furthermore, in large commercial buildings, HVAC systems always represent the largest primary energy end-use (P. Huang, Huang, and Wang 2015). Commercial buildings represent 18% of US primary energy consumption and carbon dioxide emissions and 36% of all US electricity use (EIA, 2015; EIA, 2017). Although the average total energy use per square foot has declined approximately 10% over the past decade, total electricity consumption in commercial buildings has been steadily climbing (EIA, 2016). Electricity now accounts for 61% of all energy consumed in commercial buildings, while natural gas accounts for 32%. The breakdown in end-use electrical consumption is as follows: heating, ventilation, and air conditioning (HVAC) 33%, miscellaneous loads 32%, lighting 17%, and refrigeration and cooking 18% (EIA, 2016; King & Perry, 2017). Therefore, the research seeking to understand the impact of HVAC+R systems during the operational stage has been extensive (Nikdel et al. 2018); (Yoshida 2006).

However, not only will the HVAC+R share of operational energy increase in the coming decades, but the number of ACs in use is expected to climb from 1.6 billion in 2018 to 5.6 billion by 2050

(OECD/IEA 2018), increasing both OC and EC associated with the equipment, distribution components, and refrigerants. The International Energy Agency projects that AC energy consumption by 2050 will have increased 4.5 times over 2010 levels for non-OECD versus 1.3 times for OECD countries (OECD/IEA 2018). Globally, stationary AC systems account for nearly 700 million metric tons of direct and indirect CO₂-equivalent emissions (MMTCO₂e) annually. Indirect emissions from electricity generation account for approximately 74% of this total, with direct emissions of HFC and hydrochlorofluorocarbon (HCFC) refrigerants accounting for 7% and 19%, respectively (W Goetzler et al. 2016). No global estimations of the EC or indirect emissions from the manufacturing and transportation have been identified.

The rapid growth of HVAC+R equipment is projected based on a number of well-documented factors such as increasing temperatures across the world due to climate change, growing population, rising incomes, and greater access to HVAC+R equipment in the Global South. Growing evidence exists of an increased incidence of overheating during warm weather in buildings without air-conditioning (Lomas and Porritt 2017). An increasing number of cities suffer extreme heat, which threatens health and livability as heat waves grow more frequent, more intense, and longer, with lethal impact² (Kelbaugh 2019). The urban heat island (UHI³) effect has been a topic of research for more than four decades and has been found to be exacerbated in cities as they become bigger and denser (Mylona 2019). Consequently, the use of energy for space cooling is growing faster than that of any other end use in buildings, more than tripling between 1990 and 2016 (OECD/IEA 2018). This overheating in cities will make more air conditioning equipment necessary to insure human health and comfort (W Goetzler et al. 2016).

Another critical aspect, aside from the EC of HVAC+R equipment, is the global concern for refrigerant use and its high GWP. Extensive work coming from atmospheric sciences on the damage to the Earth's ozone layer caused by refrigerants in HVAC+R systems and foams during the seventies prompted the signing of the Montreal Protocol, a 1987 international treaty ratified by more than 190 countries that has since been hailed as one of the most successful environmental agreements (Velders, Solomon, and Daniel 2014). At the time the protocol was signed, chlorofluorocarbons (CFC) in foams

² The 2003 pan-European heatwave caused 15,000 premature deaths, while in July 2018, urban heat waves caused 1032 deaths in Japan (Imada et al. 2019).

³ Urban Heat Island (UHI) is a term describing the concentration of higher air and surface temperatures in cities compared to their surrounding territory, which can cause temperatures as much as 12°C hotter than those of surrounding areas in the evening hours, because city buildings release heat absorbed during the day. UHIs are brought on by dark surfaces heated by the sun and exacerbated by “waste heat,” such as the hot emissions released from tailpipes, chimneys, and air conditioning systems.

and refrigerants comprised the primary cause of ozone loss and were thus the primary halocarbon addressed and set to be phased out globally by 2010. While most countries have banned CFCs, recent studies indicate increase of CFC-11 emissions has arisen from unreported new production (Montzka et al. 2018) accounting for up to an increase in trichlorofluoromethane (CFC-11) of 40 to 60 percent, originated in and around the Chinese provinces (Rigby et al. 2019).

Decades after the Montreal Protocol, CFCs have been replaced by HCFC and HFC that cause no damage to the ozone, albeit with a global warming potential (GWP)⁴ up to 14,800 times greater than CO₂e (UNEP 2016). HCFCs are now scheduled to be phased out globally by 2040 and are being replaced by HFCs, resulting in atmospheric concentrations of HFC growing by 10-15% per year (Velders, Solomon, and Daniel 2014). The various fluorinated gases, also called “F-gas banks,”⁵ include the remaining ozone depleting substances (ODS): chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and their replacement hydrofluorocarbons (HFCs). Mitigation of the existing F-gas banks has been identified as the single largest opportunity for reducing emissions in terms of carbon dioxide equivalent (EIA 2018). If no action is taken, global HFC emissions could reach 5.5 billion–8.8 billion tons of CO₂e per year by 2050, equaling 9%–19% of projected global CO₂ emissions under a business-as-usual (BAU) scenario (IFC 2017).

In 2016, the Kigali Amendment (KA)⁶ to the Montreal Protocol was signed to phase down HFC consumption by 2050. This amendment would avoid release of an estimated 105 gigatons of CO₂e by 2050 and mitigate up to 0.4°C of potential global warming by the end of the century, while continuing to protect the ozone layer (IFC 2017). Mitigation of banks of fluorinated gases, or “F-banks,” represents the most impactful near term strategy to achieve deeper mitigation of F-gases consistent with limiting warming to within a 1.5 °C pathway (EIA 2018). Addressing the refrigerant banks through refrigerant management practices such as minimizing leaks and increasing end of life recovery, reclamation, and destruction has the potential to avoid up to 96.5 gigatons of CO₂e (GTCO₂e) globally between 2020-2050 (Project Drawdown 2009). In the US alone, an estimated 75 million metric tons of CO₂ equivalent (MTCO₂e) emissions annually can be avoided in 2020 through collection and destruction of F-gas banks

⁴ The GWP is an index comparing the integrated radiative forcing of an emission of a greenhouse gas, typically integrated over one hundred years, relative to that of emitting the same mass of carbon dioxide (IPCC/TEAP, 2005 in (Velders, Solomon, and Daniel 2014).

⁵ F-banks are the total quantity of fluorinated gases that have been or are to be produced and will be emitted into the atmosphere unless sustainably managed and disposed. (IPCC/TEAP 2005).

⁶ The Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer reached agreement at their 28th Meeting of the Parties on 15 October 2016 in Kigali, Rwanda, to phase down hydrofluorocarbons (HFCs) (UNEP 2016).

at the end of life (ICF 2018). The Kigali Amendment adds the replacement of target refrigerants for main applications with low GWP refrigerants⁷. Currently, no universal solutions for the refrigerants are available if one takes into consideration all relevant aspects such as size of cooling capacity, temperature regime, type of application, cost, available service, energy efficiency, ambient air, safety, regulations, and environment (Ciconkov 2018).

In the US, where buildings rely mainly on electricity for a significant portion of their energy demands, 79% of commercial buildings' emissions were attributable to electricity consumption for lighting, heating, cooling, and operating appliances in the commercial sector in 2007, causing the sector to account for 18% of CO₂ emissions from fossil fuel combustion. Electricity generators consumed 36% of US energy generated from fossil fuels and emitted 42% of total CO₂ from fossil fuel combustion in 2007 (Al-Sallal 2016).

The Commercial Building Energy Consumption Survey (CBECS) administered by the U.S. Department of Energy is the most comprehensive publicly available dataset for energy use in commercial buildings in the US. Despite a 14% increase in total buildings and a 22% increase in total floorspace since 2003, energy use in estimated 5.6 million U.S. commercial buildings was up just 7% during the same period, according to the survey from 2012. Slower growth in commercial building energy demand since 2003 is explained in part by newer construction built to higher energy performance standards, occupied by less energy intensive building activities, and built more often in temperate regions. The improved efficiency of key energy-consuming equipment is also decreasing demand. Since 2003, for example, space heating and lighting have each been down by 11% in their share of energy use in buildings (EIA 2012). While national policies continue to reduce operational energy and its related GHG emissions in commercial office buildings, embodied carbon remains overlooked. The same is true for refrigerant banks in commercial buildings in the US, where currently no mandatory policies apply to minimizing refrigerant leakages and increasing end of life recovery, reclamation and destruction in commercial buildings.

⁷ The target refrigerants for main applications will include low GWP refrigerants such as R-717, R-744, hydrocarbons (HCs), unsaturated halochemicals such as hydrofluoroolefins (unsaturated HFCs often referred to as HFOs), hydrofluorochloroolefins (unsaturated HCFCs, often referred to as HCFOs), and blends of these refrigerants (UNEP RTOC 2018)

1.2 The importance of simplified Life Cycle Assessment Methods for widespread use in the building industry

WBLCA has proven a complex exercise practiced by experts (Giesekam et al., 2016), and although it has been incorporated into Green Building Rating Systems (GBRS), only in recent years have standardized methodologies become accessible for building designers. The methodologies available are diverse and use a variety of international standards as main reference. This variation causes differences in goals and scope, particularly in the description of the functional or reference units and system boundaries. The varied approaches to WBLCA available in different GBRS to evaluate embodied carbon pose a barrier for precise comparisons among buildings assessed with different tools, and therefore for the development of baselines to drive reductions in environmental impact (Bowick, O ’connor, and Meil 2014). In order to continue the advancement of holistic environmental assessment in buildings, including more robust databases and a large body of knowledge, a standardized WBLCA methodology must be established for the building industry using simplified tools.

A life cycle assessment (LCA) tool is used by industry professionals to select environmentally preferable products, assemblies, or entire functional areas, with a reference service life of 60 years. Typically, only one method of analysis or tool may be utilized for a given building project. Results of an LCA are reported in terms of the environmental impacts listed in this practice and state whether operating energy was included in the LCA (ASHRAE 2016b). In recent years, simplified LCA methods have been developed for industry practitioners (i.e. Tally plug-in for REVIT). A recent review by Soust-Verdage et. al indicates that BIM models for organizing building information are currently being used to estimate environmental and energy consumption impacts based on LCA, using templates and plug-ins for BIM software and automated processes for combining different data and software (Soust-Verdager, Llatas, and García-Martínez 2017). BIM can help simplify estimation of carbon emissions over a building's life cycle because it provides a majority of the information and calculation tools necessary for performing a life cycle assessment (LCA), which may alleviate the problem of insufficient information when executing an LCA of a building (Peng 2016). BIM-enabled environmental impact feedback processes can assist designers in making decisions with large impact during the early design stages while deferring decisions with marginal impact to later design stages (Basbagill et al. 2013b).

WBLCA shows promise for evaluating and motivating lower impact buildings; however, better LCA data – i.e. guidelines for conducting whole building LCAs and databases with a large quantity of reference buildings – will be needed in order to accurately assess the actual improvement of a specific building (Simonen, 2015). Previous reviews have looked at WBLCA case studies of residential and non-residential buildings and also the tools used to carry out the assessment (Cabeza, et al., 2014; Ortiz,

Castells, & Sonnerman, 2009) and have also found gaps regarding environmental indicators, easily understandable presentation of LCA results to users, and adaptation of LCA to various purposes (Bribian, Uson, & Scarpellini, 2009).

The intersection between these different knowledge realms- embodied carbon, HVAC+R systems, and simplified whole building life cycle tools for the AEC industry- give shape to the overarching question of this dissertation:

- 1) What is the relative contribution of Heating Ventilation and Air Conditioning and Refrigerants (HVAC+R) systems in commercial office buildings of the Pacific Northwest to whole life cycle carbon carbon (WLC)? And in particular, what is the relative contribution of embodied carbon from this systems in relation to the impact of the use phase, including replacement?

In order to respond to these empirical questions a simplified method to assess embodied carbon is proposed. The five objectives are to 1) To identify the gaps and barriers of current Whole Building Life Cycle Assessment (WBLCA) Methods available for the AEC industry 2) To develop a systematic framework to assess total embodied carbon in HVAC+R systems in office buildings using simplified LCA . 3) To assess material quantities and embodied carbon of HVAC+R building systems in a sample of hypothetical representative office buildings in the Pacific Northwest. 4) To assess material quantities and embodied carbon of HVAC building systems in a sample of twenty case study buildings in Washington State and finally 5) To assess two HVAC+R systems in two building case studies using an in-depth method for material quantities.

This dissertation research is framed within a larger project entitled “LCA for Low Carbon Construction” funded by the Charles Pankow Foundation, Skanska and the Oregon Department of Environmental Quality (DEQ) and developed by a research team at Carbon Leadership Forum at the University of Washington, led by principal investigator, Profesor Kate Simonen .The first stage of this project, the Embodied Carbon Benchmark (ECB) Study identified (1) the lack of data for MEP and interior TI fit out as a critical source of uncertainty in our understanding of the total embodied carbon in buildings, The second stage of this project, the “Practice Guide: LCA for Low Carbon Construction” (Carbon Leadership Forum 2018) aimed to provide data to building industry professionals integrating embodied carbon into life cycle decision making, the second chapter of this dissertation is a literature review and taxonomy developed in the context of this practice guide for the industry. The third stage of this project was the Life Cycle Assessment (LCA) for Low Carbon Construction Commercial Office Building MEP & Interiors Data” (B.X. Rodriguez et al. 2019) developed in 2018, the third and fourth chapters of this dissertation build from this third stage. Chapter five is an application of the simplified

method to real case studies in Washington State and chapter six presents an alternative method to assess material quantities applied to a building case study as seen in Figure 1.

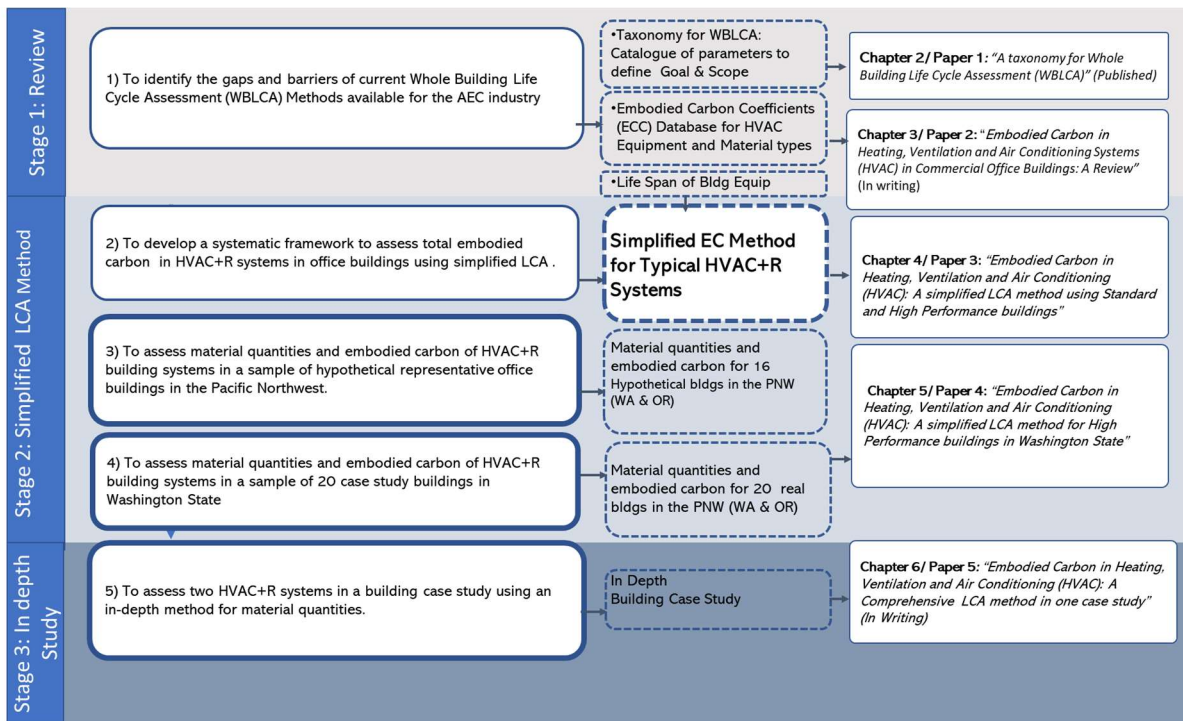


Figure 1.1 Overview of research project

Table 1.1 Data gathering method for the material quantities in each study

Exercise	Material quantities for Equipment MEQ [kg/m ²]	Material quantities for distribution DMQ [kg/m ²]	Refrigerant Charge Rc [kg/m ²]
Ch 4 Advisory Committee	Based on historical data from each contractor	Based on historical data from each contractor. Midpoint calculated	Data not provided. Only one contractor provided an estimate equal for all systems from a low of 0.8kg (1.74lb)) to 3.6 kg (8 lb) per cooling ton
Ch 5 LEED Data	Equipment description in LEED documentation	Based on the estimates from Advisory Committee	Refrigerant charge recorded in LEED template for Refrigerant Management Credit
Ch 6 In depth case study	Equipment description in project documentation	Accurate estimation using mechanical drawings for each case study using bluebeam.	Refrigerant charge for each equipment described in project documentation.

Chapter two presents an analysis of common parameters in existing tools that provide guidance to carry out WBLCA and proposes a new taxonomy – a catalogue of parameters for the definition of the Goal and Scope (G&S) in WBLCA. A content analysis approach was used to identify, code, and analyze parameters in existing WBLCA tools. Finally, a catalogue of parameters was organized into a new taxonomy. Identified were 650 distinct parameter names related to the definition of goal and scope from 16 WBLCA tools available in North America, Europe, and Australia. Building on the analysis of existing taxonomies, a new taxonomy of 54 parameters is proposed in order to describe the G&S of WBLCA. The analysis of parameters in WBLCA tools does not include Green Building Rating Systems (GBRS) and is limited to tools available in English. This taxonomy enables architecture, engineering and construction (AEC) practitioners to contribute to current WBLCA practice. A study of common parameters in existing tools contributes to identifying the type of data required to describe buildings and to building a standardized framework for LCA reporting, which would facilitate consistency across future studies and serve as a checklist for practitioners when conducting the G&S stage of WBLCA.

Chapter 2 explores the application of LCA in heating, ventilation, and air conditioning (HVAC) systems, examining different LCA studies in Environmental Product Declarations (EPD) and Life Cycle Assessment (LCI) databases to identify embodied carbon coefficients (ECC) and typical lifespan for HVAC+R components. A second line of inquiry in this review aimed to understand how LCA study of HVAC equipment and material types is currently being developed. A metanalysis was developed to assess the ECC of mechanical equipment and materials.

The main challenges to the incorporation in LCA of the ECC identified in the study include differences in functional units, life cycle boundaries, and lifespan of the equipment used across the studies. A particular difference between published studies versus EPD and open databases centers on the different levels of complexity in modelling the various components and materials of HVAC equipment. Published studies typically address specific HVAC systems with various bundles of equipment and material types that prevent comparison, while EPD and open databases offer a more uniform description of typical HVAC component types. In this context, this study identifies an opportunity for a broader application of ECC from EPD and open databases that could lead to a broader application of EPD data in simplified LCA.

Chapter 3 provides estimates of material quantities and embodied impacts of heating, ventilation, and air conditioning (HVAC) systems for typical commercial office buildings in the Pacific Northwest (PNW) – the first study to do so – and presents the simplified LCA method approach. The research plan included the active participation of an advisory committee, formed by three HVAC contractors based in Seattle. In the first stage, representative high performance and standard office buildings and typical HVAC systems were identified. During a second stage, material quantities for each equipment and

material type were described per system type. Embodied Carbon Coefficients (ECC), LCA impacts from different data sources such as EPD, LCA peer-reviewed articles and reports, and open databases.

Simplified impact data was compiled into a spreadsheet and recorded for Global Warming Potential (GWP). Finally, a two-way ANOVA was used to analyze the data. The results show that the total material quantity for HVAC of typical commercial office buildings in the PNW ranges from 9.8 to 13.8 (kg/m²) for standard buildings and from 11.5 to 17.9 (kg/m²) for high-performance buildings. Embodied carbon ranges in standard buildings range from 27.8 to 48.2 kg CO₂ eq/m² for HVAC, and in high-performance buildings from 35.8 to 60 kg CO₂ eq/m² across sixteen typical building models.

Chapter 4 aims to identify typical HVAC systems used in office building design in Washington State and to explore the effects of current practice on total energy use and operational and embodied CO₂e. The study sample is composed of twenty office buildings in Washington State registered under the LEED v3 2009 version, of which 15 have obtained LEED certification in the last two years. The projects are registered under the New Construction (NC), Core and Shell (CS), and Existing Buildings and Operation and Maintenance (EB:OM) products and comply with the requirements established in the ASHRAE 90.1-2007 energy standard. The results show that typical HVAC system selection is often a combination of different technologies for ventilation, heating, and cooling, and that in general smaller buildings tend to incorporate high efficiency packaged units while medium and large size buildings typically rely on high performance variable air volume (HPVAV) systems with a central plant or hydronic systems such as chilled beams and water source heat pumps (WSHP). The results also indicate that data available through the LEED v3 2009 documentation system on embodied carbon of the mechanical systems is limited and that simplified methods to assess embodied carbon of HVAC are needed in order to integrate EC into whole life assessment of Mechanical Systems.

Chapter 5 aims to provide a different method to assess material quantities compared to the one used in Chapter 3 and Chapter 4. An alternative method to estimate the embodied carbon was used a case studies of commercial office with two types of HVAC+R systems. The case study is located in California and uses a HPVAV systems in a tenant improvement (TI) scope .

2. Review of existing WBLCA methods and a taxonomy for the definition of Goal and Scope⁸

This chapter presents an analysis of common parameters in existing tools that provide guidance to carry out WBLCA and proposes a new taxonomy, a catalogue of parameters, for the definition of the Goal and Scope (G&S) in WBLCA. A content analysis approach is used to identify, code and analyze parameters in existing WBLCA tools. Finally, a catalogue of parameters is organized into a new taxonomy. 650 distinct parameters names related to the definition of goal and scope from sixteen WBLCA tools available in North America, Europe and Australia are identified. Building on the analysis of existing taxonomies, a new taxonomy of 54 parameters is proposed in order to describe the G&S of WBLCA. The analysis of parameters in WBLCA tools does not include Green Building Rating Systems (GBRS) and is only limited to tools available in English. This taxonomy enables architecture, engineering and construction (AEC) practitioners to contribute to current WBLCA practice. A study of common parameters in existing tools contributes to identifying the type of data that is required to describe buildings and contribute to build a standardized framework for LCA reporting, which would facilitate consistency across future studies and can serve as a checklist for practitioners when conducting the G&S stage of WBLCA.

2.1 Introduction

Life Cycle Assessment (LCA) of buildings is a fast growing research area with a number of publications that has more than doubled in the last 5 years (Anand and Amor 2017). LCA is a method for systematically analyzing environmental performance of products or processes over their entire life cycle, including raw material extraction, manufacturing, use, and end-of-life (EOL) disposal and recycling (Cabeza et al. 2014). A Whole Building Life Cycle Assessment (WBLCA) is an LCA exercise where the entire building project is considered holistically (Athena 2014a) and can assist building designers in reducing environmental impacts of a building, however, one of the most critical obstacles in this field of study is the variety of ways in which WBLCA are conducted. It has been widely accepted that different methods applied to an identical case can generate different results (Buyle, Braet, and Audenaert 2013); that studies that comply with ISO standards can have significant differences in methodology (Hammond and Jones 2008) and that many decisions made during the LCA such as functional unit choice, LCA system boundaries, description of the physical characteristics of the building, among others, influence greatly the LCA results (Rasmussen

⁸ This chapter is an adaptation of a published article (Barbara X. Rodriguez et al. 2019)

et al. 2018). LCAs of building remain difficult to compare due, in part, to the broad array of guidance on how to carry out the assessment (Giesekam and Pomponi 2017).

Another important but often overlooked barrier for comparing LCA of buildings studies is the lack of a consistent terminology to describe building parameters, particularly during the goal and scope (G&S) phase. The G&S phase includes the description of the object of assessment- a building in the case of WBLCA- and is therefore critical in performing WBLCA. Current WBLCA studies do not describe the G&S consistently, hence the results are not comparable. This is due, in part, because the tools used for WBLCA guidance do not provide a consistent list of parameters for the definition of G&S.

This was demonstrated in the recent “Embodied Benchmark Study” that included 1,191 buildings from 23 different data sources. The data were not directly comparable due to uncertainties and inconsistencies in descriptions of building scope and insufficient information collected to classify the buildings (Simonen, Rodriguez, Strain, et al. 2017). Hence, most studies even when using the same source of guidance, are difficult to aggregate and compare due to:

- a) individual differences in LCA parameter names for each study (i.e. functional unit definitions and building descriptions) and
- b) a lack of standardized reporting system for WBLCAs.

WBLCA shows promise for evaluating and achieving lower impacts in buildings, however larger consistency across reports will be needed. This study contributes to increasing consistency by, first, providing an analysis of common parameters in existing tools that provide guidance to carry out a WBLCA and secondly, proposing a taxonomy, a catalogue of parameters, for the definition of the G&S phase applicable to future WBLCA. This new taxonomy would allow practitioners to provide the minimum necessary parameters to describe Goal (Assessment goal and background information on the assessment) and Scope (Minimum required project information, functional unit, reference study period and system boundary).

2.2 Literature review

2.2.1 Life Cycle Assessment (LCA) in Practice, Barriers and Harmonization efforts

LCA is currently one of the most widely used methodologies to assess environmental impacts and has a large history in the realm of industrial ecology. The ISO 14040/44 standards define the steps of performing LCAs (Weidema 2014) and these standards describe the four main stages: G&S definition, life cycle inventory, impact assessment, and interpretation (ISO 2006a). A unique characteristic of LCA is the focus

on products in a life-cycle perspective, this comprehensive scope is useful in order to avoid problem-shifting from one phase of the life-cycle to another (Finnveden et al. 2009).

Since its inception, many studies have been developed in order to identify the barriers to wider LCA adoption in the industry. Authors have identified problems in each of the LCA stages that may affect the accuracy of the methodology (Reap et al. 2008). Some of the several problems that practitioners struggle with are time requirements for the collection of data and complexity of the LCA method (Cooper and Fava 2006). In recent years, actions to overcome these barriers have emerged, including the proliferation of methods and tools offering simplifications to conduct an LCA, reducing the time-consuming process of the life cycle inventory phase, for instance. LCA tools can be defined broadly as ‘any systematic means for dealing with environmental issues during the product development process’ (Baumann, Boons, and Bragd 2002). Over the last decades LCA tools have proliferated extensively in all sectors of the economy (Guinée et al. 2011). This proliferation of tools has enabled a wider adoption of LCA yet increasing inconsistencies across studies.

In response to the methodological differences in most LCA approaches, several efforts have been developed towards harmonization. In 2013, the Joint Research Centre of the European Commission (JRC) performed a study providing specific recommendations to the LCA practitioner (Hauschild et al. 2013). Different sectors have also led their own internal efforts in harmonizing database development and reporting (Heath and Mann 2012). Specific LCI databases, such as the Ecoinvent have also implemented quality guidelines in order to ensure coherent data acquisition and reporting (Frischknecht and Rebitzer 2005). Most of these efforts are developed, however, in parallel to an ever-growing number of studies (Hellweg and Canals 2014).

2.2.3 WBLCA tools and inconsistencies

WBLCA is currently the predominant method to quantify the environmental impacts of buildings. The proliferation of WBLCA studies triggered the development of LCA tools particularly targeted to AEC practitioners. One of the major barriers of using general LCA tools, such as the ones specific for LCA practitioners, during early stages of design, is that LCA is not design-oriented (Devanathan, Srikanth Ramanujan et al. 2010). Several authors recognize that the development of user-friendly tools in recent years encourages architects and engineers to look at the embodied CO_{2e} of their designs (De Wolf, Pomponi, and Moncaster 2017). Environmental assessment tools for buildings have proliferated and have been reviewed in several studies (Lamé, Leroy, and Yannou 2017). Broadly, tools reviewed in the literature can be classified into: green building rating systems (GBRS) (Mattoni et al. 2018), standards, software, guidelines, and databases (Haapio and Viitaniemi 2008).

It is currently widely recognized that the different approaches to WBLCA will become a barrier to precise comparisons between buildings assessed with different tools, hindering the development of baselines to drive reductions in environmental impact (Bowick, O'Connor, and Meil 2014), and that inappropriate comparisons can easily lead to design decisions that might contribute to a worse environmental impact compared to that of business-as-usual (Athena 2017). However, the current state of research is plagued by a lack of accurate and consistent data methodology (Dixit et al. 2012).

The G&S phase is the first stage of an LCA as per ISO 14040 standards and one of the stages that includes the largest inconsistencies in typical WBLCA. This stage should provide a sufficiently well-defined scope to ensure that the breadth of the study are sufficient to address the stated goal (ISO 2006a). However key components of the G&S offer significant variation in different WBLCA studies. System boundary definition, a key component of the G&S stage, varies across studies (Rasmussen et al. 2018), as these define their system boundary subjectively (Dixit, Culp, and Fernández-Solís 2013). Key parameters and assumptions are frequently not stated (Giesekam and Pomponi 2017) and the same parameter may be named differently across studies, such as the case of “Building area”, which may be defined as “gross area”, “internal area”, or “exterior area” indistinctively in projects (Simonen, Rodriguez, Barrera, et al. 2017). Hence, one of the most critical barriers for comparing WBLCA studies is the use of different parameter names in published reports.

2.2.4 Taxonomies and classification systems in the AEC industry

According to EN 15978 the scope should also include the description of the object of assessment (CEN 2011)- the building- in the case of WBLCA. The description of the building has remained a challenge for many subdisciplines in the AEC industries outside of LCA practice. Buildings are complex artifacts and numerous classification systems have been proposed to organize construction entities in a standardized way, enabling comparison. Taxonomies serve this purpose by describing concepts and entities in a subclass hierarchy through an “is-a” relationship, and are developed to standardize terms in a number of industries (Cheng et al. 2009). Some of the most well-known taxonomies in AEC are OmniClass Construction Classification System (known as OmniClass™ or OCCS) (Construction Specifications Institute (CSI) 2006), MasterFormat, and UniFormat in North America (Afsari and Eastman 2016). Numerous studies in the past have examined the existing semantic structures in the AEC industry for the purposes of describing the building (Solnosky and Hill 2013) (Ekholm, Häggström, and Haggstrom@caad 2011). This study evaluates existing taxonomies to be applied in WBLCA and indicates when distinct taxonomies could be merged under terms in a more consolidated system such as Omniclass™.

2.3 Methods

The present study was developed within the framework of the project entitled “LCA for Low Carbon Construction, Stage 2: LCA Practice Guide”. The project aimed to introduce the use of LCA to building professionals for analyzing the environmental impacts of buildings in North America. During the process of developing this project, an Advisory Committee was formed. This expert group included thirty-five LCA experts from different geographical locations. The Advisory Committee was asked to identify prominent sources of guidance for performing LCAs of buildings – referred to as “tools” from this point forward – and later to provide input on the development of the LCA taxonomy. The final taxonomy was presented in a workshop where the experts were consulted in person about the results.

The taxonomy was developed in three methodological stages as shown in Figure 2.1. Once the tools were selected, the second stage was ‘Parameter Analysis’, this stage included three steps: data gathering, literature review, content analysis. A second stage consolidated the final taxonomy structure. This stage, resulted in a new taxonomy structure, including proposed names for common or similar parameters that were named differently in the sources.

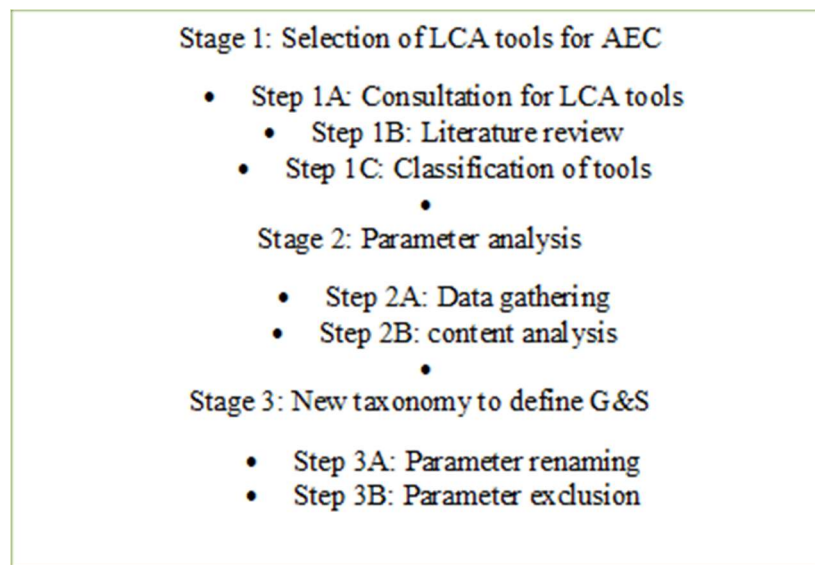


Figure 2.1 Methodological stages for the development of a taxonomy to describe the Goal and Scope (G&S) stage of a WBLCA

2.3.1 Stage 1: Selection of LCA tools for AEC

WBLCA tools used by the AEC industry were developed using two separate methodologies: consultation with the advisory committee (Step 1A) and using a systematic literature review (Step 1B).

The advisory committee was first consulted about different tools available in all regions around the world, commonly used by their organizations. The research team obtained direct feedback on the selection of this sources through a series of teleconferences between April 2017 and December 2018, and during three face to face workshops held in May 2017, November 2017 and June 2018. The research team used a basecamp website where both technical group and professional group added their inputs that was compiled into a list of reference documents.

In parallel to the tools indicated by the Advisory Committee, the research team developed a literature review based on a defined methodology and following a set of three inclusion criteria. The tools included in the study (1) Are intended to be used by the AEC sector, this means, that the guidance provided is specific to the building industry for the development of assessment of buildings, (2) Describe a ‘method’, understood in the context of this study as a ‘specific procedures (plural) for gathering and/or analyzing data’ (Gerring 2012) and (3) Provide a list of parameters to characterize the object of assessment, in this case, a building. It is worth noting that the tools defined in the scope of this study include only those that provide guidance on what type of data input is required to carry out an assessment. In other words, this study only includes tools that address the specific input parameters required to comply with each stage of a typical assessment. GBRS and local state and national codes are excluded of this study since these do not exclusively address how to perform WBLCA and instead provide guidance on various other environmental assessments such as building energy performance or water efficiency. Nevertheless, many of the LCA standards typically referenced in GBRSs are included in the scope of this study. Common databases such as Gabi database or Ecoinvent are outside of the scope of this project, since these are not a source of guidance exclusively for the AEC industry.

To carry out the review, a ‘method matrix’ was developed to consistently record each WBLCA tool found in the literature. The ‘method matrix’ tracked the following variables for each tool: Type/Name of Document, release date, author, goal, normative referenced, functional equivalent, definition of product and system boundaries. Once this stage was finalized, the list of tools suggested by the Advisory Committee was compared to this matrix for consistency.

After the first two steps, a total of sixteen WBLCA tools were selected. The tools selected from North America, Europe, and Australia were limited to those that were available in the English language. These sources offer guidance on carrying out a partial or complete WBLCA and are classified into: In the WBLCA review study the different tools are classified in four separate types: software, online database, standard and guidelines. The list of sources is shown in Table 3.1.

Table 2.1 WBLCA tools included in the sample

Name	Title	Type	Author	Geographic region
1. Athena v5.1.0102	Athena Impact Estimator for Buildings	Software	(Athena 2014b)	Canada, U.S.
2. DDx	AIA 2030 Design Data Exchange	Online database	(AIA 2018)	U.S.
3. deQo	database of embodied Quantity outputs	Online database	(DeWolf 2018)	Worldwide
4. EN 15978	Sustainability of construction works - Assessment of environmental performance of buildings -	European Standard	(CEN 2011)	European Union
5. ENSLIC	Energy Saving through promotion of Life Cycle analysis in Building	Guidelines	(Glauman et al. 2010)	European Union, Spain
6. eTool	eToolLCD	Software	(eToolglobal 2018)	Australia
7. HQE	HQE Performance Life Cycle Assessment: Specific Rules of new buildings in line with EN 15978 standard For the HQE Performance 2012 Experiment	Guidelines	(CSTB 2012)	France
8. IESVE	IES Virtual Environment LifeCycle Analysis (LCA) Module	Software	(IESVE 2018)	U.K.
9. One Click	One Click LCA	Software	(Bionova LTD 2018)	Finland
10. Tally	Tally	Software (plug-in for Revit)	(KT Innovations 2016)	U.S.
11. WRAP	WRAP Embodied Carbon Database	Online database	(WRAP 2018)	U.K.
12. RICS	Whole life carbon measurement: implementation in the built environment- Professional statement	Guidelines	(RICS 2017)	U.K.
13. EU JRC Technical Report - Levels	A common EU framework of core sustainability indicators for office and residential buildings-Part 3 Levels	Standard	(JRC 2017b)	European Union
14. ASTM E2921 – 16a	Standard Practice for Minimum Criteria for Comparing Whole Building Life Cycle Assessments for Use with Building Codes, Standards, and Rating Systems	Standard	(ASTM 2014)	U.S.

15. ASCE	Guide to Definition of the Reference Building Structure and Strategies in Whole Building Life Cycle Assessment	Guidelines	(ASCE 2017)	U.S.
16. PCR for Buildings v2	International EPD System	Guidelines	(IEPDS 2018)	Sweden

2.3.2 Stage 2: Parameter Analysis

Step 2A: Data Gathering: Parameter Classification

After the tools were selected, each tool was reviewed independently by two different researchers. Each individual parameter was identified, highlighted, and recorded in a master database template.

Step 2B: Content analysis

In step 2b of the parameter analysis, the different tools were analyzed using content analysis. The parameters were coded and classified under the four stages of a typical LCA. The parameters were grouped together with similar items, under “generic parameter names” or topics. Therefore, the parameters recorded were organized by topic, such as:

Example 1: “Area” (e.g. “Building footprint area”, “site area,” “conditioned floor area”, “gross internal floor area (GIFA)”, etc.)

The large topic groups and subtopic groups were organized under the taxonomy skeleton where appropriate. Generally, parameters that described the physical characteristics of the building went under “G&S” > “Scope” > “Functional unit”. The topic group “Project information” was placed under “Scope”, while the topic group “Background information on assessment” was placed under “Goal.” Categories up to six levels were identified to organize each parameter.

In parallel, the parameters were also coded into three categories by parameter types: “Building descriptor”, “LCA descriptor” and “LCA indicator.”

2.3.3 Stage 3 New Taxonomy for the definition of G&S Stage

Based on the analysis of existing parameters, a catalogue of parameters is organized proposing a new taxonomy. This stage considered the results from Stage 1 and Stage 2, such as total count of parameters per LCA method categories and total count of parameters for parameter types..

Once the parameters were analyzed, the first step was to rename common parameters that appeared with different names across the sources. A second step included or excluded parameters from the taxonomy depending on the number of counts. Excluded parameters either because they were 1) obscure, 2) covered elsewhere by a different or similar parameter, 3) an LCA indicator, or 4) an LCA system boundary item (which would be covered in the system boundary section of the taxonomy, described per Omniclass).

Finally, a third step consolidated the final version of the taxonomy by indicating whether parameters were Required vs. Optional. This was done mostly by designating parameters that had more than two “votes” by the sources as ‘Required’ and the remaining as ‘Optional’, unless a parameter was deemed to be irrelevant or unnecessary.

2.4. Results

The results of this study are presented in different subsections. Section 4.1 presents background information on the LCA tools in the sample and compliance with well-established standards. Section 4.2 details a summary and a frequency analysis for the total parameters coded by source in the sample. Section 4.3 presents an analysis of parameters by topic. Finally, Section 4.4 presents the final proposed taxonomy.

2.4.1 Background information on the LCA tools included in the sample

The sample included 16 sources categorized by type of tool in Table 2. Most tools in the sample encompass guidelines and standards providing guidance for simplified LCA. The software packages in the sample are intended for simplified LCA. Software and guidelines state their compliance with ISO 14040/14044 series, EN 15978:2011 and the product category rules for Environmental Product Declarations (EPDs) for construction products, EN 15804:2012. These standards provide a general framework, but they do not provide names for specific key parameters to describe the G&S stage. EN 15978 is referenced as the main LCA based calculation method for WBLCA in tools from Europe, North America and Australia

2.4.2 Details a summary and a frequency analysis for the total parameters coded by source in the sample.

Each individual LCA tool was analyzed to identify, copy and categorize each parameter related during the G&S stage. A total of 650 different parameters were reported in 16 different tools, as shown in Table 2.2. From this total number of parameters, only 12 parameters were used more than two times. 547 unique parameters were used only once.

Table 2.2 Number and Names of Unique Parameters

Number of Unique Parameters	Frequency of use	Parameter Name
1	6	'Project name'
1	5	'Roof'
2	4	'Foundations'; 'external walls'
8	3	'power and communication systems'; 'non load-bearing elements'; 'internal walls'; 'design number of building occupants'; 'ceiling'; 'building type'; 'Reference Period'
30	2	(not displayed here)
547	1	(not displayed here)
650	Total	

The parameters were classified under “Building Descriptors” and “LCA Descriptors”. 540 “Building Descriptors” and 110 “LCA Descriptors” were found, as shown in Table 2.3.

Table 2.3 Number of parameters types categorized by tool

Type of Tool	Name	Building Descriptor	LCA Descriptor	Total Amount of G&S Parameters
Software	Athena v5.1	5	0	5
	eTool	8	21	29
	IESVE	13	1	14
	One Click	1	0	1
	Tally	8	8	16
Online database	DDx	31	3	34
	deQo	8	0	8
	WRAP	44	32	76
Guidelines	ENSLIC	33	9	42
	HQE	148	2	150
	PCR for Buildings v2	41	2	43
	RICS	29	14	41
	ASCE	28	3	31
	JRC Technical Report -Levels	61	2	63
Standard	EN 15978	41	13	53
	ASTM E2921 – 16a	41	0	41
		540	110	650

2.4.3 Analysis of parameters by topic and subtopics

In order to classify the parameters, the parameters were classified under six larger topics “Assessment Goal”; “Background Information on Assessment” “Project Information”, “Functional Unit”, “Reference Study Period” and “System Boundaries”. System Boundary parameters had the most counts (372) followed by Functional Unit parameters (174). The parameters counts in the topics are shown in Table 2.4.

Table 2.4 Number of parameters according to G&S topic

Topics	Total
Assessment goal	9
Background info on assessment	47
Functional unit	174
Project information	41
Reference study period	7
System Boundary	372
Grand Total	650

Functional Unit parameters with a total count of 174 parameters, were further classified into “Building Scale and Performance” and “Geographic and Site Characteristics”.

Under ‘functional unit’, the large number of unique parameters listed describing ‘Area Characteristics’ offers an illustrative example of the large variety of parameter names used to define the same building descriptor, as shown in Table 9. For instance, “Area” can be represented by different parameters in each tool, such as “Area”; “Floor Area”, “Gross Building Area”, “Gross Internal Area (GIA)”. In a practical application, the large variability of this single parameter, can become an important barrier to comparing studies. Most WBLCA studies use a common carbon intensity factor expressed in $\text{kCO}_2\text{e}/\text{m}^2$ to report the indicator for embodied carbon. Studies that describe the ‘area characteristics’ of the functional unit in total gross floor area cannot be compared to others using net internal area.

Table 2.5 Parameters names listed under “Area Characteristics” for “Functional Unit”

Area characteristics	Gross internal floor area (GIFA)
	Units for functional equivalent
	Total gross floor area
	The total net gross floor area (GFA)

The total floor area
The ground area
Site area, m ²
Reference area, m ²
Net Internal floor area (NIA) (m ²)
Net internal floor area (NIA)
Land area (m ²)
GSA (m ²)
Gross internal area (GIA)
Gross floor area (GFA) (m ²)
Gross Building Area (ft ²)
Floor area, m ²
Floor area
Area

System Boundary parameters with a total of 372 parameters, were classified under “Building Scope”, “Other Inclusions” and “Non-Categorized”. The most populated parameter category is ‘Building Scope’, where the definition of building ‘Services’ includes the largest number of parameters. The definition of building ‘Shell’ encompasses 70 parameter names across the tools.

2.4.4 Final proposed taxonomy

After the parameter analysis, each individual parameter name was revised for clarity. For instance, long parameters names were reduced to shorter names that matched similar ones under the same topic. After the parameter renaming, some parameters were excluded from the taxonomy based on the following criteria: ‘covered elsewhere’; ‘LCA indicators’, ‘too obscure’; and ‘system boundary’. Finally, a new taxonomy of 54 parameters is proposed to accurately describe the G&S of future WBLCA as shown in Tables 6a and 6b. For the description of ‘Building Scope’ it is recommended that scope parameters are replaced by terms present in consolidated taxonomy systems for buildings such as OmniClass.

Table 2.6 Proposed taxonomy for the definition of the WBLCA goal

<i>Category Level 1</i>	<i>Category Level 2</i>	<i>Category Level 3</i>	<i>Category Level 4</i>	<i>Category Level 5</i>	<i>Category Level 6</i>
<i>1. Goal and Scope</i>					
	Goal	Assessment goal			
			<ul style="list-style-type: none"> • Intended application • Reasons for carrying out the study • Intended audience • Whether results are intended to be used in comparative assertions 		
		Background information on assessment			
		General information on LCA			
			<ul style="list-style-type: none"> • Date of LCA assessment • Assessment stage: Project phase at time of LCA assessment • Client for assessment • Name and qualification of LCA assessor • Organization of assessor 		
		Verification			
			<ul style="list-style-type: none"> • Name and qualification of LCA verifier • A statement asserting if verification is "internal" or "external" • A statement categorizing competence of the verifier • Date of verification • Signature of verifier • Statement of which items were verified 		
		LCA data and methods			
			<ul style="list-style-type: none"> • Source, type and quality of LCA data • LCA impacts and assessment method including version number and reference • Tool version and date 		
		Assumptions and scenarios			
			<ul style="list-style-type: none"> • HVAC, natural ventilation and daylight simulation performed • Source, type and quality of building data • BIM model available (Y/N) 		

Table 2.7 Proposed taxonomy for the definition of the WBLCA scope

Category Level 1	Category Level 2	Category Level 3	Category Level 4	Category Level 5	Category Level 6
1. Goal and Scope					
Scope					
Project information					
<ul style="list-style-type: none"> •Project name •Project type •Building architect, engineer, and/or contractor •Building owner, developer, and/or manager •Project construction cost •Rating scheme •Rating achieved •Year of building construction completion •Year of building commissioning •Year of occupancy •Year of refurbishment 					
Functional unit					
Building scale and performance					
Area characteristics					
<ul style="list-style-type: none"> •Building footprint area •Total gross floor area (GFA) •Parking lot size 					
Height characteristics					
<ul style="list-style-type: none"> •Average ceiling height •Building total height •Number of stories above grade •Number of stories below grade 					
Relevant technical and functional requirements					
<ul style="list-style-type: none"> •Building use type(s) •Building occupancy type •Design number of building occupants •Design life expectancy in years •Typical floor and roof live load 					

- Structural type (per IBC)

Geographic and site characteristics

- Class of noise exposure
- Climate zone (per IECC)
- Landscaping description
- Seismic design category (per IBC)
- Soil site class (per IBC)

Location - address

- Location - Street address
- Location - state/province
- Location - country
- Location - city

Life Cycle Scope

Reference study period (RSP) per EN 15978 (shall be presented separately for all the building life cycle stages and for module D)

System boundary

Building scope per Omniclass or RICS Professional Statement

2.5 Discussion

The results show that a broad range of parameters is used for the definition of the G&S stage across the different software, databases, standards, and guideline tools. The frequency analysis resulted in 650 distinct counts of parameters, from which 547 parameters are used only once across different tools that provide guidance on WBLCA. Only 12 unique parameter names are used more than two times in the total sample. These results lend credence to the argument that different methodologies and parameters in current data and databases leave the industry with published values that are not comparable (Dixit et al. 2012). This parameter inconsistency in current tools for the AEC industry affect comparability since for an accurate comparison and informed decision, the environmental impact of buildings should be measured based on similar parameters.

The parameter analysis indicates a high inconsistency in the data required for the definition of the G&S across different types of tools. WBLCA tools use different numbers of parameters, different parameters names, and address the larger topics related to description of the building and the assessment differently. WBLCA software and online databases have a lower median number of parameters compared to WBLCA guidelines and standards. From the different types of tools, WBLCA guidelines offer the most detailed

guidance on how to carry out the assessment. These findings support earlier research explaining the specific roles that different tools play during the design process (Franzoni 2011).

For this study, parameters were classified under “Building Descriptors” (n=540) and “LCA Descriptors” (n=107). Parameters intended to provide definition of the object of assessment or the building are much broader in breadth and scope than parameters intended to describe the LCA. While the exact names of the parameters varied, a number of topics such as “Functional Unit”, “Project Information”, “Background Information on Assessment” and “System Boundary” were addressed in the different tools. System Boundary parameters had the most counts with 540 unique counts followed by Functional Unit parameters with a total of 152 parameters.

From most of the building descriptors that fall under “System Boundary”, “Building Scope” is the largest source of parameter variation. The tools analyzed do not reference a particular taxonomy or classification system for building components, and instead describe the building elements in general categories or in vague terms. The lack of precision in the description of the building elements becomes a barrier for the accurate comparison of WBLCA reports.

2.6 Conclusion

WBLCA is currently a well-established method used to evaluate buildings, assisting building designers in reducing environmental impacts of a building. Different tools provide guidance to practitioners on how to carry out the assessment. The proliferation of tools brings numerous challenges to the accuracy and comparability of the study since the results in each study can vary with regards to which parts of the building were included and the parameter used to describe the study. This study found individual significant differences in key parameter names in each tool. Given the lack of standardization in WBLCA methods, this research proposes a taxonomy of parameters which could be used in all WBLCA reports in the future.

3. Embodied Carbon Coefficients (ECC) for Heating, Ventilation, Air Conditioning and Refrigerants (HVAC+R) Systems in the context of office buildings: A review of published articles, EPD and open databases

This review chapter explores the application of LCA in heating, ventilation and air conditioning (HVAC+R) systems and presents an analysis of existing LCA studies, in published articles, Environmental Product Declarations (EPD) and Life Cycle Assessment (LCI) databases. The research goal is to identify embodied carbon coefficients (ECC) and typical lifespan for HVAC+R components. A second line of inquiry in this review aims to understand how LCA studies of HVAC+R equipment and material types are currently developed.

The main challenges to the incorporation in LCA of the ECC identified in the study are: difference in functional units, life cycle boundaries and lifespan of the equipment used across the studies. A particular difference between published studies, EPD and open databases is the different levels of complexity in modelling the various components and materials of HVAC+R equipment. Published studies typically address specific HVAC+R systems with various combinations of equipments and distribution material types that prevents comparison, while EPD and open databases offer a more uniform description of typical HVAC+R component types. In this context, this study identifies an opportunity for a broader application of ECC from EPD and open databases that could lead to a broader application of EPD data in simplified LCA methods.

3.1 Introduction

In recent years, with more stringent codes for energy efficiency, operational carbon (OC) of heating ventilation, air conditioning and refrigerants (HVAC+R) has been reduced and there has been an increasing interest to understand the remaining life cycle stages of the equipment, as there is a renewed interest on the embodied carbon (EC) of different building systems (Pomponi and Moncaster 2016a). In one of the first studies comparing two AC systems in an office building the conclusion is that LCA of HVAC+R is possible and recommends the evaluation of the whole system as instead of limiting the attention to only one parameter, such as energy use intensities (EUI), (Heikkila 2004). A review developed by Tan et al. indicate that the embodied energy in the HVAC+R equipment from material and manufacture can be large in magnitude, yet small when compared to operational energy impact (Jong Tan and Nutter 2011). Nevertheless, more recent LCA studies of HVAC+R equipment demonstrate that

building services can represent anywhere from 11% (Bagenal George, Hamot, and Levey 2019) to 15% of initial EC of a typical office building (Cheshire 2014), while recurring EC of building services from 30 years of maintenance and replacement may be six times the value of initial EC (Medas M. et al. 2015). Another study by Hoxha and Jusselme concluded that appliances are responsible for about 25% of a building's overall impacts using a case study in Switzerland(Hoxha and Jusselme 2017).

3.1.1 LCA methods for the building industry

Life cycle assessment methods tailored for the building industry, rely on the increasing knowledge of both: environmental data for materials and total material quantities for the different construction systems. In the case of embodied carbon assessment, the result is expressed in terms of the global warming potential (GWP) of a building system (expressed in $\text{kgCO}_2\text{e}/\text{m}^2$) that is obtained by multiplying two key variables: the material quantities (MQ, expressed in $\text{kg}_{\text{material}}/\text{m}^2$ or kgm/m^2) and the embodied carbon coefficients (ECC) expressed in kgCO_2e per kg of material (kgm) (De Wolf, Iuorio, and Ochsendorf 2014), where CO_2e stands for the equivalent in carbon dioxide of the greenhouse gases (GHG) produced for the manufacturing and transportation of these materials (Dias and Pooliyadda 2004). Since the focus of whole building life cycle assessment (WBLCA) has been on structural systems, various efforts have developed ECC of typical structural materials such as concrete and steel (De Wolf et al. 2015)(Hammond and Jones 2008), however no systematic review has examined ECC of typical materials and equipment of HVAC+R systems, to the best of the author's knowledge.

3.1.2 LCA data in environmental product declarations (EPD) and product specific LCA databases

In recent years, the proliferation of WBLCA studies triggered the development of LCA tools particularly targeted to AEC practitioners. Several authors recognize that the development of user-friendly tools in recent years encourages architects and engineers to look at the embodied CO_2e of their designs (De Wolf, Pomponi, and Moncaster 2017). Environmental assessment tools for buildings such as green building rating systems (GBRS), standards, software, guidelines, and databases (Haapio and Viitaniemi 2008), have proliferated and have been reviewed in several studies (Lamé, Leroy, and Yannou 2017).

WBLCA tools rely on LCA data to assess the impact of different building systems. The increasing demand for better LCA data and ECC, is currently being satisfied in part with the proliferation of ecolabels in the form of Type III also known as environmental product declarations (EPDs) and product specific LCA databases available online. Currently, EPD programs and open databases offer some of the most important sources of LCA data for construction products. Typically, EPD datasets for specific products and companies are calculated using well established LCA tool, the datasets are then integrated

into a central repository or product specific LCA database, and these are later integrated into other tools for WBLCA or calculating the environmental footprint of an entire building (Okebaudat 2018).

EPD or Type III ecolabels provide quantified environmental data and independently verified environmental information over the life cycle of goods and services (ISO 2006b). EPD are based on LCA methodology and developed according to pre-defined Product Category Rules (PCR). In the last decades, EPD have been used extensively in order to reduce the embodied impacts of products across their entire life cycle, particularly in the building sector (Minkov et al. 2015).

In the construction sector, one of the most important harmonization efforts across EPD programs is the European Standard 15804 that defines the ‘core rule’ for PCR (Frischknecht et al. 2015). However, several methodological challenges remain in order to enable a wider EPD use by the architectural, engineering and construction (AEC) community. Studies have demonstrated that most PCRs are inconsistent among the EPD program operators using 14025 as the basis (Ingwersen and Subramanian 2014). A recent study developed by Gelowitz and McArthur, uses a comparison matrix to analyze 50 product specific EPD and the underlying 13 PCRs across three categories: insulation, flooring, and cladding. The results show that the lack of harmonization between several PCRs limited the comparability between EPD in the same category and even between products in the same PCR (Gelowitz and McArthur 2017). A comparison or an evaluation of EPD data is only possible if all the data sets to be compared were created according to EN 15804 and that the product-specific characteristics of performance are taken into account (BSI EN 15804 2014).

In France, there is a clear distinction between EPDs for construction products and building equipment for mechanical building and plumbing . In 2004 INIES was created as the main public EPD database for construction products and building equipment in France providing free access to the data for users (INIES 2017). As of May 2019, the INIES repository contained 2809 EPD for building from which 853 are equipment for MEP sold in France. 159 EPDs for HVAC+R, mostly from the PEP Ecopassport® program, which is specific to electrical, electronic and HVAC+R equipment used in construction, industry and infrastructures and complies with ISO 14025 (PEP Ecopassport 2017). The PEP Ecopassport® program currently uses one PCR document for all the product categories (Hassanzadeh et al. 2013) that is used as the basis for a total of 131 EPD published for HVAC+R equipment as of May 2019 (P.E.P Ecopassport® 2016).

Generic Databases have been an important source of LCI background data for LCA during the last ten years, however new product-specific databases are currently being developed to assist in WBLCA

(Lasvaux et al. 2015). Until recently most life cycle inventory databases in the building industry only included basic material types and do not include composites (Hammond and Jones 2008).

In Germany, the ÖKOBAUDAT, released in November 2017, is the mandatory standardized database within the Assessment System for Sustainable Building (BNB) provided by the Federal Ministry of the Interior, Building and Community (BMI) for ecological evaluations of buildings (BMI / BBSR 2017). Building materials, construction and transport processes are described regarding their ecological effects. The data set represents the country specific situation in Germany, focusing on the main technologies, the regional specific characteristics and / or import statistics(Okebaudat 2017a). The provided data comply with DIN EN 15804 and are generated based on GaBi background data. As of May 2019, 1210 datasets are available from which 205 were available for “Building Service Engineering”; 82 for Heating and 17 entries available for Air conditioning and ventilation (BMI / BBSR n.d.) . The ÖKOBAUDAT is expected to enable the wide use of LCA in the German building industry, however some of the shortcomings reported of this database include ‘incorrect linking of building life cycle inventory data with environmental information, incorrect documentation of functional units, missing generic datasets, the modeling of energy use data or the lack of a uniform structuring, or material classification’(Gantner et al. 2018).

In North America, most EPDs for HVAC+R are registered under the UL Environment (ULE) EPD Program, that as of May 2019 includes 17 EPDs for HVAC+R products (“SPOT UL Environmental EPD Program” 2019) . The Quartz database, originally developed by google compiled in 2015 and no longer being updated, includes environmental data for one HVAC+R product.(Quartz n.d.)

HVAC+R System Choice and Design

HVAC+R system choices made by designers must balance a wide range of issues including first cost, energy cost, maintenance effort and cost, coordination with other trades, spatial requirement, acoustics, flexibility, architectural aesthetics, among other (California Energy Commission 2003). The size of the heating, cooling and ventilation system is based on providing an optimal indoor environment taking into account the external climate conditions, thermal envelope and internal loads. The internal loads are dependent on the lighting, plug loads, and heat from occupants. Therefore the larger the internal and external loads of the building, the larger the capacity of the overall HVAC+R system; larger required generation equipment and distribution systems. Different studies have been developed identifying the typical parts of HVAC+R systems in office buildings: chillers, boilers, air handling units (AHUs), rooftop units (RTUs), fan coil units (FCUs), heat pump units (HPUs),

variable air volume boxes (VAVs) (Shaikh et al. 2014). In general HVAC+R systems can be classified into ducted and ductless systems (AMCA 2017) in the following categories:

Ducted Systems:

- *Packaged Rooftop Units (RTU)*: Rooftop units are one of the most common types of HVAC+R systems for small commercial office buildings because of their flexibility of heating and cooling options.
- *High Performance VAV (HPVAV)*: Variable air volume (VAV) systems vary their supply air volume flow rate to satisfy the reduction of space load (Yu et al. 2016) during part-load operation to maintain a predetermined space parameter, usually air temperature, and to conserve fan power at reduced volume flow (Yao et al. 2007). VAV systems are the most common type of systems in standard commercial office buildings (California Energy Commission 2003). For this study, an Air Handling Unit (AHU) with Parallel Fan Powered (PFP) terminals is described. In these systems, each zone is served by a terminal box with a fan that mixes return air with supply air from the primary VAV system.

Ductless Systems:

- *Water Source Heat Pump (WSHP)* systems rely on a large piping loop that circulates water used to reject the heat. The large piping loop combines water-source heat pumps with a typical heat rejector and a boiler.
- *Variable Refrigerant Flow (VRF)*: A refrigerant system that varies the refrigerant flow rate assisted by a variable speed compressor and electronic expansion valves (EEVs) from each indoor unit to match the space cooling/heating load in order to maintain the zone air temperature at the indoor set temperature (Aynur 2010). These systems were introduced in Asia more than 20 years ago, but have gradually expanded its market presence in the U.S in the last decade.
- *Chilled Beam Systems*: Use water pipes in modular units mounted to ceilings and can be classified in passive and active (Roth et al. 2007).
- *DOAS ERV*: Dedicated Outdoor Air System (DOAS) systems decouple the indoor air quality function of an HVAC+R system from the thermal control function, hence an entirely separate system is designed to provide for ventilation (Grondzik 2016). This type of systems requires to be coupled with a heating/cooling system.

Based on this initial understanding of equipment types, a comprehensive list of all the different equipment for each type of system as shown in Figure 1.

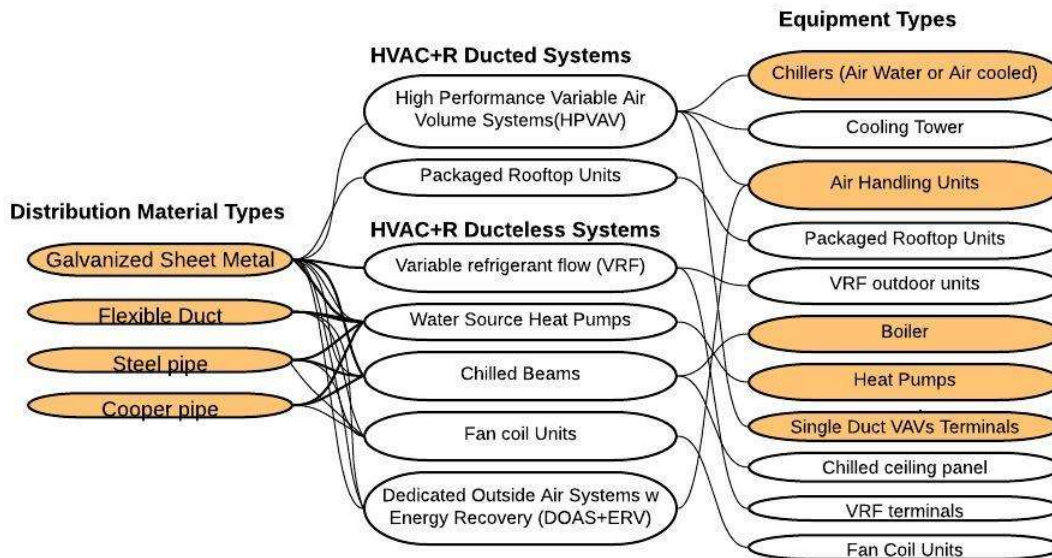


Figure 3.1 HVAC+R distribution material types and equipment types for different ducted and ductless systems. Highlighted in orange are distribution material and equipment types for which there is data available in LCA studies

In order to support the continuing effort of integrating LCA of HVAC+R equipment into WBLCA, this paper aims to respond to the question: What are the typical ranges of ECC of typical HVAC+R equipment and distribution material types?. This study responds to this question by developing a systematic literature review of LCA studies available in databases, EPD and published journals. A second line of inquiry aims to synthesize the challenges, sources of uncertainty and future area of research in the different stages of LCA of HVAC+R equipment. In order to achieve this goal, the focus is on life cycle assessments for typical HVAC+R equipment based in process-analysis LCA presented in EPD, open databases and journal articles. Since most of these studies come from different geographical locations representing different energy mixes, the different environmental impact results of these studies are not directly comparable. Nevertheless, several authors in the past have been able to compare methodological decisions in LCA studies using a comparative analysis approach. This study is structured using the method proposed by other LCA reviews (Rashid and Yusoff 2015) (Anand and Amor 2017) where the analysis follows the four well known stages of LCA mentioned in the ISO standards: Goals and Scope definition; inventory analysis; impact assessment and interpretation. The article summarizes the knowledge gaps and the research opportunities.

3.2 Methodology

3.2.1 Stage 1: Selection of HVAC+R systems and components

HVAC+R systems are diverse and emergent technologies are available in the marketplace. For this study three different HVAC+R contractors were consulted and requested to provide descriptions for typical HVAC+R systems for commercial office buildings. In addition, a literature review of studies of commercial office buildings was developed to redefine the initial selection of mechanical systems.

After the development of a comprehensive list of typical building equipment, a second stage focused on identifying LCA studies for each type in EPD, Open Databases and published articles.

3.2.2 Stage 2: Selection of the data sample: EPD, Open Databases and published articles

Although HVAC+R systems encompass a large variety of equipment, the literature offers LCA studies for only a small number of equipment types. The criteria for inclusion in the sample for this study are: 1) LCA studies of HVAC+R equipment and material types in the context of commercial buildings; 2) Process – based LCA studies that follow the main categories described in the family of ISO 14040:44 standards and 3) LCA studies that provide results for at least two environmental impacts: embodied carbon coefficients (ECC) or GWP and embodied energy coefficients (EEC). This review excludes HVAC+R equipment analyzed in the context of other building uses such as residential or industrial and also excludes studies that use other types of LCA (i.e. EIO LCA, LCC).

Table 3.1 Number of Published Studies for HVAC+R Equipment and materials published in Journals, EPD programs and Open Databases (as of May 2019)

Source Name	Type	Region	Number of Studies
Published Articles	Journal Publication	Global	6
UL Environment	EPD Program	NorthAmerica	6
INIES-FR	EPD Program	France	157 (131 PEP)
PEP Ecopassport	EPD Program	France	131
Quartz Database	Open Database	NorthAmerica	3
Okebaudat Database	Open Database	Germany	

Table 3.2 Published Studies for HVAC+R Equipment in Scientific Journals and other

Author/year	Country	HVAC+R System Scope	Lifespan (years)	CO2e calculation method
(Bagenal George, Hamot, and Levey 2019)	UK	Boiler, CHP, ASHP and VRF	20	RICS

(Liu, Schulz, Sapar, et al. 2016)	Singapore	Chilled Beam (CC) vs Conventional Variable Air Volume (VAV)	20	CML 2001 method
(Shi et al. 2015)	China	Refrigeration Compressors	NA	Chinese LCI Database
(Medas et al. 2015)	UK	Water-side fan coil units (FCUs)	NA	ICE Database
(Rey et al. 2011)	Spain	Semi-indirect ceramic evaporative cooler w heat pipe (SIEC HP) vs split class heat pump	15	EPS 2000
(Rey et al. 2004)	Spain	Heat pumps (air- air)		EPS 2000
(Nyman and Simonson 2004)	US	Air Handling Units (AHU) small and normal, with and w/o air-to-air heat exchange	20	Impact Analysis

Table 3.3 Existing LCA data for HVAC+R distribution

Author/year	Country	HVAC+R System Scope	Lifespan (years)	CO2e calculation method	Uncertainty margin
(Okebaudat 2017a)	Germany	Air Ventilation Duct (zinc coated steel plate)	20	Thinkstep	20
(Quartz 2015a)	USA	Copper Piping	20		
(Quartz 2015b)	USA	Galvanized Steel Ducts			
(Okebaudat 2019d)	Germany	Steel Pipe	NA	Thinkstep	20
(Okebaudat 2017b)	Germany	Underfloor heating system copper (200mm distance)	30	Thinkstep	20
(ULE 2014)	USA	Aluminum Cold-Rolled Sheet and plate (functional unit converted from 1 ton to 1 kg)	NA	GaBi 6 GaBi2012 databases	20
(PEP 2016b)	France	Caisson de ventilation individuelle double flux avec filtres	17	EIME software version 5.5.0.11 with the database version HAGER 2014 V1	20
(PEP 2016a)	France	Caisson de ventilation simple flux collective ou tertiaire Airvent CRITAIR EC	17	EIME software version 5.5.0.11 with the database version HAGER 2014 V1	20
(PEP 2016c)	France	Caisson de ventilation simple flux collective ou tertiaire Airvent PA 1500/2000	17	EIME software version 5.5.0.11 with the database version HAGER 2014 V1	20
(PEP 2015a)	France	Caisson de ventilation simple flux collective ou tertiaire, ou tourelle ou ventilateur CRITAIR BC 500 C4	17	EIME software version 5.5.0.11 with the database version HAGER 2014 V1	20
(PEP 2018b)	France	Metal circular Conduit	30	EIME software version 5.5.0.11 with the database version HAGER 2014 V1	20

Table 3.4 Existing LCA data for HVAC+R equipment

Author/year	Country	HVAC+R System Scope	Lifespan (years)	CO2e calculation method	Uncertainty margin
(Okebaudat 2019e)	Germany	Ventilation centralized per 30.000 m3/h, 168kg.	20	Thinkstep	20
(Okebaudat 2019f)	Germany	Ventilation centralized per 10.000 m3/h, 68kg.	20	Thinkstep	20
(Ministère de l'environnement 2017)	France	Groupe de production d'eau glacée [500 kW]	25	ELCD 3.0 & Ecoinvent V3.1	30
(Ministère de l'environnement 2016)	France	Groupe de production d'eau glacée [100 kW]	25	ELCD 3.0 & Ecoinvent V3.1	30
(Okebaudat 2019c)	Germany	Gas condensing boiler 120-400 kW (upright unit); 1 piece	20	Thinkstep	20
(Okebaudat 2019b)	Germany	Electric heat pump (water-water) 70 kW; 1 piece (en)	NA	Thinkstep	20
(Okebaudat 2019)	Germany	Electric heat pump (water-water) 20 kW; 1 piece (en)	NA	Thinkstep	20
(Okebaudat 2019)	Germany	Electric heat pump (water-water) 10 kW; 1 piece (en)	NA	Thinkstep	20
(Okebaudat 2019)	Germany	Electric heat pump (air-water) 7 kW; 1 piece (140kg)	NA	Thinkstep	20
(Okebaudat 2019)	Germany	Electric heat pump (air-water) 14 kW; 1 piece (140kg)	NA	Thinkstep	20
(Okebaudat 2019)	Germany	Electric heat pump (air-water) 10 kW; 1 piece (140kg)	NA	Thinkstep	20
(ULE 2016)	USA	Magnitude magnetic bearing centrifugal chillers (375 tons)			
(ULE 2015)	USA	Centravac Chiller Portafolio (1840 tons)			
(PEP 2015c)	France	Condensinox Chaudière gas [100 kw]			
(PEP 2018a)	France	Chaudière gaz collective à condensation chauffage seul			
(PEP 2017)	France	Centrale double flux collective ou tertiaire			
(PEP 2017)	France	Centrale de traitement d'air double flux collectif ou tertiaire Duotech			
(ULE 2016)	USA	Magnitude magnetic bearing centrifugal chillers (375 tons)			
(Nyman and Simonson 2004)	Finland	Small AHU Air-to-Air Heat Exchange Rotating Wheel			
		Small AHU Air-to-Air Heat Exchange Plate			
		Small AHU			
		Normal AHU Air-to-Air Heat Exchange Rotating Wheel			
		Normal AHU Air-to-Air Heat Exchange Plate			
		Normal AHU			

3.3 Results

3.3.1 Studies in HVAC+R: Components vs Systems

While a broad array of LCA studies are available for residential heating and air conditioning systems, only a limited number of publications in journals contain data on the embodied CO_{2e} of HVAC+R equipment in the context of commercial buildings. The studies developed for these types of systems can be broadly divided into two groups: LCA of single HVAC+R components and LCA of HVAC+R systems.

Among the many LCA studies of HVAC+R components, Rey developed a comparison of heat pumps (24kW) and a natural gas boiler in commercial buildings and concluded that heat pump had a larger impact during the manufacturing stage, yet it was much more efficient and had environmental impact than the boiler during the operation stage (Rey et al. 2004). Nyman and Simonson analyzed small (4m/s) and normal (4 m/s) air-handling units (AHUs) with and without energy recovery in office buildings over a 20-year life cycle and concluded that although the smaller AHU had about 20% less CO_{2e} emissions during the manufacturing stage, it was less efficient than the normal AHU and consumed more energy over its lifetime (Nyman and Simonson 2004). More recently, Shi et al. developed a LCA of a refrigeration compressor using a Chinese life cycle database for seven impact categories, and indicated that the use stage has the strongest impact followed by raw material production and component manufacturing where primary energy demand, ecotoxicity, and global warming potential are three predominant impacts accounting for 36, 34, and 16 % of total impact across the life cycle of the compressor (Shi et al. 2015).

LCA studies of HVAC+R Systems, involve the LCA of different components and configurations where the results are presented in aggregate for the total system. For instance, Chen et al. compared a variable air volume (VAV) system, a chilled beam system and underfloor air distribution (UAD) system through a case study based on an office building (14337.57 m²), and found that while the UAD system had the lowest impact in the manufacturing stage, the chilled beam system had the lowest environmental impact over a 50 year time frame (Chen and Zhang 2013). Similarly, Liu et al. performed a LCA of a chilled beam system compared to a conventional air-based VAV system, and found that the chilled beam system performed better due to the greater savings in electricity consumption and that the chiller plant causes the greatest impact due to the high material content (Liu, Schulz, Haji Sagar, et al. 2016). Nitkiewicz and Sekret compared the life cycle impacts of three heating systems: electric water-water heat pump, absorption water-water heat pump and natural gas fired boiler the absorption heat pump has lower environmental impact than electrical heat pumps (Nitekiewicz and Sekret 2014). In a more recent study, Bagenal Geroge et al. compared the embodied carbon of four types of heat-generation equipment: gas boiler, gas fired combined heat and power (CHP), air source heat pump (ASHP), and variable refrigerant flow systems (VRF), and found that

carbon emissions from refrigerant leakage make up a large proportion of embodied carbon in the ASHP and VRF systems because of the GWP of refrigerants most commonly used (Bagenal George, Hamot, and Levey 2019).

3.3.2 Goal and Scope Stage

Referenced standards

The vast majority of LCA studies for HVAC+R systems and equipment reference the core ISO 14040s standards as the basis for the analysis, as Table 3.5 shows, however not all of these studies reference standards that have been put in place after the publication of the core standards to standardize the LCA studies of building products.

Table 3.5 Reference standards used by type of source

Source Name	Type	Region	Referenced Standards				
			ISO 14040-44	ISO 21930	ISO 14025	EN 15978	EN 15804
Published Articles	Journal Publication	Global	Yes	No	No	No	No
UL Environment	EPD Program	North America	Yes	Yes	Yes	Yes	Yes
INIES-FR	EPD Program	France	Yes	Yes	Yes	Yes	Yes
PEP Ecopassport	EPD Program	France	Yes	No	Yes	No	No
Quartz Database	Open Database	North America	Yes	No	No	No	No
Okebaudat Database	Open Database	Germany	Yes	No	No	No	Yes

Systems scopes: Descriptions and breakdown of material types

Published studies use divergent approaches to describe the components and material types of composite HVAC+R products. For instance, Liu et al. analyzed a chilled beam system consisting of chilled ceiling panels, AHU, chiller, pumps, and the air distribution systems (including ductwork and pipes) (Liu, Schulz, Sagar, et al. 2016). Medas et al. study water-side fan coil units (FCUs) in which the main components are (a) galvanized steel casing lined with polyurethane acoustic foam, (b) fans and motors made mainly of steel, aluminium and copper and (c) aluminium and copper heating and cooling coils (Medas M. et al. 2015). In the case of LCA data for distribution material types, the breakdown of the materials is the least complex.

Life Cycle Boundaries

The two most common life cycle stages covered in LCA studies of HVAC+R are life cycle stage A and Stage C, as shown in Table 3.3. Most data, (i.e. Quartz data) does not separate the LCA data by modules. Additionally, not all data sources cover the same modules, which means that the impacts for each life cycle

stage do necessarily cover all modules within each stage. Some EPDs only covered modules A1-A3, while others covered A1-A5. Quartz, a major source of LCA data for this project, covered “c2g” or “cradle-to-gate,” which usually means A1-A3.

Also, not all data sources evaluated all impact measures the same way. TRACI and CML, which are the main impact characterization methods for North America and Europe, respectively

Table 3.6 Life Cycle Boundaries according to ISO 21930

	Product Stage			Construction Process Stage			Use Stage					End of Life Stage					
	Raw Material supply	Transport	Manufacturing	Transport	Construction-installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy use	Operational water use	De-construction demolition	Transport	Waste Processing	Disposal	Reuse-Recovery-Potential
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
ULE	X	X	X			X	X				X				X	X	X
INIES	X	X	X	X	X	X							X				
PEP	X	X	X	X	X	X							X				
Quartz	X	X	X										X				
Okebaudat	X	X	X											X		X	X

Functional Units and Reference flows

A functional equivalent is defined per EN 15978 as “the quantified functional requirements and/or technical requirements for a building or an assembled system (part of works) for use as a basis for comparison”(CEN 2011). For HVAC+R equipment functional units represent large variability. In some published studies, functional units are defined based on the unit of equipment itself, while in others only a declare unit is used. For instance, for the study of a compressor, Shi et al. used “a C-SB5HP R22 refrigeration compressor used for five years” was used as the functional unit(Shi et al. 2015). For a comparison between chilled beams and VAV systems, the functional unit is “the whole technical system (CC or VAV) operated and maintained in an office space for a life span of 20 years operating from 8 a.m. to 6 p.m. everyday and assumed to meet the cooling demand and thermal comfort requirement based on ASHRAE Standard 55” (Liu, Schulz, Sagar, et al. 2016). To define the functional equivalent, typically the studies include other parameters, such as

thermal comfort parameters, and hours of operation(Liu, Schulz, Sapar, et al. 2016). Chen et al. compared a VAV, Chilled beam and UAD system using m² of building area as the declared unit (Chen and Zhang 2013).

Table 3.7 Functional Units and Reference Flows for HVAC+R distribution

Author/year	HVAC+R System Scope	System Boundary	Functional Unit	Reference Flow
(Okebaudat 2017a)	Air Ventilation Duct (zinc coated steel plate)	A-C-D	NA	1 kg
(Quartz 2015a)	Copper Piping	A -C	NA	1 kg
(Quartz 2015b)	Galvanized Steel Ducts	A -C	NA	1 kg
(Okebaudat 2019d)	Steel Pipe	A-C-D	NA	1 kg
(Okebaudat 2017b)	Underfloor heating system copper (200mm distance)	A-C-D	NA	Underfloor heating system (copper 200 mm distance) 1 sqm Area. 3.3 kg/m ²
(ULE, 2016)	Aluminum Cold-Rolled Sheet and plate (functional unit converted from 1 ton to 1 kg)	A1-A3	Declared unit is the production and end-of-life treatment for one metric ton	One ton of hot rolled-aluminum
(PEP 2016b)	Caisson de ventilation individuelle double flux avec filtres	A-C	Ensure an air transfer of 1m ³ /h for ventilation during the 17 years of reference life.	One unit of product
(PEP 2016a)	Caisson de ventilation simple flux collective ou tertiaire Airvent CRITAIR EC	A-C	Ensure an air transfer of 1m ³ /h for ventilation during the 17 years of reference life.	One unit of product
(PEP 2016c)	Caisson de ventilation simple flux collective ou tertiaire Airvent PA 1500/2000	A-C	Ensure an air transfer of 1m ³ /h for ventilation during the 17 years of reference life.	One unit of product
(PEP 2015a)	Caisson de ventilation simple flux collective ou tertiaire, ou tourelle ou ventilateur CRITAIR BC 500 C4	A-C	Ensure an air transfer of 1m ³ /h for ventilation during the 17 years of reference life.	One unit of product
(PEP 2018b)	Metal circular conduit	A-C	Ensure an air transfer via one linear meter of ventilation conduit during the 30 years of reference life.	One unit of product

Table 3.8 Functional Units and Reference Flows for HVAC+R equipment

Author/year	HVAC+R System Scope	System Boundaries	Functional Unit	Reference Flow
(Okebaudat 2019e)	Ventilation centralized per 30.000 m ³ /h, 168kg.	A-C-D	NA	1 unit
(Okebaudat 2019f)	Ventilation centralized per 10.000 m ³ /h, 68kg.	A-C-D	NA	1 unit
(Ministère de l'environnement 2017)	Groupe de production d'eau glacée [500 kW]	A-B-C	Provide chiller function with a capacity of 500 kW cooling capacity for a reference life of 25 years.	1 unit
(Ministère de l'environnement 2016)	Groupe de production d'eau glacée [100 kW]	A-B-C	Provide chiller function with a capacity of 500 kW cooling capacity for a reference life of 25 years.	1 unit
(Okebaudat 2019c)	Gas condensing boiler 120-400 kW (upright unit); 1 piece	A-C-D	NA	1 unit
(Okebaudat 2019b)	Electric heat pump (water-water) 70 kW; 1 piece (en)	A-C-D	NA	1 unit
(Okebaudat 2019)	Electric heat pump (water-water) 20 kW; 1 piece (en)	A-C-D	NA	1 unit
(Okebaudat 2019)	Electric heat pump (water-water) 10 kW; 1 piece (en)	A-C-D	NA	1 unit
(Okebaudat 2019)	Electric heat pump (air-water) 7 kW; 1 piece (140kg)	A-C-D	NA	1 unit
(Okebaudat 2019)	Electric heat pump (air-water) 14 kW; 1 piece (140kg)	A-C-D	NA	1 unit
(Okebaudat 2019)	Electric heat pump (air-water) 10 kW; 1 piece (140kg)	A-C-D	NA	1 unit
(ULE 2016)	Magnitude magnetic bearing centrifugal chillers (375 tons)	A-B-C-D	one ton of cooling capacity based on a 375-ton "average chiller."	1 kg per declared unit
(ULE 2015)	Centravac Chiller Portafolio (1840 tons)	A-B-C-D	one ton of cooling capacity based on a 1840-ton "average chiller."	1 kg per declared unit
(PEP 2015c)	Condensinox Chaudière gas [100 kw]	A-B-C	Provide a kWh of heating and / or domestic hot water production for the duration of 21 years	1 unit
(PEP 2017)	Centrale double flux collective ou tertiaire	A-B-C	Ensure an air transfer of 1m ³ /h for ventilation during the 17 years of reference life.	1 unit
(PEP 2017)	Centrale de traitement d'air double flux collectif ou tertiaire Duotech	A-B-C	Ensure an air transfer of 1m ³ /h for ventilation during the 17 years of reference life.	1 unit
(ULE 2016)	Magnitude magnetic bearing centrifugal chillers (375 tons)		one ton of cooling capacity based on a 1840-ton "average chiller."	1 kg per declared unit
(Nyman and Simonson 2004)	Small AHU Air-to-Air Heat Exchange Rotating Wheel		one ton of cooling capacity	1 kg per declared unit
	Small AHU Air-to-Air Heat Exchange Plate			

Small AHU
Normal AHU Air-to-Air Heat Exchange Rotating Wheel
Normal AHU Air-to-Air Heat Exchange Plate
Normal AHU

Table 3.9 Functional Units and Reference Flows for equipment types

Author/year	HVAC+R System Scope	System Boundary	Functional Unit	Reference Flow
(Bagenal George, Hamot, and Levey 2019)	Boiler, CHP, ASHP and VRF	Cradle to Grave	kgCO ₂ e per 100kW of heating capacity of each heat generation equipment type.	Unit of Equipment
(Liu, Schulz, Sapor, et al. 2016)	Chilled Beam (CC) vs Conventional Variable Air Volume (VAV)	Cradle to Grave	whole technical system (CC or VAV system) operated and maintained in an office space	Unit of Equipment
(Shi et al. 2015)	Refrigeration Compressors	Cradle to Grave		Unit of Equipment
(Medas et al. 2015)	Water-side fan coil units (FCUs)	Cradle to Grave	Cooling capacity	ICE Database
(Rey et al. 2011)	Semi-indirect ceramic evaporative cooler w heat pipe (SIEC HP) vs split class heat pump		Unit of Equipment	EPS 2000
(Rey et al. 2004)	Heat pumps (air-air)	Cradle-to-Grave	Unit of equipment	EPS 2000
(Nyman and Simonson 2004)	Air Handling Units (AHU) small and normal, with and w/o air-to-air heat exchange	Production and operation	Outdoor ventilation airflow of 2 m ³ /s (4200 cfm)	Impact Analysis

Lifespan

It is common that EPD do not address the service lives for the product and therefore make no specific claim as to a typical reference service life (ULE 2014). However, in this study most EPD, databases mentioned the specific lifespan for each equipment or distribution material type as shown in Figure 3.2.

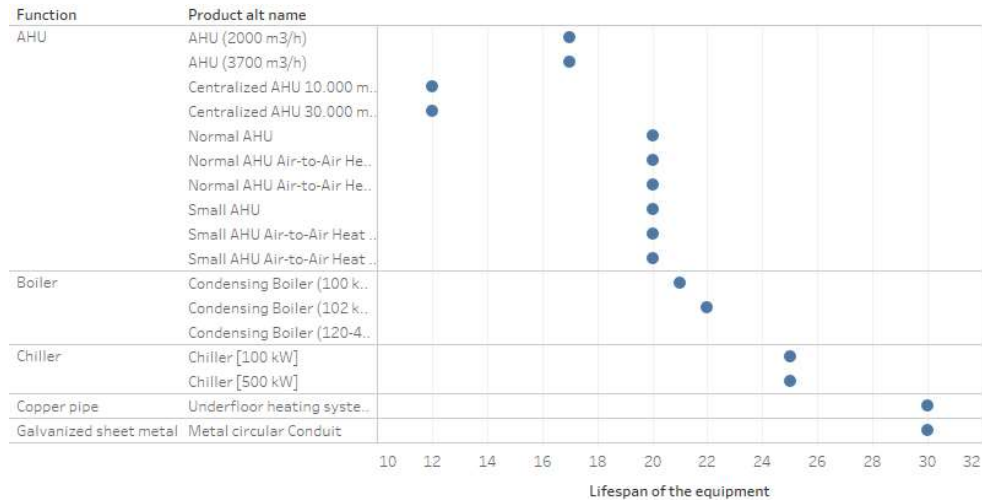


Figure 3.2 Typical lifespan for HVAC+R equipment

3.3.3 Inventory Analysis

Data Sources

The data sources vary considerably across the different studies. Typical LCA databases used in open databases and EPD are associated to LCA tools and specific to each one of the tools (i.e. GaBi, Sima Pro). For instance, in the case of EPD from PEP Ecopassport Program, the method on which the assessment is based complies with the criteria described by the PCR-ed3-FR-2015 04 02 of the PEP ecopassport® Program. The functional unit and the scenarios of the distribution, use and treatment of waste is in accordance with the assumptions set out in PSR-0008-ed 2.0-EN-2018 02 09. The results are obtained using the EIME software version 5.5.0.11 and its database (PEP 2015b).

Other types of studies involve the combination of various types of sources. For instance, the copper pipe study is developed with GaBi dataset adapted from industry average data from European companies. Background data is US-specific, as is the clean scrap content used during the pipe fabrication. Copper cathode data is representative of a global average(Quartz 2015a). This is also the case for hot roll aluminum, where primary data collected from the participating companies and from their operational activities is then complemented with data necessary to model raw material production, energy generation, etc (ULE 2014)

3.3.4 Impact Assessment Stage

Impacts assessed

Typical impact categories assessed in LCA of HVAC+R systems are global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation (POCP), acidification (AC), and eutrophication (EU) (Liu, Schulz, Sapor, et al. 2016). In comparing the SIEC-HP vs the Split Class heat pump, Rey et al. conclude that abiotic resources is the class that has the highest contribution to the categories of damage in both equipments, and that newer designs with a more careful study of the materials is required, minimizing the use of copper (Rey et al, 2014). In comparing a VAV, Chilled beams and UAD system Chen et al found that the embodied energy used in chilled beam systems was the highest: twice as much as in VAV systems, and three times as much as that in UAD systems, due to the additional water pipes and air ducts required for an air-water system. (Chen and Zhang 2013).

Under Okebaudat it is anticipated that the recycling quote of big appliances like boilers, air conditioning, and ventilation systems is 95%. For pipes or cables which are often flush-mounted a 90% recycling quote is expected, the values are expressed in stage D as shown in Figure 3.3. The quotes are only related to metals and plastics. For mineral materials like mineral wool, concrete or ceramics inert landfilling is assumed, as well as for 5-10% of metals and plastics (e.g. cable waste and pipe pieces) that are not recycled.

In terms of the results for GWP and ECC for each study, the manufacturing stage, also known as Stage A, as shown in Figure 3.3 and Figure 3.5, was found to be the most significant stage across all equipment and distribution material types. In the studies that incorporate impacts for the operational stage (module B), operational impacts were the most significant. In general, the larger the capacity of HVAC+R equipment, the larger the overall weight of the equipment. Since embodied carbon is largely correlated to the total material quantity (weight), HVAC+R equipment with larger capacities have larger embodied carbon per unit of equipment.

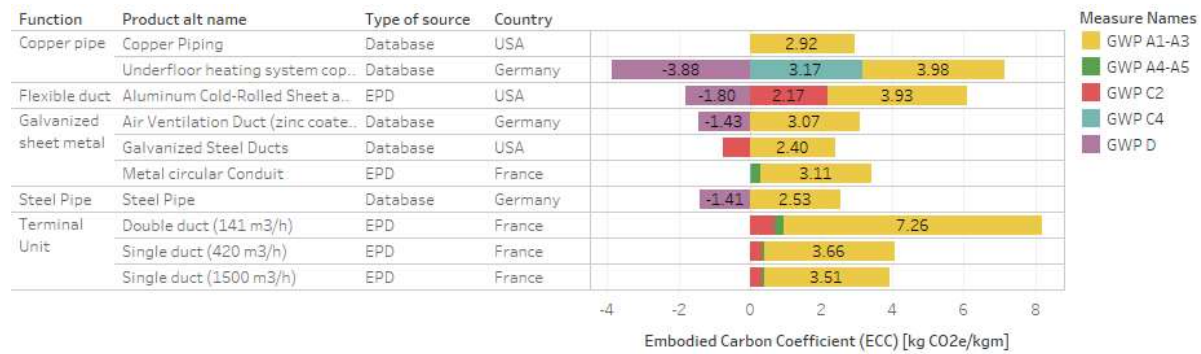


Figure 3.3 Embodied Carbon Coefficient of distribution material types per kg

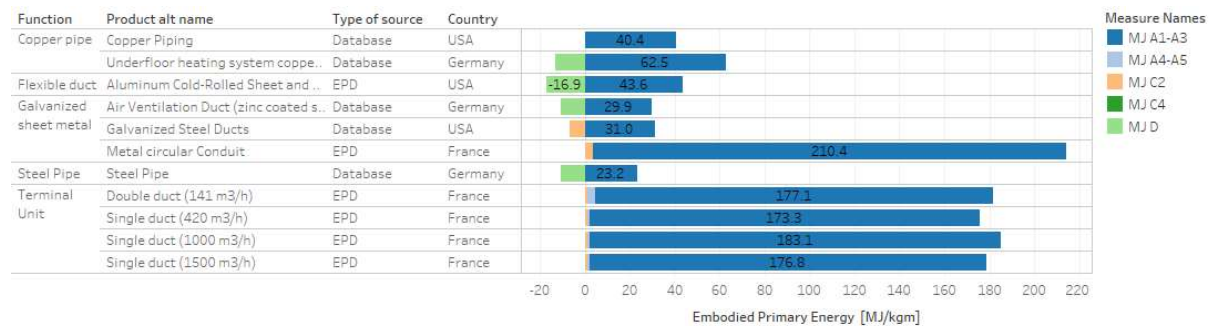


Figure 3.4 Embodied energy per distribution material type

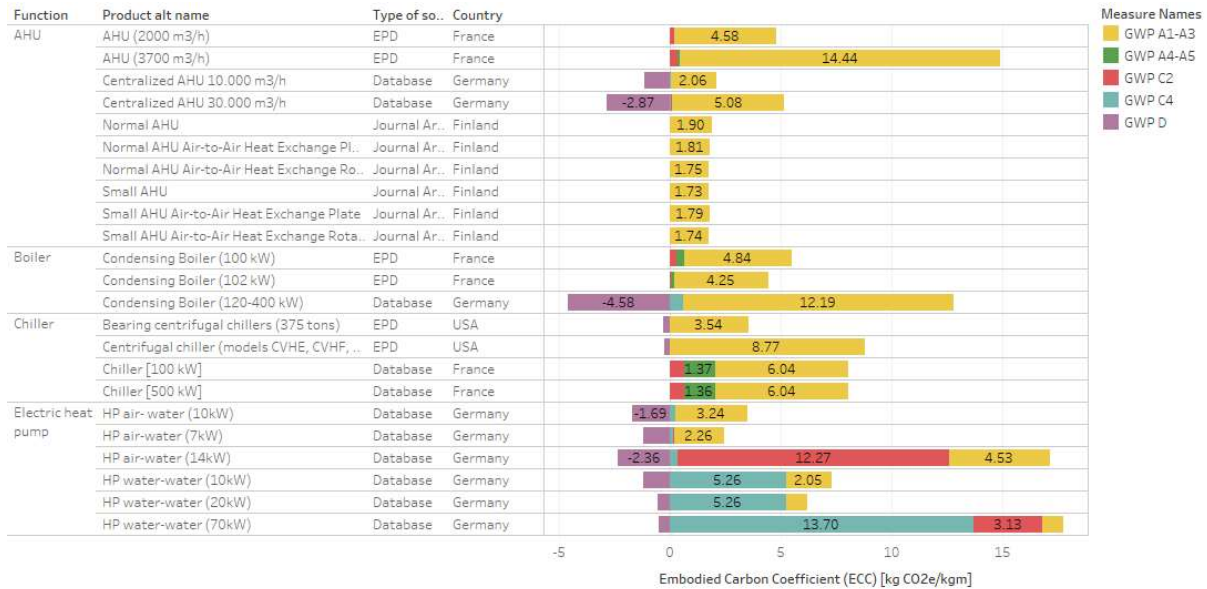


Figure 3.5 Embodied carbon for each equipment type

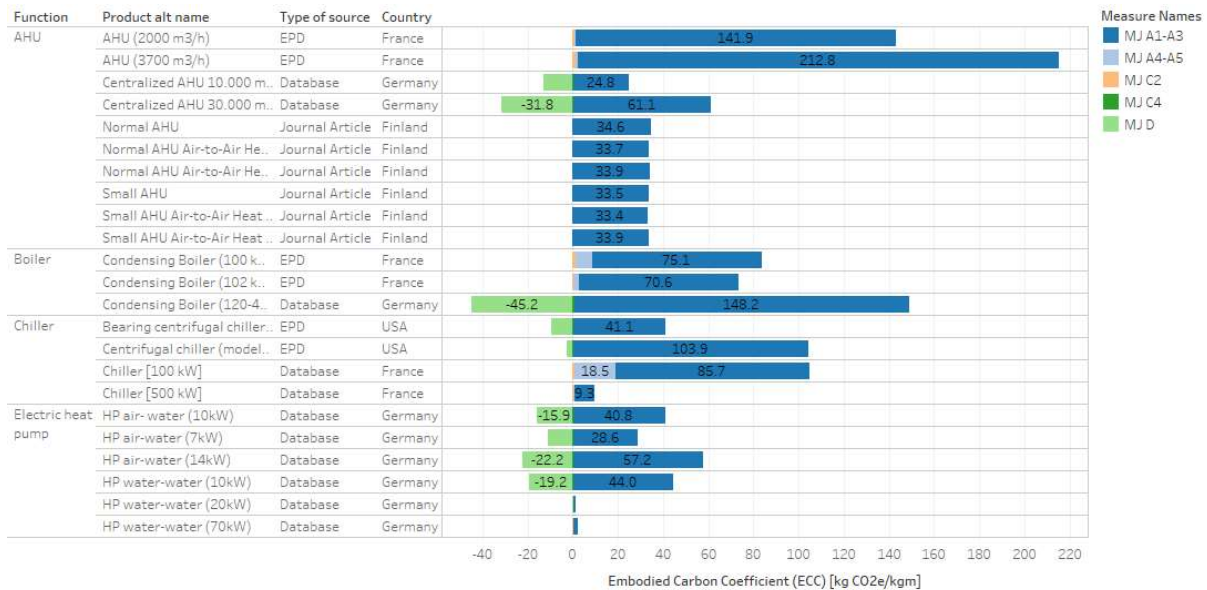


Figure 3.6 Embodied carbon for each equipment type per item

In the study of a chilled beam system vs VAV system, including five equipment types (chiller plant, AHU, pump, chilled beam panel and air distribution system), chiller plant causes the highest environmental burden due to the high material content and the high annual electricity consumption during the operation stages (Liu, Schulz, Sapar, et al. 2016). When compared with VAV system, CC system performs better in all five impact categories investigated for this study (Liu, Schulz, Sapar, et al. 2016).

3.4 Discussion

LCA data for HVAC+R materials and equipment types presents the same challenges of variation and lack of scientifically accepted methodologies that have been discussed in the literature in the last two decades (Anand and Amor 2017). In the case of LCA data for HVAC+R the largest discrepancies are defined in the Goal and Scope stage, specifically in the use of different: standards that serve as reference, system scopes definition, life cycle boundaries, selection of functional units, reference flows and lifespans. Nevertheless, a closer understanding at the different commonalities and discrepancies can shed light on potential ways to move forward in the development of WBLCA in the future.

During the goal and scope stage of a typical LCA, the referenced standard used in the assessment largely determines the possibility of integrating the data with other data in future WBLCA. LCA data for HVAC+R systems can be found in published studies, EPD and open databases, however not all of these types of sources present the data in a way that can be integrated into a WBLCA. EPD programs and LCA databases that model the data according to ISO standard 15978 or EN 15804 illustrate the results in modules that allow for the structured expression of results over the entire life cycle. Modular presentation of the data enables aggregation with data from other sources and thus enables the use of LCA data into future WBLCA. Data presented in modular form is available through EPD programs PEP, UL and open databases OKEBAUDAT, INIES and QUARTZ database. Most published data in journals and reports do not follow the modular presentation and are therefore not suitable to compare or aggregate with other data in the context of WBLCA. Currently, EPD and open databases offer the most suitable LCA data to be integrated into WBLCA, from these two sources EPD should be preferred due to their third party verification.

The modular presentation of the data also enables the user to choose the data from each module, this is typically the case of WBLCA that focus only on manufacturing and transportation (stage A). Most studies use different life cycle boundaries, some focus on cradle to grave, while others include stage D or recycling potential (Okebaudat 2019a). In most cases each stage includes different modules, for instance one study might consider the manufacturing stage (A1) under stage A, while other studies include A1 and A2. Many studies (PEP ECOPASSPORT 2010) include the impacts during the operation stage (B1).

System scopes also vary in typical HVAC+R. Published studies such as the analysis of a chilled ceiling system in Liu et al. (2016) or a comparison of three ventilation methods done by Fong et al. (2017) are focused on the entire system, whereas EPD and open databases focus on a particular equipment or distribution component of the system. The focus on the component, instead of a large array of equipments, enables other users to integrate the data into other studies.

The functional unit is the most divergent and the item that varies the most across the different studies. Most published studies use variations of the entire technical system installed and operated in an office space, during an entire lifespan of the equipment, however other databases use a declared unit in the form of a weight unit (kg) as the basis of comparison. In order to make meaningful comparisons, LCA data should be expressed in the same functional unit. As per ISO 21930, “the primary purpose of the functional unit is to provide a reference to which the material flows (input and output data) of a building product are normalized mathematically. That reference is necessary for the comparability of LCA data” (ISO 2017)(pag.33).

The lifespan of the different equipment and material types also varies, small self contained equipment such as heat pumps, split units typically have a lifespan between 10-15 years, while larger equipment such as AHU, cooling tower and boiler range between 20-25 years. Chillers are the items with the largest lifespan with typically 25-30 years of operational life. The relative short lifespan of HVAC+R equipment compared to the typical referenced service of buildings life ranging between 50 and 60 years (USGBC 2013) in most WBLCA, as seen in Appendix A should be taken into account, since in real life application, the recurring instalments of these systems would add up embodied carbon overtime.

In terms of the results for GWP and ECC for each study, the manufacturing stage, also known as Stage A was found to be the most significant stage across all equipment and distribution material types. In the studies that incorporate impacts for the operational stage (module B), operational impacts were the most significant. In general, the larger the capacity of HVAC+R equipment, the larger the overall weight of the equipment. Since embodied carbon is largely correlated to the total material quantity (weight), HVAC+R equipment with larger capacities have larger embodied carbon per unit of equipment.

3.5 Conclusion

LCA data for HVAC+R materials and equipment types presents the same challenges of variation and lack of scientifically accepted methodologies that have been discussed in the literature in the last two decades for building LCAs. In the case of LCA data for HVAC+R the largest discrepancies are defined in the Goal and Scope stage, specifically in the use of different: standards that serve as reference, system scopes definition, life cycle boundaries, selection of functional units, reference flows and lifespans.

LCA data for HVAC+R systems for both equipment and distribution components, can be found in published studies, EPD and open databases, however not all of these types of sources offer data that can be integrated into a WBLCA. To date EPD and open databases for the construction sector offer the data that can be most

useful in the context of integrating into a WBLCA. In order to continue the integration of LCA data for HVAC+R systems into WBLCA, the gaps identified in this study should be addressed as well as a larger production of LCA data for HVAC+R systems in the northamerican context.

4. Embodied Carbon in Heating, Ventilation and Air Conditioning (HVAC+R): A simplified method for standard and high-performance buildings

The objective of this chapter is to provide estimates of material quantities and embodied carbon impacts of heating, ventilation, and air conditioning (HVAC+R) systems for typical commercial office buildings in the Pacific Northwest (PNW) using a simplified LCA method approach. The research plan included the active participation of an Advisory Committee, formed by three HVAC+R contractors based in Seattle. The first stage identifies representative high performance (HPB) and standard performance (SPB) office buildings and typical HVAC+R systems. The second stage describes, material quantities for each equipment and material types per system type. Embodied Carbon Coefficients (ECC), the LCA impact, was estimated from different data sources such as EPD, LCA peer reviewed articles and reports, and open databases. A simplified carbon impact data was compiled into a spreadsheet and recorded for Global Warming Potential (GWP). Finally, the results from a two-way ANOVA indicated that the total material quantity for HVAC+R of typical commercial office buildings in the PNW ranges from 9.8 to 13.8 kg/m² for office buildings and from 11.5 to 17.9 kg/m² for HP buildings. Embodied carbon ranges in SP buildings are 27.8 to 48.2 kg CO₂ eq/m² for HVAC, and in HP buildings ranges from 35.8 to 60 kg CO₂ eq/m² across 16 typical building models.

4.1 Introduction

The wide variety of approaches to LCA as an early-stage design decision tool for buildings is only one of the many barriers to a wider understanding of EC in buildings. Some of the other barriers recognized in the literature are 1) the time consuming process behind most LCA methods; (2) limited availability of building LCI data; (3) limited availability of material quantity data (Bruce-Hyrkäs, Pasanen, and Castro 2018), and (4) a focus on structural, foundation and enclosure systems in the building scope of most whole building life cycle assessment studies (WBLCA) (Simonen, Rodriguez, Strain, et al. 2017). In order to obtain more reliable and accurate results for EC using LCA, more consistent methods are required with a wider adoption of tools by non LCA experts, such as AEC professional (i.e. architects, structural engineers, contractors). Researchers are increasingly advocating for access to improved data quality and the development of more transparent and simplified methodology for the industry (Zabalza Bribiá, Usó, and Scarpellini 2009). The latest European Level(s) framework encourages design professionals to begin using LCA by supporting and allowing users to carry out simplified methods (JRC 2017a).

4.2 Methodology

This study was developed as part of an earlier study entitled “LCA of Mechanical, Electrical and Plumbing Systems”(B.X. Rodriguez et al. 2019) and followed a four-stage method in consultation with an Advisory Committee. As a preliminary study, the aim of the first stage was to provide embodied carbon ranges of typical HVAC+R systems in High Performance Buildings (HPB) and standard performance buildings (SPB) using 16 hypothetical building models. The second research stage was to propose a simplified LCA method based on the results gathered in the first stage, and finally in the third stage an ANOVA analysis is performed to understand the association between building size, HVAC+R component type (material or equipment) and material quantities.

4.2.1 Stage 1: Embodied Carbon in Hypothetical Building Models

Substage 1: Proposing Hypothetical Building Models

For this study, the research team in conjunction with the advisory committee proposed hypothetical buildings in order to describe typical HVAC+R systems used in the PNW. The development of hypothetical building models as a methodological approach has been used extensively in operational energy studies (Deru et al. 2011). The use of hypothetical building models for this study was decided because the project scope is limited to:

- 1) Evaluating hypothetical buildings by working with an industry advisory committee to assist in defining the systems and establishing material quantity estimates using the historical data from the firm
- 2) Identifying generic HVAC+R systems according to each building size, and using these generic descriptions to estimate material quantities and EC that can be generalized to the larger PNW commercial office market.

For each building HVAC+R system, material quantities are determined through direct inputs from the Advisory Committee composed of three mechanical contractors located in Seattle, Washington. The data in this study is limited to the material quantity data provided by contractors available for this study within the time limitation of the research project. The data came from different estimation methods and depends largely on each firm’s experience and historical project data. Each system incorporated material quantities for both material types and equipment separately. After obtaining the results from each individual contractor, the different material ranges were aggregated. The aggregation of all range values was done with using a Finite Aggregation Model, and the underlying assumption was that all distributions

differ and there is no ‘true average’. In order to aggregate these different ranges, a midpoint is calculated based on the values from each contractor.

Compilation of Embodied Carbon Coefficients (ECC)

This study uses embodied carbon coefficients (ECC) from different existing sources in order to estimate the total GWP potential for each HVAC+R system. ECC are typically expressed in kg of CO₂e (kgCO₂e) per kg of material (kgm), where CO₂e stands for the equivalent in carbon dioxide of the greenhouse gases (GHG) produced for the manufacturing and transportation of these materials (De Wolf, Iuorio, and Ochsendorf 2014). In the past, several studies used existing ECC from different sources to understand the overall GWP of building structures (Ezema, Opoko, and Oluwatayo 2016). Currently, there is no consensus on the best available ECC for HVAC+R system components, hence this study ECC used for the study corresponds to the best available data based on the following list in order of importance: EPDs (local), EPDs (global), Open Database (Okebaudat) available online.

Database Development

During the final substage is the result of multiplying the ECC compiled in the earlier stages with the material quantities estimated by the contractor. All material quantities and ECC will be published open source including a matrix model to calculate the total EC per building system. The matrix model is an Excel file that enables users to update LCA impacts as desired. This data is also used in context of recently completed whole building LCA study of structure and enclosure (Simonen, DeWolf, and Rodriguez 2017).

4.2.2 Stage 2: Development of a simplified LCA method for HVAC+R

Typical WBLCA methods rely on material quantities and LCA data to estimate the total life cycle impact of target buildings. In that regard, the second stage is to propose a simplified LCA method for HVAC+R. Traditionally, the embodied carbon of building materials has been calculated using Equation (1), where E_i is the total embodied GHG emissions of all building materials (in kgs CO₂e) M_j^i is the amount of building material j (in kg); and f_j^i is the GHG emission factor for building material j (in kg CO₂e/kg) (Yan et al. 2010).

$$E_i = \sum M_{ij} * f_j^i \quad (1)$$

In recent years, different adaptations of this method have been used for specific types of systems in buildings such as the one described by De Wolf et al. to assess embodied carbon in building structure, as shown in Equation 2.

$$\mathbf{GWP} \text{ (kgCO}_2\text{e/m}^2\text{)} = \mathbf{SMQ} \text{ (kg}_m\text{/m}^2\text{)} \times \mathbf{ECC} \text{ (kgCO}_2\text{e/kg}_m\text{)} \quad (2)$$

where Structural Material Quantities (SMQ) are expressed in kg of material per declared unit, and Embodied Carbon Coefficients (ECC) are expressed in kg of CO₂e per kg of material (De Wolf, Iuorio, and Ochsendorf 2014)

The simplified method to assess the EC of HVAC+R is calculated by using three independent types of calculation for each one of the system components; mechanical equipment, distribution systems and refrigerants, as shown in Equation 1.

$$\mathbf{GWP}_{\text{HVAC+R}} \text{ (kgCO}_2\text{e/m}^2\text{)} = \mathbf{GWP}_{\text{equipment}} + \mathbf{GWP}_{\text{distribution}} + \mathbf{GWP}_{\text{Refrigerant}} \quad (1)$$

$$\mathbf{GWP}_{\text{equipment}} \text{ (kgCO}_2\text{e/m}^2\text{)} = \mathbf{MEQ} \text{ (kg}_m\text{/m}^2\text{)} * \mathbf{ECC}_e \text{ (kgCO}_2\text{e/kg}_m\text{)} \quad (2)$$

$$\mathbf{GWP}_{\text{distribution}} \text{ (kgCO}_2\text{e/m}^2\text{)} = \mathbf{DMQ} \text{ (kg}_m\text{/m}^2\text{)} * \mathbf{ECC}_d \text{ (kgCO}_2\text{e/kg}_m\text{)} \quad (3)$$

$$\mathbf{GWP}_{\text{refrigerant}} \text{ (kgCO}_2\text{e/m}^2\text{)} = \mathbf{Rc} \text{ (kg}_r\text{/TON)} * \mathbf{Cooling capacity} \text{ (TON)} * \mathbf{ECC}_r \text{ (kgCO}_2\text{e/kg}_r\text{)} \quad (4)$$

This method is based on three independent calculations due to different nature of each one of the HVAC+R components.. Equation 2 shows the model for GWP of equipment, where mechanical equipment quantities (MEQs) represent the total weight of unitary equipment such as boilers or chillers, that are typically a composite of different materials, while in equation 3 distribution material quantities (DMQs) represents a single material that can be quantified individually (copper piping, galvanized sheet metal). Due to their different material nature, HFC gases, refrigerants are quantified separately as shown in equation 3.

In addition to the calculation of embodied and operational CO₂e for equipment and materials in this study, this method proposes a separate calculation for the total impact of refrigerants. This study does not include the total quantity of refrigerants per system type in building, since the range of refrigerant

4.2.3 Stage 3: Analyzing the Data Using Two-way ANOVA Test

In the last stage of the research, the data is analyzed using a two-way Analysis of Variance (ANOVA). A two-way ANOVA is also called analysis of covariance (ANCOVA), and there are two independent categorical variables. ANOVA is a widely used method in various fields and in the building science in recent years. In the present study, a two-way ANOVA is used to find any relationship between the different building size (four categories) and different types of components in HVAC+R systems (material/equipment) in material quantities in commercial office buildings in the PNW. The two independent variables are different building size (four categories) and different types of components in HVAC+R systems (distribution material or equipment) while the dependant variables is material quantities (kg/m^2).

The ANOVA analysis aims to respond the following research question:

- *Do material quantities of HVAC+R systems significantly differ with different building sizes (extra small, small, medium and large commercial office buildings)?.*
- *Do material quantities of HVAC+R systems significantly differ with different HVAC+R item type (equipment or material)?.*
- *Does an interaction occur between building size and item type (equipment or material) in affecting the final material quantity?*

The three null hypotheses and alternative hypotheses are described as follows:

Ho1: There is no significant difference in the material quantity means between the four building size groups.

Ho2: There is no significant difference in the material quantity means between the HVAC+R item type (materials and equipment)

Ho3: There is no interaction between the two independent variables of building size and HVAC+R item type

Ha1: There is a significant difference in the material quantity means between the four building size groups.

Ha2: There is a significant difference in the material quantity means between the HVAC+R item type (materials and equipment)

Ha3: There is an interaction between the two independent variables of building size and HVAC+R item type

4.3 Results and discussion

The results of this study are presented and discussed in the following three different sections: (1) the results of the hypothetical buildings model; (2) the EC results; (3) the results of the ANOVA.

4.3.1 Stage 1: Embodied Carbon in Hypothetical Building Models

Substage 1: Defining Hypothetical Buildings

The base building, that serves as the model for all building categories as described above, is a typical new commercial office (Core & Shell) Class A building, including large floorplates, open spaces, high ceilings with ample glazing to provide natural light and flexible collaborative spaces. This base building is described for the four building size categories for both standard and high-performance buildings, giving a total of eight independent building models. For each one of the eight building models, two typical HVAC+R systems are described for a total of 16 HVAC+R systems used as case studies, as shown in Table 1.

Table 4.1 Sixteen HVAC+R Systems according to four building size categories for Commercial Office SP and HP Buildings in the Pacific Northwest (PNW)

Base Building (ft)	Base Building (m²)	Building Size Category	HVAC+R system (Standard)	HVAC+R system (High performance)
7000	650	XSmall a	Packaged rooftop heat pump	DOAS ERV + VRF
		XSmall b	Packaged rooftop AC + Furnace	DOAS ERV + Packaged Rooftop Heat Pump
25000	2322	Small a	Packaged rooftop heat pump	DOAS ERV + VRF
		Small b	VAV AHU w/ PFP Terminals	DOAS ERV + Packaged Rooftop Heat Pump
80000	7432	Medium a	VAV AHU w/ PFP Terminals	DOAS + VRF
		Medium b	WSHP	DOAS + WSHP
260000	25155	Large a	VAV AHU w/ PFP Terminals	DOAS + Chilled Beam
		Large b	WSHP	DOAS + WSHP

For the purpose of this study, a “standard performance building” (SPB) is defined as a building designed under the Oregon State Energy Code, while a “High Performance building” (HPB) is defined as a building design under the Washington code. It is worth noting, that the 2015 Seattle Energy Code, one of the strictest energy codes nationwide (even more stringent than the WSEC), came into full effect on Jan. 1, 2018 (Seattle Department of Construction and Inspections 2015). According to the U.S. Department of Energy (DOE) Building Energy Codes Program⁹, the OEESC is equivalent to ASHRAE 90.1-2010¹⁰ standard while the WSEC is more efficient than ASHRAE 90.1-2013.

HVAC+R systems are diverse and emergent technologies are available in the marketplace. For this study only the two most representative mechanical systems are considered for each building size category under the standard and high-performance categories. Building system design choices are dependent on various factors, in the light of economic and time constraints (Arroyo et al. 2016). Operational efficiency, noise requirements, environmental restrictions.

- *Packaged Rooftop Units (RTU)*: Rooftop units are one of the most common types of HVAC+R systems for small commercial office buildings because of their flexibility of heating and cooling options.
- *VAV AHU w/PFP Terminals*: Variable air volume (VAV) systems vary their supply air volume flow rate to satisfy different space heating/cooling loads (Yu et al. 2016). VAV systems are the most common type of systems in standard commercial office buildings (California Energy Commission 2003). For this study, an Air Handling Unit (AHU) with Parallel Fan Powered (PFP) terminals is described. In these systems, each zone is served by a terminal box with a fan that mixes return air with supply air from the primary VAV system.
- *WSHP*: Water Source Heat Pump (WSHP) systems rely on a large piping loop that circulates water used to reject the heat. The large piping loop combines water-source heat pumps with a typical heat rejector and a boiler.
- *DOAS ERV*: Dedicated Outdoor Air System (DOAS) systems separate the indoor air quality function of a typical HVAC+R system from the thermal control function, hence an entirely

⁹ The U.S. Department of Energy (DOE) Building Energy Codes Program reviews adoption of energy codes for residential and commercial buildings. State adoption is reviewed based on the national model energy codes—the International Energy Conservation Code (IECC) for residential buildings and Standard 90.1 for commercial buildings (42 USC 6833) (U.S. DOE 2018).

¹⁰ Standard 90.1 has been a benchmark for commercial building energy codes in the United States and a key basis for codes and standards around the world for more than 35 years. This standard provides the minimum requirements for energy-efficient design of most buildings, except low-rise residential buildings (ASHRAE 2016a).

separate system is designed to provide for ventilation (Grondzik 2016). Energy recovery Ventilators (ERV) recover both sensible and latent heat) as part of packaged RTUs and DOASs to increase the energy efficiency of buildings (William Goetzler 2017).

- *Variable Flow Refrigerant (VRF)*: A refrigerant system that varies the refrigerant flow rate assisted by a variable speed compressor and electronic expansion valves (EEVs) from each indoor unit to match the space cooling/heating load in order to maintain the zone air temperature at the indoor set temperature (Aynur 2010). These systems were introduced in Asia more than 20 years ago, but have gradually expanded its market presence in the U.S in the last decade.
- *Chilled Beams*: Use water pipes in modular units mounted to ceilings and can be classified in passive and active (Roth et al. 2007). Chilled beam systems are the most prevalent systems in European office buildings and have been widely applied in the PNW.

Substage 2 Estimation of material quantities in hypothetical buildings

In this study, material quantities are estimated separately for material types and equipment types for each system described under each individual building size category. Material types for all HVAC+R systems include flexible duct, galvanized sheet metal, cooper pipe, and steel pipe. Refrigerants and insulation are not considered in this study, since only one contractor provided this data point and the results include high variability in the values compared to other materials and equipment types.

Mechanical equipment types for HVAC+R systems in S buildings include packaged rooftop heat pumps and boilers. The equipment for HP buildings is increasingly complex and includes: chilling towers, DOAS ERV w/electric heat, DOAS w/heat recovery, VRF outdoor units, VRF cassettes, packaged units, water source heat pump and chilled beams, among other.

This analysis reveals that material quantities are 9.8 to 13.8 (kg/m²) for S buildings and 11.5 to 17.9 (kg/m²) for HP buildings. Material quantities are slightly higher in HP buildings compared to S buildings for all HVAC+R systems across all building size categories. It is worth noting that the quantities for standard and high-performance HVAC+R systems are not directly comparable since these serve different purposes with different energy targets. However, a comparison of the mid-point, resulting from aggregating the different material intensities (kg/m²) provided by the three HVAC+R contractors, shows that HVAC+R systems in HP buildings that incorporate a DOAS require larger amounts of material per square meter. The larger material quantity is due to the increasing use of galvanized sheet metal in these buildings, as shown in Figure 2.

Other items that contribute to larger material quantities in HP buildings are specific types of equipment such as ‘DOAS ERV w/ electric heat’; ‘Single duct VAV or CAVs’; ‘VRF outdoor units’; ‘VRF Cassettes’; ‘VRF fan coils’; and the ‘Air or Water cooled chiller’. Within the high performance building category, WSHP systems require the largest amount of material mainly due to the “Distributed Zone WSHP” equipment.

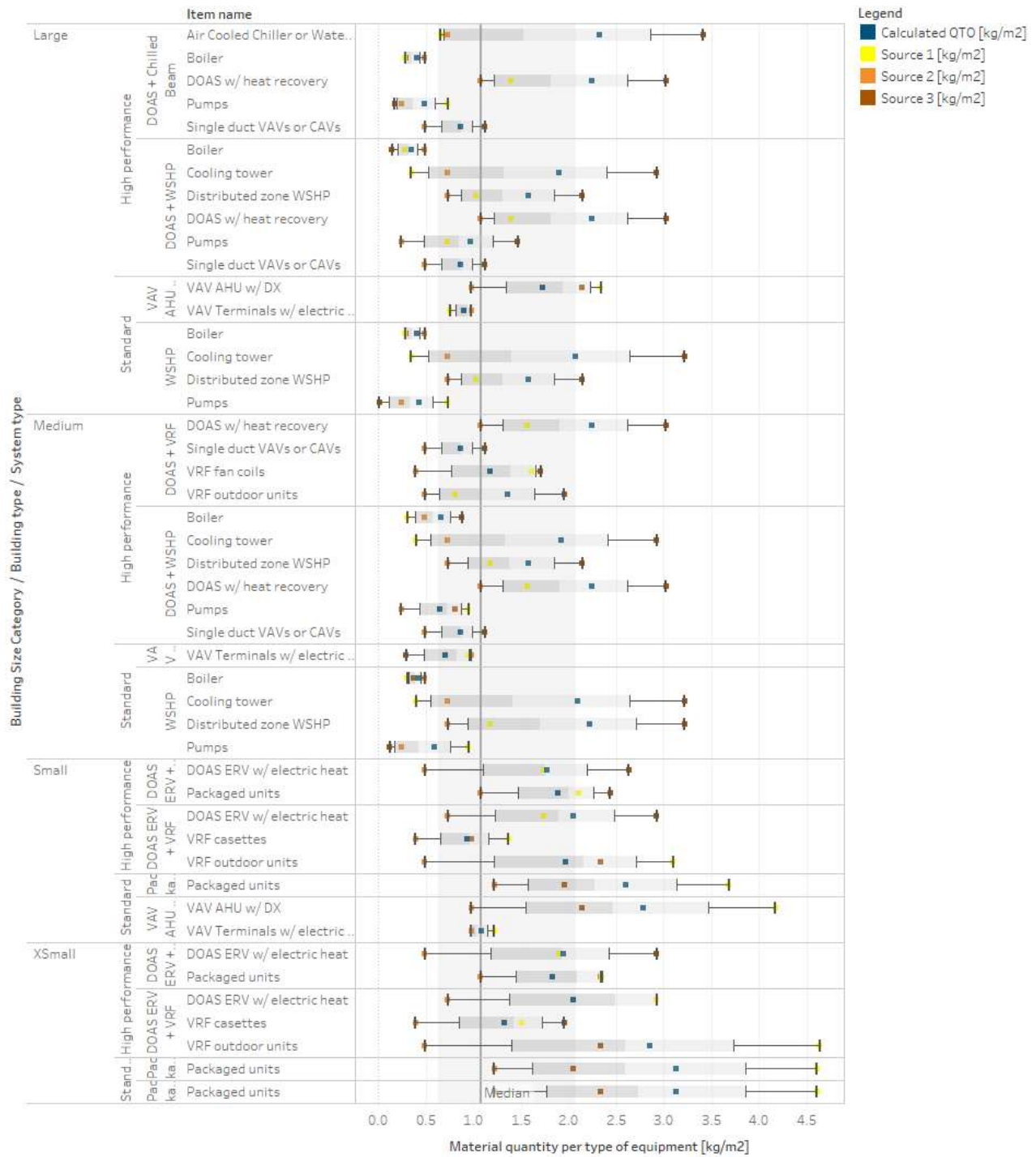


Figure 4.1 Material Quantities for Equipment Types of HVAC+R systems in Standard and High Performance Buildings (kg/m²)

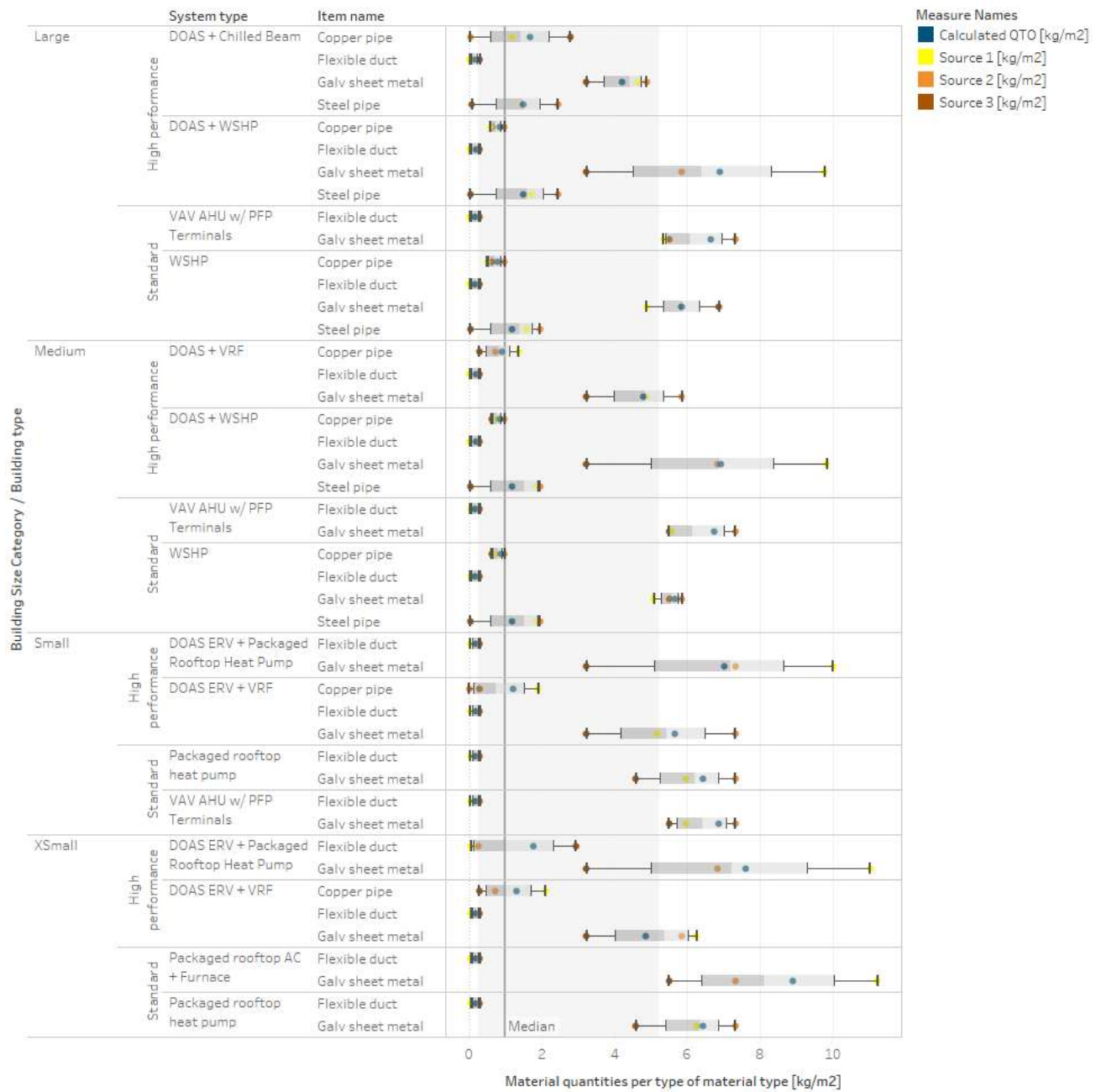


Figure 4.2 Material Quantities for Material Types of HVAC+R systems in Standard and High Performance Buildings (kg/m2)

Substage 2 LCA Database Development and Embodied Carbon

In order to obtain the total GWP of each HVAC+R System, ECC of typical HVAC+R equipment and material types is compiled from different sources. The ÖKOBAUDAT, the German mandatory data source within the Bewertungssystem Nachhaltiges Bauen (BNB), offers the largest amount of data for mechanical components (210 out of 1186 datasets are mechanical systems LCA data), therefore served as the main source of ECC for HVAC+R mechanical equipment and material types in this study. The second source of data for this study is the Quartz database, a “collaborative open data initiative that promotes the transparency of building materials and their impacts on human and environmental health” (Quartz n.d.). Only some EPD’s are used, since there are scarce EPD for HVAC+R equipment in existing EPD.

4.3.2 Stage 2: Development of a simplified LCA method for HVAC

During the final stage of this project, the LCA results are calculated by multiplying the ECC with the material quantities from the second substage. Figures 3 and 4 show the global warming potential (GWP) for all building systems for the different material and equipment types in 16 building models respectively.

The results of this stage illustrate that HVAC+R adds a large contribution compared to the rest of the building. Embodied carbon ranges in SP buildings is 27.8 to 48.2 kg CO₂ eq/m² for HVAC, and in HP buildings ranges from 35.8 to 60 kg CO₂ eq/m². The significant contribution of HVAC+R equipment and material types becomes increasingly greater with the addition of refrigerants, which adds up to 1,890 kg CO₂ eq/kg. Refrigeration and HVAC+R systems contribute to GHG emissions due to operational energy consumption and use of refrigerant fluids that have high global warming potential (GWP) (Bovea, Cabello, and Querol 2007). HFCs are commonly used refrigerants and are one of the seven top GHGs (Kyoto Protocol, 1997), having a warming effect on the atmosphere up to 23000 times greater than CO₂ (Bortolini et al. 2015).

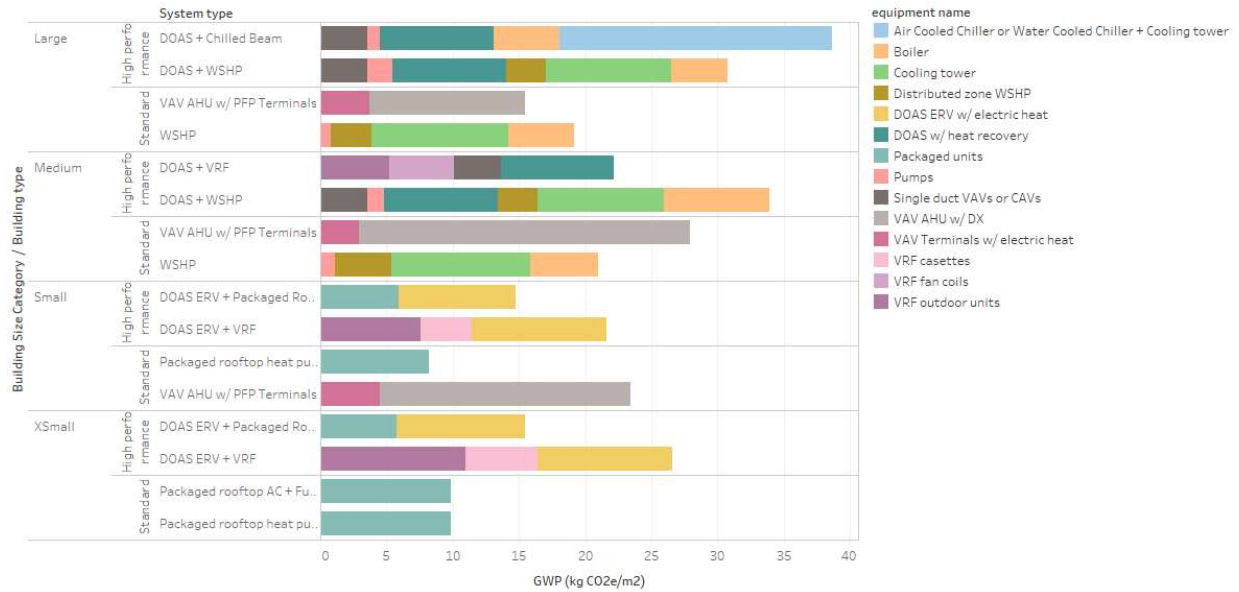


Figure 4.3 Global Warming Potential (GWP) for equipment types in HVAC+R systems Standard Buildings and High Performance Buildings (kg CO₂e/m²)

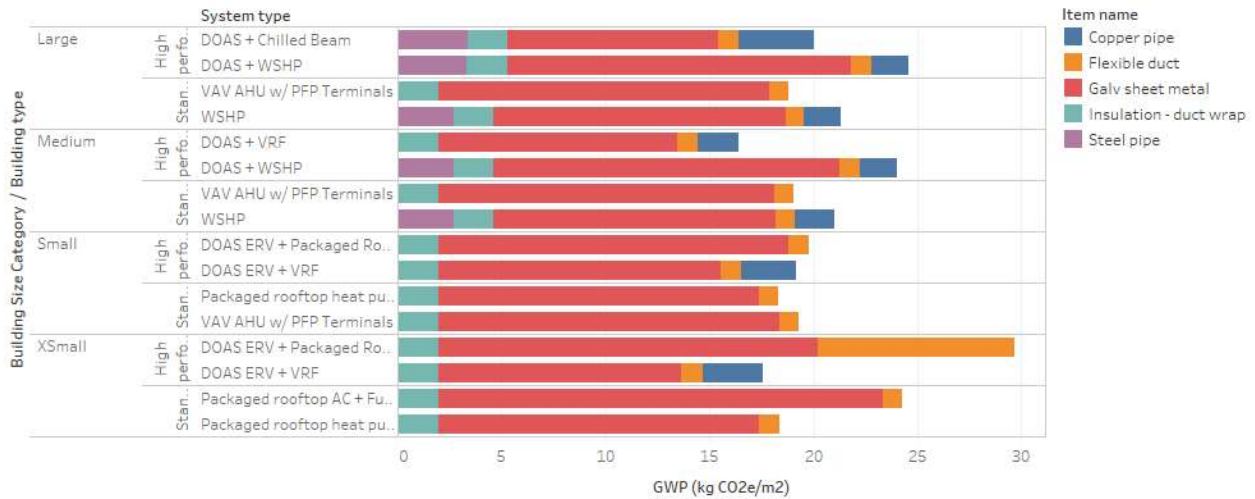


Figure 4.4: Global Warming Potential (GWP) for material types in HVAC+R system types in Standard Buildings and High Performance Buildings (kg CO₂e/m²)

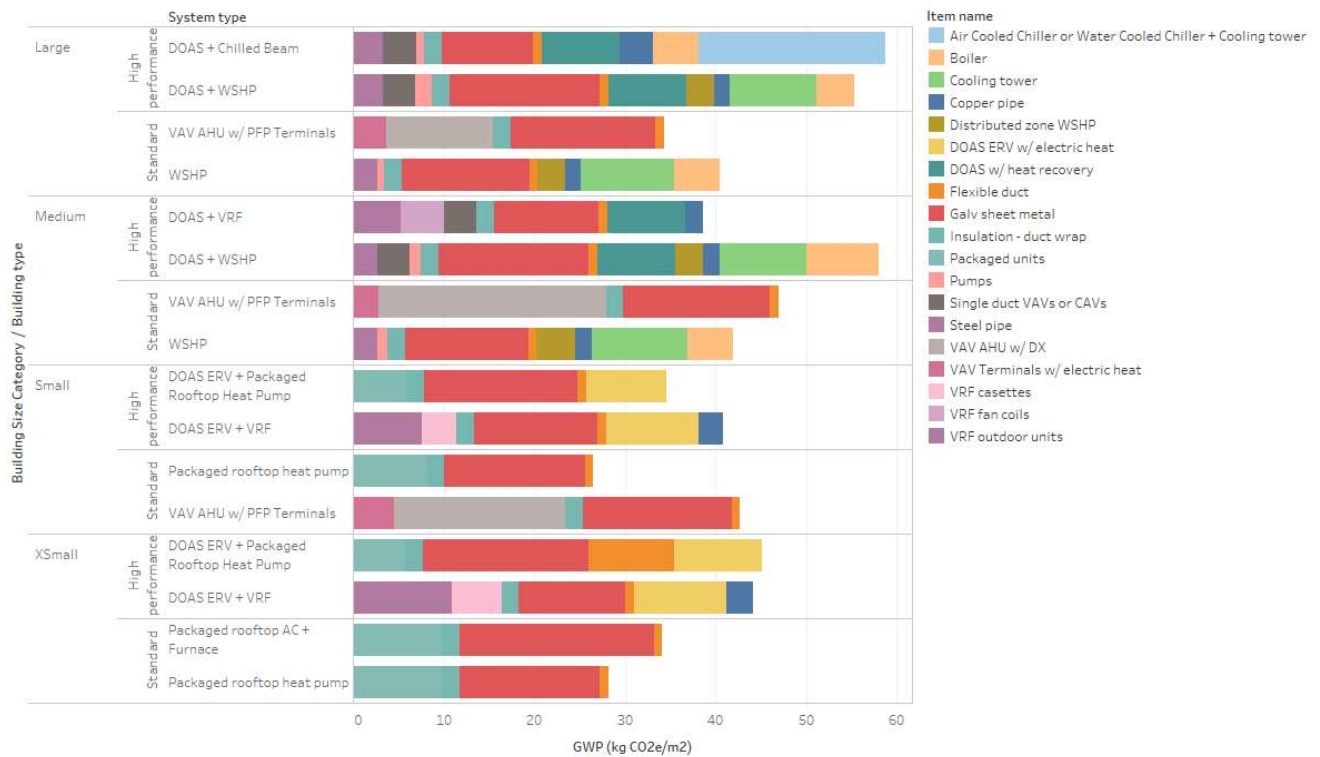


Figure 4.4 Global Warming Potential (GWP) for HVAC+R System Types in Standard Buildings and High Performance Buildings (kg CO2eq/m2)

4.3.3 Stage 3: Two-way ANOVA test

Based on the data, as shown in Table 4.2, the quantities of both material and equipment types increase in large and medium buildings which means that larger buildings include a larger variety of equipment and material types. Table 4.2 also shows that the frequency of equipment types is more than material types for large and medium buildings

Table 4.2 Descriptive Statistics for Building size and HVAC+R item type

Dependent Variable: Material Quantity Estimate [kg/m²]				
Building Size Category		Mean	Std. Deviation	N
Large	Equipment	1.26	0.73	17

	Material	2.27	2.51	14
	Total	1.71	1.81	31
Medium	Equipment	1.45	0.89	16
	Material	2.29	2.67	13
	Total	1.83	1.91	29
Small	Equipment	1.89	0.64	8
	Material	3.10	3.26	9
	Total	2.53	2.43	17
XSmall	Equipment	2.32	0.71	7
	Material	3.50	3.49	9
	Total	2.99	2.66	16
Total	Equipment	1.58	0.84	48
	Material	2.69	2.87	45
	Total	2.12	2.14	93

Table 4.3 shows that the significance value for HVAC+R item type (distribution material or equipment) is 0.023, i.e., significant at 95% confidence. This is not the case for building size or the interaction between the two independent variables. These results indicate that the test failed to reject Ho1 and Ho3, while Ho2 is rejected. This means that total material quantities are not associated to building size, but are affected by the HVAC+R item type (distribution material or equipment). There is no interaction between building size and HVAC+R item types as shown in Figure 4.3.

Table 4.3 Two Way ANOVA Table for dependent variable material quantity estimate (calculated) [kg/m²]

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Ho
Corrected Model	46.941a	7	6.706	1.516	.173	
Intercept	430.483	1	430.483	97.319	.000	
BuildingSizeCategory	17.908	3	5.969	1.349	.264	Fail to reject
Itemtype	23.627	1	23.627	5.341	.023	reject
BuildingSizeCategory * Itemtype	.495	3	.165	.037	.990	Fail to reject
Error	375.990	85	4.423			
Total	840.131	93				
Corrected Total	422.931	92				

a. R Squared = .111 (Adjusted R Squared = .038)

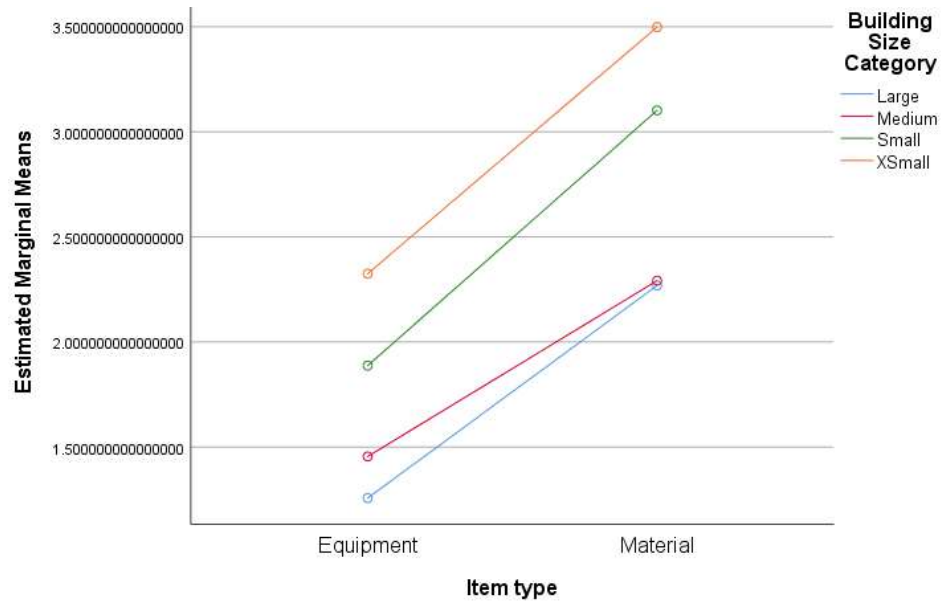


Figure 4.5 Interaction between building size category and HVAC+R item type

4.4 Conclusions and recommendations

The goal of this research was to offer reasonable estimates of embodied carbon and life cycle impacts of HVAC+R systems in commercial office buildings in the PNW. The first stage was guided by an Advisory Committee and demonstrated that HVAC+R systems are inherently different and present differing levels of equipment complexity that allows for different opportunities of standardization. Since HVAC+R systems are complex and highly dependent on the design decisions of the project team, only the two most representative HVAC+R systems are considered for each building size category under the SPB and HPB categories in this study. The second substage of this research revealed that material quantities for HVAC+R systems are slightly higher in HPB compared to SPB across all building size categories .

Following the first stage, a simplified LCA method was proposed that can assist design teams to assess the overall environmental impact of HVAC+R systems in early stages of design. This approach allows design teams to calculate the impacts of mechanical and material equipment separately according to the different type of LCA available for equipment or material types.

Future EC study is suggested by focusing on HVAC+R would greatly benefit from a statistically representative sample of commercial office buildings from different code compliant cities in the region. Another future study can be focused on typical case studies, describing a complete list of HVAC+R equipment and materials, specific to each case. A more complete list of HVAC+R equipment and materials, specific to each system and also more accurate assessment of total refrigerant use for each building type is required to better assess both material quantities and the EC associated to HVAC+R systems. This type of research could incorporate a survey targeted to contractors and building managers to estimate total refrigerant quantities, leakages during operation and end of life scenarios. To date, and to the best of our knowledge, there are limited EPD for HVAC+R equipment in the North America, thus more robust databases and EPD for the North American region is urgently needed.

5. Embodied and Operational Carbon of Typical Heating, Ventilation and Air Conditioning (HVAC) Systems in Office Buildings in Washington State: A study of buildings registered under LEED v3 2009

This paper aims to identify typical HVAC+R systems used in office building design in Washington State and explore the effects of current practice on total energy use, operational and embodied CO₂e. The study sample is composed of twenty office buildings in Washington State registered under the LEED v3 2009 version, from which 15 have obtained LEED certification in the last two years. The projects are registered under the New Construction (NC), Core and Shell (CS) and Existing Buildings and Operation and Maintenance (EB:OM) certification types and comply with the requirements established in the ASHRAE 90.1-2007 energy standard. The results show that typical HVAC+R system selection is often a combination of different technologies for ventilation, heating and cooling, and that in general: smaller buildings tend to incorporate high efficiency packaged units while medium and large size buildings typically rely on High Performance Variable Air Volume (HPVAV) systems or hydronic systems such as chilled beams and water source heat pumps (WSHP).

5.1 Introduction

5.1.1 Whole Building Carbon: Operational Energy and CO₂e of Buildings and HVAC+R

In the face of climate change, policy efforts around the world for all new buildings to operate at net zero CO₂e by 2030 have increased in recent years (WGBC 2017). Net Zero Carbon buildings (NZC) are defined as ‘a highly energy efficient building that produces on-site, or procures, enough carbon-free renewable energy to meet building operations energy consumption annually’ (Architecture 2030, 2016). In general, NZC buildings only account for operational energy, using the site energy use intensity (EUI) indicator. With a better understanding of embodied carbon impacts, the term whole building carbon has been incorporated to account for both embodied carbon (EC) and operational carbon (OC). Whole life cycle CO₂ emissions of buildings are often divided into operational carbon (OC) and embodied carbon (EC). Operational carbon are the CO₂e emissions generated from the burning of fossil fuels used to heat, cool and power the building space during its service life, while EC encompasses the CO₂e emissions equivalent to producing, procuring, installing, maintaining, repairing and disposing of the materials and components that make up the building (Cabeza et al. 2014). In this context, CO₂e emissions have been widely regarded as a key metric to understand a building’s negative impact on the environment and its capacity to incorporate renewable energy sources (WGBC 2017). A

metric that uses CO₂e emissions instead of site energy intensity (SEI) or source energy intensity (OEI) includes other strategies to mitigate or defer global warming, such as CO₂e sequestration (Wang et al. 2017).

Another important omission in the study of whole life cycle carbon in buildings are the impact of refrigerants, as the direct emissions provoked by refrigerants are typically considered a use stage impact. HFCs in traditional commercial refrigerants are powerful GHGs, with GWPs hundred to thousands of times more damaging to the climate than CO₂. For example just 1 kg of R-410A leaking into the atmosphere equates to the climate impact of two tonnes of CO₂. It is worth noting that this study considers the GWP of the HFC gases in the refrigerant and does not consider initial 'embodied' impact or EoL in manufacturing these refrigerants.

According to UNEP, refrigerant management is an approach to optimize the use of available refrigerants in the existing equipment and minimizing the demand for virgin refrigerants for servicing through technical and regulatory measures (UNEP 2010). The assessment report of UNEP program's Refrigeration, Air-conditioning and Heat Pumps Technical Committee or RTOC discusses refrigerant conservation as an important measure for extending the life of refrigeration equipment (RTOC 2011). This can be undertaken through:

- a. refrigerant recovery, recycle and reuse
- b. proper disposal or destruction of refrigerant banks in existing stock of appliances and
- c. eliminating leakages from systems.

In recent years, national policies continue to reduce operational energy and its related GHG emissions in commercial office buildings, despite these efforts policies to tackle embodied CO₂e emissions are much more scarce. The Commercial Building Energy Consumption Survey (CBECS) administered by the US Department of Energy is the most comprehensive publicly available dataset for energy use in commercial buildings in the United States. Despite a 14% increase in total buildings and a 22% increase in total floorspace since 2003, energy use in estimated 5.6 million U.S. commercial buildings was up just 7% during the same period, according to the survey from 2012. Slower growth in commercial building energy demand since 2003 is explained in part by newer construction that is built to higher energy performance standards, occupied by less energy intensive building activities, and more often built in temperate regions. In this context the study of EC will be essential in order to meet the 2050 GHG targets.

5.1.2 LEED Rating System and Building Regulation in Washington State

In the United States most state energy codes are based on model codes ANSI/ASHRAE/IES 90.1 (Standard 90.1) or the International Code Council (ICC) International Energy Conservation Code (IECC). The requirements of these codes vary by state and the control requirements can be difficult to implement, yet the assumption is that these codes are implemented and working correctly (Rosenberg et al. 2017). The ASHRAE Standard 90.1 developed by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) and first published in 1976 is one of the leading codes in the U.S in reducing energy demands (Baniassadi, Heusinger, and Sailor 2018).

The LEED Rating System on the other hand is a voluntary green building rating system developed by the United States Green Building Council (USGBC), and considered widely as one of the most popular green building rating systems around the world (Wu et al. 2017). The LEED Rating system focus is on operational energy and consequently OC, however in the more recent versions of LEED (v4 and v4.1), the concept of “building life- cycle impact reduction” and “building product disclosures and optimizations” have been introduced (Meneghelli 2018).

In Washington State, a number of local and state-level policies encourage green building development and energy efficiency. According to Building Energy Codes Program from the U.S. Department of Energy (DOE), the first statewide Washington State Energy Code (WSEC) was adopted in 1986 applicable to all buildings and was based on ANSI/ASHRAE/IES Standard 90A-1980 (U.S. DOE 2018). The first amendment to the commercial energy standards came in 1991, and from that date progressive modifications for HVAC+R systems have included increased equipment efficiencies, more restrictive controls, and minimum motor efficiencies (SBCC 2018). The 2012 WSEC went into effect on July 1, 2013 (WSU Energy Program 2018). The latest version, the 2015 WSEC is one of the most stringent energy codes in the country and is more efficient than ASHRAE 90.1-2013. Washington is one of the only four states in the country that has adopted a standard with this level of requirements.

Within Washington State, the city of Seattle has a large tradition of environmental stewardship which is reflected in innovative green building policy adoption. In February 2000, Seattle enacted the first green building policy in the US, mandating for new city-funded projects and renovations with over 5,000 square feet of occupied space to achieve a LEED Silver rating (WWF 2012). In 2011, Resolution 31326 set the goal for city-owned properties new construction and major renovation 5,000 sq ft or greater meet LEED Gold, and for all tenant improvements 5,000 square feet or greater, with a scope of work that includes mechanical, electrical and plumbing that must meet LEED Gold (City of Seattle 2011).

Since 2008, the city of Seattle is one of the leading cities around the world in developing outcome based energy code¹¹, focused on compliance through verified energy performance (Feng et al. 2017). The outcome based targets setting, shown in Table 5.1, is established from the data disclosed by building owners through the Seattle Energy Benchmarking and Reporting Program ¹². In April 2017, Seattle’s Office of Sustainability and Environment (OSE) publicly released the 2015 energy performance data for over 3,300 buildings reporting data through the city’s benchmarking program. In 2018, a report of this data show that from 2014 to 2016, total energy use for these buildings declined 3.7% and total emissions declined 4.8%, with office buildings have seen some of the biggest improvements—the median EUI for large office buildings declined 7% from 2014 to 2016, from 61.4 to 56.9 kBtu/ft² per year (Seattle OSE 2018).

Table 5.1 Outcome based targets of the City of Seattle Energy Code for office buildings

Building Type	EUI target – kWh/m² (kBtu/ft²)
B- occupancy office	126 (40)
B- occupancy office	157.5 (50)

In relation to energy conservation, the Seattle Energy Code (SEC) has a history of stringent requirements above ASHRAE 90.1. The 2001 Seattle Energy Code strived for 20% total building energy savings compared to Standard 90.1 1999. A study using textual comparison, identified seventy-one 2012 SEC provisions more stringent than Standard 90.1-2010, including: much higher minimum insulation requirements for all envelope components, requirements for building air leakage testing and compliance with a maximum leakage of 0.4 CFM/ft at 75PA, full commissioning with plan, preliminary and final commissioning reports, and requires hourly metering of all energy sources and

¹¹ Outcome-based performance codes development is based on collecting data from pilots and tracking actual operation energy performance. An outcome-based is particularly important to address emissions in existing buildings since this gives building owners the flexibility to increase energy efficiency through techniques and technologies that may not be included in prescriptive building energy codes (i.e. upgrading the building envelope through a retrofit process, which could degrade the character of historic building)(Conover et al. 2011). In order to comply with the outcome based code, the building needs to be continuously operated for at least 12 months and to have 75 % or more its space occupied (Feng et al. 2017).

¹² Ordinances 123226 and 123993 requires owners of commercial and multifamily buildings (20,000 square feet or greater) to annually benchmark the energy performance of their building with the EPA’s ENERGY STAR Portfolio Manager. The energy performance data must be reported to the City of Seattle and disclosed to any current or prospective tenant, buyer, or lender upon request(Seattle OSE 2015).

major end uses (Kennedy 2014). The 2015 Seattle Energy Code, is even more stringent than WSEC and came into full effect on Jan. 1, 2018.

Washington is one of the states with the largest number of certified projects in the United States. One of the enablers of a wide adoption of the LEED rating system, was the enactment of Chapter 99, Laws of 2011, that required that “All major facility projects of public agencies receiving any funding in a state capital budget, or projects financed through a financing contract must be designed, constructed, and certified to at least the LEED silver standard”. According to the 2017 USGBC annual ranking of LEED Buildings per state, Washington came in 11th place in 2017, with 12,469,420 total square feet of LEED-certified space from 74 certified projects, equating to 1.93 square feet of LEED space per capita (USGBC 2018a). Of the 74 projects, seven achieved LEED Platinum certification, 26 achieved Gold, 26 reached Silver and 15 were LEED Certified. According to another study, in 2017 Seattle-Tacoma-Bellevue was number seven in the ranking of urban areas with the largest LEED-certified commercial projects, with a total of 708 certified projects equating 110,850,956 square feet of LEED space (ABODO 2017). As of September 2018, there are a total of 2131 registered buildings and 1108 certified buildings in Washington State, 903 of these buildings are registered and 458 buildings certified under v3 LEED 2009 (USGBC 2018b).

5.1.3 New HVAC+R Technologies and Reduction of Operational Energy and CO₂e in Office Buildings

In the past, countless studies have demonstrated the role of HVAC+R technologies in reducing operational energy. Torcellini et al. described HVAC+R equipment for large, medium and small offices for post-1980 building models, indicating that for efficiency purposes, large buildings usually incorporate boilers, chillers and multi zone variable air volume (MZVAV) systems, while medium and small offices incorporated furnaces, packaged air conditioned units (PACU) and Single Zones Constant Air Volume system (CAV)(Torcellini et al. 2008). Other studies have compared different technologies and have demonstrated that achieving energy efficiency in HVAC+R systems is more related to designing systems that use novel configurations of existing system components (Vakiloroaya et al. 2014)

Industry research has also characterized and compared HVAC+R technologies extensively. In response to exotic alternatives that are gaining popularity as high-efficiency systems, a study demonstrated that if air systems such as High Performance Rooftop (HPVAV) are done right these typically cost less than piped systems such as Variable Refrigerant Volume (VRF), and consume up to 20% less energy (Smith 2013).

5.2 Method

This study aims to respond the following research questions: 1) What are the typical HVAC+R systems and equipment used in high performance buildings of Washington State and, 2) what is the contribution of to the whole lifecycle carbon (WLC), OC and EC in the building. In order to respond to these questions, a two-stage research plan is proposed. The first stage, follows a systematic review of the project LEED data retrieved from the USGBC project management platform, the second stage analyzes each HVAC+R system against the different performance indicators commonly used in LEED certification at the time of design for OC, and the indicators for EC added from the simplified life cycle carbon for HVAC+R presented previously.

This study accounts for refrigerant use in each system. In the previous study for hypothetical buildings, the Advisory Committee did not address the specific refrigerant charge for each type of equipment, as this study is based on data from LEED documentation, the refrigerant impacts are calculated for each individual system. The GWP of refrigerants in the HVAC+R system is calculated separately from the rest of the equipment, due to the differences in their physical nature.

In this study, in order to calculate the leakages and therefore the GWP impact of refrigerant, we used the industry standard for refrigerant quantity calculation, the formula provided for enhanced refrigeration management in LEED v4 2009 (USGBC 2013). Leakage GWP impacts are calculated based on the chemical composition of the refrigerants as converted to greenhouse gasses. LEED recommends assumptions of leakage of 2% per year and 10% at the EOL, therefore 40% for equipment with a 15 year lifespan . .

In this calculation shown in equation (1), Life Cycle Global Warming Potential (LCGWP) and Life Cycle Ozone Depletion Potential (LCODP) are calculated for a weighted average of all multiple types of HVAC+R equipment in the building across a period of 15 years. LCGWP is calculated using equation (2) where Global Warming Potential of Refrigerant (GWPr) is multiplied by the result of a leakage rate of (2.0% default value) for each year of equipment life (10 years default) and End-of-life Refrigerant Loss (10% default value). This study is based on the impacts reported under the LEED Rating System for HFC-410A (R410A), one of the most common types of refrigerants used in commercial HVAC (GWP of 1,890 kg CO₂ eq/kg of refrigerant), where Lr: Refrigerant Leakage Rate (2.0%); Life: Equipment Life (10 years; default based on equipment type, unless otherwise demonstrated); Mr: End-of-life Refrigerant Loss (10%); R_c: Refrigerant Charge (0.5 to 5.0 lbs of refrigerant per ton of gross AHRI rated cooling capacity).

$$\sum [(LCGWP + LCODP \times 105) \times Q_{unit} \leq 100] / Q_{total} \quad (1)$$

LCGWP = $[GWPr \times (Lr \times Life + Mr) \times Rc] / Life$ Where: GWPr: Global Warming Potential of Refrigerant (0 to 12,000 lb CO₂/lbr). (2)

5.2.3 Data Gathering Process

The data for this project was obtained via USGBC LEED online system, the official platform for design and construction team members to upload the data for projects undergoing LEED certification process. The data available for each project are credit templates and supporting documentation to demonstrate compliance with each credit. The credit templates offer standardized data for all projects, however the organization of the template varies depending on the LEED product: New Construction (NC), Core and Shell (CS), Existing Buildings, and Operation and Maintenance (EB:OM). The type of supporting documentation is clearly indicated for each project under each credit, however the data is submitted by each project in unstructured content types. The project data was gathered during 12 months from June 2017 to June 2018 directly from the LEED Online website.

The data from the website was summarized and recorded into a template for each project, the data recorded in these templates are: System Description Narratives, and Equipment List. During the second stage, specific parameters are organized into a structured database, the parameters included in this database are based on the taxonomy for the goal and scope definition developed in a previous stage of the research.

Table 5.2 Categorical and numerical HVAC+R variables used in the study

Categorical Variables	Continuous Variables (SI)
Building Size Category (small, medium, large)	Total gross floor area GFA [m ²]
HVAC&R Item Type (Equipment, distribution, refrigerants)	Total conditioned office floor area [m ²]
HVAC+R System Type (HPVAV, DOAS+Chilled Beam, DOAS ERV+VRF, PRHP, PRAC)	Total GHG Operational [MTCO ₂ e]
Certification type (LEED NC, EB, CS)	Total GHG Operational Intensity [MTCO ₂ e/m ²]
	Cooling capacity (TON)
	Total Energy Use [kWh]
	Site Energy Use Intensity EUI [kWh/m ²]
	Operational Carbon (OC) [MTCO ₂ e]
	Operational Carbon Intensity [kgCO ₂ e/m ²]
	HVAC+R Operational Carbon Intensity [kgCO ₂ e/m ²]
	Mechanical equipment quantities MEQ [kg _m /m ²]
	Distribution material quantities DMQ [kg _m /m ²]
	Refrigerant Charge Rc [kg _r /TON]
	EC equipment [kgCO ₂ e/ m ²]
	EC distribution [CO ₂ e/ m ²]

GWP refrigerant [kgCO₂e/ m²]

Total EC HVAC+R [kgCO₂e/ m²]

Information about the sample

The twenty buildings analyzed are office buildings registered under the LEED 2009 version 3.0 for either New Construction (NC), Core and Shell (CS) and Existing Building (EB), and 15 have obtained some level of certification over the past two years. All buildings included in the sample are located in the State of Washington, and more specifically in the city of: Seattle (n=15); Other (n=5). Buildings registered under LEED EB:OM (n=4) demonstrate energy performance using historical energy consumption data, while buildings registered under LEED NC, CS, and EB are modeled to estimate energy consumption via building energy simulation programs (i.e. eQuest, EnergysPro, HAP, Trace and IES). Building energy simulation (BES) has been used extensively in the industry in order to estimate energy consumption patterns and to compare of proposed design projects relative to standard designs in early stages of design. BES does not provide predictive accuracy of the future energy use of the buildings or HVAC+R systems and its limitations have been extensively documented in the literature. BES analysis is conducted by first using the software to model the proposed building geometry and the different building parameters such as: climate data, envelope materials, schedules and mechanical, electrical and plumbing systems. The proposed building is then compared to a baseline model designed following the parameters in ASHRAE 90.1 2007. Appendix G guidelines. All projects comply with the 2012 Seattle Energy Code, which is 8 to 12 percent more efficient than ASHRAE 90.1-2010 for all office building sizes (Kennedy 2014)

All buildings analyzed using BES in the sample are located in ASHRAE climate zone 4C. This climatic zone is characterized by a marine moist with moderate temperatures for the Summer and Winter and at least four months with mean temperatures above 50° F (Briggs, Lucas, and Taylor 2003), the climatic data used are 4,908 heating degree days (HDD) and 2,021 cooling degree days (CDD) as indicated in the ASHRAE standard.

Due to the large variation of the building parameters across all buildings in the sample, the office buildings were classified according to their size in three categories: Small, Medium, Large as shown in Table 2. Per USGBC requirements, data accessed via LEED Online, describing attributes of individual buildings should not be revealed publicly, all data from the platform must be reported in aggregate, therefore all data used in this study is only presented in aggregate for different building categories.

In order to obtain data for the EC of the HVAC+R equipment, this study uses the equipment descriptions submitted in compliance with Credit 4: Enhanced Refrigerant Management under the Energy and Atmosphere Category for LEED-NC and LEED- CS and Credit 5 for LEED EB:OM. Only 16 buildings in

the sample complied with the enhanced refrigerant management credit. The equipment weights were calculated using industry technical sheets for each type of equipment.

Table 5.3 Twenty sample buildings classified according to LEED Certification types and the three building size categories

Project ID	Certification type	Certification Level	Building Base Area [sf]	Building size range [sf]	Building Size Category
WS1	LEED-NC v2009	NA	55,000	10,000-80,000	Small
WS2	LEED-NC v2009	Gold			
WS3	LEED-EB:OM v2009	Silver			
WS4	LEED-CS v2009	NA	135,000	80,000-300,000	Medium
WS5	LEED-EB:OM v2009	Silver			
WS6	LEED-CS v2009	Platinum			
WS7	LEED-CS v2009	Gold			
WS8	LEED-CS v2009	Gold			
WS9	LEED-CS v2009	NA			
WS10	LEED-CS v2009	Gold			
WS11	LEED-NC v2009	Platinum	700,000	300,000-800,000	Large
WS12	LEED-EB:OM v2009	Gold			
WS13	LEED-CS v2009	Gold			
WS14	LEED-CS v2009	Gold			
WS15	LEED-EB:OM v2009	Platinum			
WS16	LEED-CS v2009	NA			
WS17	LEED-CS v2009	Gold			
WS18	LEED-CS v2009	Gold			
WS19	LEED-EB:OM v2009	Gold			
WS20	LEED-CS v2009	Gold			

5.2.4 Analyzing the Data Using Two-way ANOVA Test

In the last stage of the research, the data is analyzed using a two-way Analysis of Variance (ANOVA). The simultaneous analysis to be considered of the effect of more than one variable on population means is termed two-way ANOVA and is used to perform a single test for the effect of different variables and the interaction between those variables. A two-way ANOVA is used to find any relationship between two independent categorical variables and the dependant variable. In this case the independent variables are system category (ducted or ductless system) and HVAC+R item type (equipment, distribution or

refrigerant), whereas the dependent variable is material quantities (kg/m^2) in commercial office buildings in the PNW.

The ANOVA analysis aims to respond the following research question:

- *Do material quantities significantly differ for typical items types, equipment, distribution and refrigerant in HVAC+R systems?.*
- *Do material quantities significantly differ for different HVAC+R system categories, ducted or ductless?*
- *Does an interaction occur between typical item types and HVAC+R system categories in affecting the final material quantity?*

In this analysis, the two independent variables are set as system category and item type, while material quantity is set as the dependent variable. The three null hypotheses and alternative hypotheses are described as follows:

Ho1: There is no significant difference in the material quantity means between the three item types.

Ho2: There is no significant difference in the material quantity means between the system category types.

Ho3: There is no interaction between the two independent variables of three item types and system category types.

Ha1: There is a significant difference in the material quantity means between the three item types.

Ha2: There is a significant difference in the material quantity means between the system category types.

Ha3: There is an interaction between the two independent variables of three item types and system category types.

5.3 Results and Discussion

The results of this study are described in two parts. The first part explains the results of the qualitative systematic review of HVAC+R systems description in LEED online supplementary information. The second part of the results describe the results of the quantitative stage of the research where each EUI and CO₂ ranges is described for each building size category and type of HVAC+R system.

5.3.1 HVAC+R Systems descriptions per type of Building Size Category

Typical HVAC+R Systems in Small Buildings (10,000-80,000)

For most small buildings, the most common type of HVAC+R system are self-contained systems, such as packaged rooftop units (RTUs). In most cases, these RTUs are packaged rooftop heat pumps serving each individual zone in the building. Typical zone numbers in small office buildings range from 10-15 and are typically served by 2.5-15 ton individual RTUs. These RTUs include economizers, power exhaust, and short cycling protection. Another type of system used in small buildings is Variable Refrigerant Flow systems VRF including heat recovery ventilators.

Typical HVAC+R Systems in Medium Buildings (80,000-300,000)

In both medium and large building size categories High Performance Variable Air Volume Systems (HPVAV) are widely used. HPVAV are characterized by the use of optimized system control strategies, fan-pressure optimization and supply-air-temperature reset (Murphy 2011). HPVAV also called High Performance Air Systems (HPAS) typically include heat recovery and efficient fans and capacity control (Smith 2013).

In various buildings in the sample, the centralized system consists of a cooler supporting office by office air handling units (AHU). Each AHU provides conditioned air to all occupied spaces using parallel fan powered terminal units (PFP). Ventilation in primary office space of medium buildings is also provided by RTUs. These RTU serve office zones through fan powered and VAV boxes located above the ceiling. Heating in this each zone is served by a series fan powered boxes with electric reheat.

Typical HVAC+R Systems in Large Buildings (300,000-800,000)

Large buildings usually include a central plant that serves the entire facility including different types of use in zones. In medium and large buildings the first retail floor is usually served by a secondary system, which is typically a water source heat pump system (WSHPs). For most efficient buildings, the WSHP are served from high temperature chilled water return to reclaim heat that is typically rejected by cooling towers.

5.3.2 Performance Results per type of HVAC+R System and Building Size Category (EUI and total CO₂e)

The median EUI of the sample, shown in Figure 5.2, is lower than buildings in Seattle and lower than the Energy Portfolio Manager. The U.S National EUI Median Reference values for an office building comparable to these building types is 166.8 [kWh/m²-year] (52.9 [kBtu/ft²-year]) (Energy Star 2018). According to the Seattle Energy Benchmarking and Reporting Program in 2017, the median site EUI for small and mid-sized office buildings was 169.4 [kWh/m²-year] (53.7 [kBtu/ft²-year]) and, 177.6 [kWh/m²-

year] (56.3 [kBtu/ft²-year]) for large office buildings. The operational carbon intensities are presented in total for each building in Figure 5.3 and for HVAC+R in particular, for each building size category in Figure 5.4, as the HVAC+R systems energy consumption range between 45 and 55% of the energy consumption in office buildings in the PNW. Due to the geographical location of these buildings heating energy is less than in typical office buildings, while ventilation, cooling, pumps and miscellaneous equipment represent larger energy use.

From comparing the results, Figure 5.4 suggest that the operational carbon intensities during the 15 years of service life of the HVAC+R system can represent up to 6 times the embodied carbon of the systems including the refrigerant leakage during the fifteen years, shown in Figure 5.5. It is worth noting, that with more stringent energy codes and cleaner energy grids this proportion may change.

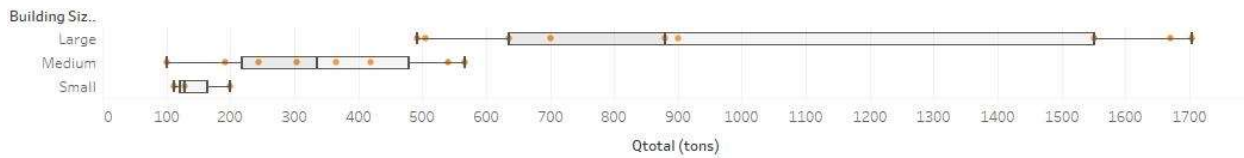


Figure 5.1 Cooling capacity [TONS] according to each building size category

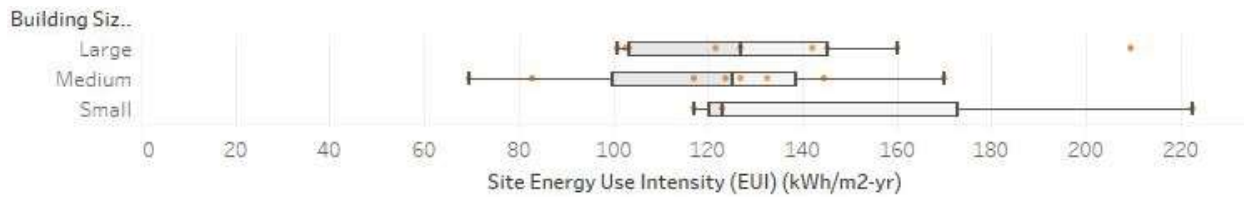


Figure 5.2 Site Energy Use Intensity (EUI) [kWh/m2-year] according to each building size category

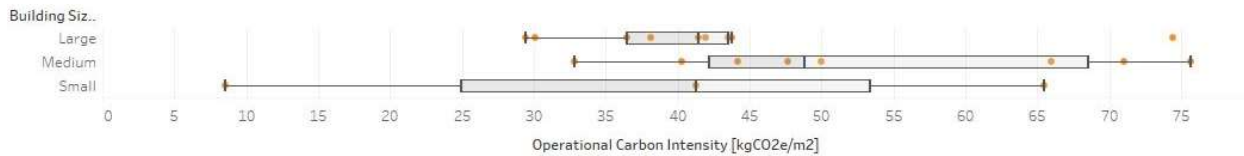


Figure 5.3 Operational Carbon Intensity [CO2e/m2-year] according to each building size category

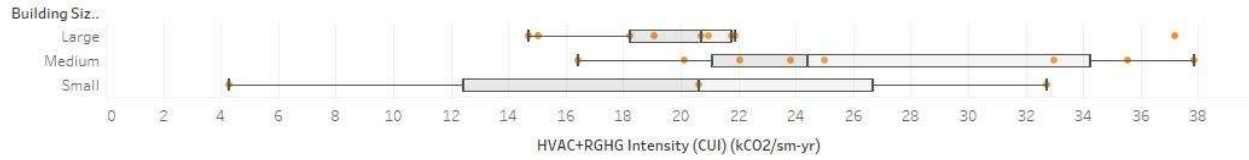


Figure 5.4 HVAC+R Total Carbon Intensity [CO₂e/m²-year -] according to each building size category

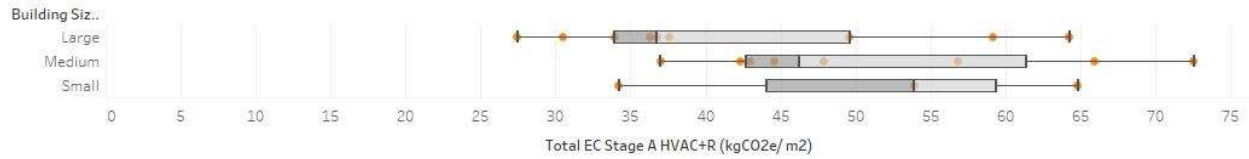


Figure 5.5 HVAC+R Embodied Carbon Intensity [CO₂e/m²] in 15 years according to each building size category

The results shown in Figure 5.5 suggest that material quantities for equipment (MEQ) are significantly lower compared to the material quantities in distribution (DMQ). The total material quantities for each building account for different equipment types but does not consider specific differences in distribution quantities, as this study uses the distribution quantities from the hypothetical calculation per building size in the previous study.

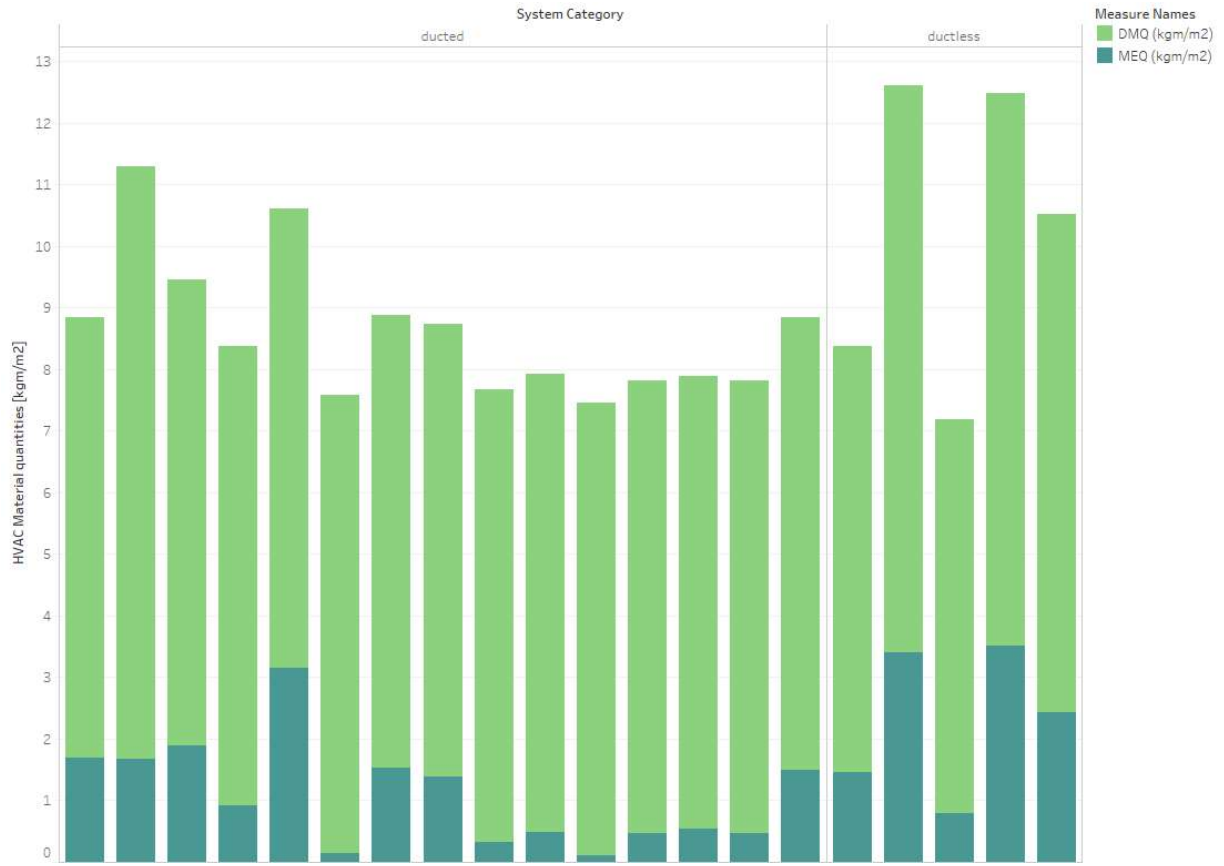


Figure 5.6 Total Material Quantities (kgm/m²) of HVAC+R systems in ducted and ductless systems

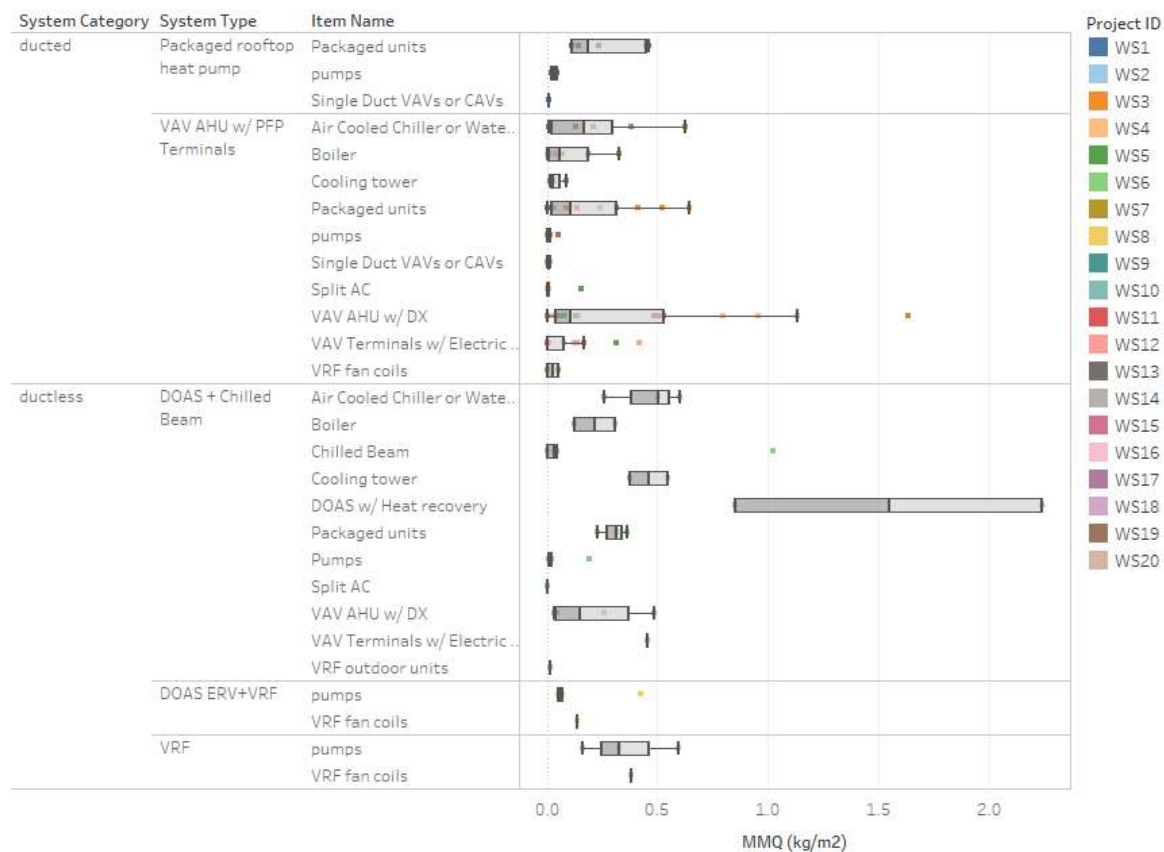


Figure 5.7 Mechanical Material Quantities (kgm/m²) of HVAC+R per equipment types

LEED v3 2009 Calculations for Refrigerants

Refrigerant charge in HVAC system varies depending on equipment type (i.e.VRF, VAV AHU), cooling capacity (i.e. number of cooling tons) and piping. Estimates for refrigerant charge range from a low of 0.8kg (1.74lb) per cooling ton (from manufactures data sheets) to 3.6 kg (8 lb) per cooling ton, according to a mechanical contractor who considers total refrigerant charge in the building including refrigerant in the piping (B.X. Rodriguez et al. 2019).

Since the refrigerant charge depends largely on the total cooling capacity of the building in tons of cooling, the total refrigerant charge for each individual equipment is larger as the cooling capacity of the equipment increases, as shown in Fig. 5.6. The results show that seven types of refrigerants are used in office buildings with a GWP range between 1320-1890 [kgCO₂e per kg of refrigerant], where type R-410A is the most common. The larger the lifespan of the equipment, as is the case of chillers, the larger the total life cycle GWP (LCGWP) due to the refrigerant leakage, as shown in Figure 5.8.

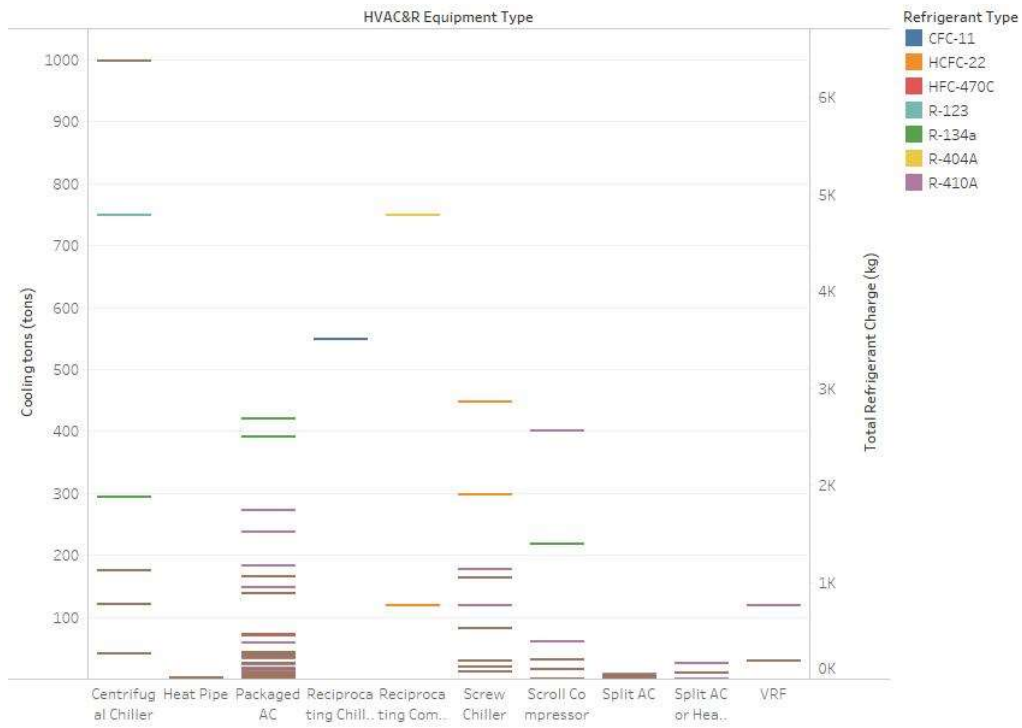


Figure 5.8 Total Refrigerant charge according to total cooling tons, per type of equipment

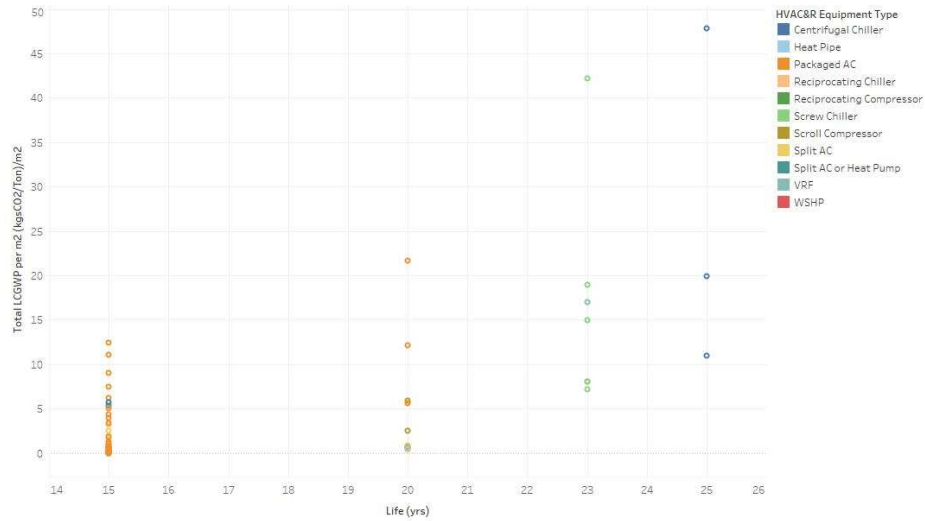


Figure 5.9 Total LCGWP per m² according to service life of each type equipment



Figure 5.10 Total EC (kgCO₂e/m²) of HVAC+R systems in ducted and ductless systems HPB

The results suggest that the EC per m² of the equipment is lower than the EC per m² of the distribution equipment. However, the impact due to the refrigerant represents anywhere between a 10-90% of the GWP in all buildings.

The results of the two-way ANOVA Test, as shown in Table 5.2, the total material quantities of both material and equipment types increase in large and medium buildings which means that larger buildings include a larger variety of equipment and material types. Table 5.4 also shows that the frequency of equipment types is more than material types for large and medium buildings

Table 5.4 Descriptive Statistics

Dependent Variable: Material Quantity Estimate [kg/m²]				
System Category		Mean	Std. Deviation	N
ducted	Equipment	0.15	0.22	131
	Material	1.88	2.89	60

	Refrigerants	0.03	0.03	15
	Total	0.64	1.75	206
ductless	Equipment	0.32	0.49	41
	Material	1.28	1.52	31
	Refrigerants	0.03	0.02	5
	Total	0.69	1.13	77
Total	Equipment	0.19	0.32	172
	Material	1.68	2.52	91
	Refrigerants	0.03	0.03	20
	Total	0.66	1.61	283

Table 5.5 shows that the significance value for System Category (ducted or ductless) is 0.614, i.e., significant at 95% confidence, this means there is no significant difference between ductless and ducted HVAC+R systems. This is not the case for item types, where the test shows that there is a significant difference between refrigerants, equipment and distribution materials. These results indicate that the test fails to reject Ho1 and Ho3, while Ho2 is rejected. This means that total material quantities are not associated to ducted systems, and instead depends on the type of items. There is no relation between building size and HVAC+R item types as shown in Figure 5.4.

Table 5.5 Two Way ANOVA Table for dependent variable material quantity estimate (calculated) [kg/m²]

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Ho
Corrected Model	148.269 ^a	5	29.654	14.185	0.000	
Intercept	38.993	1	38.993	18.652	0.000	
System Category	0.534	1	0.534	0.256	0.614	Fail to reject
Itemtype	96.784	2	48.392	23.148	0.000	reject
SystemCategory * Itemtype	7.595	2	3.797	1.816	0.165	Fail to reject
Error	579.072	277	2.091			
Total	849.088	283				
Corrected Total	727.341	282				

a. R Squared = .204 (Adjusted R Squared = .189)

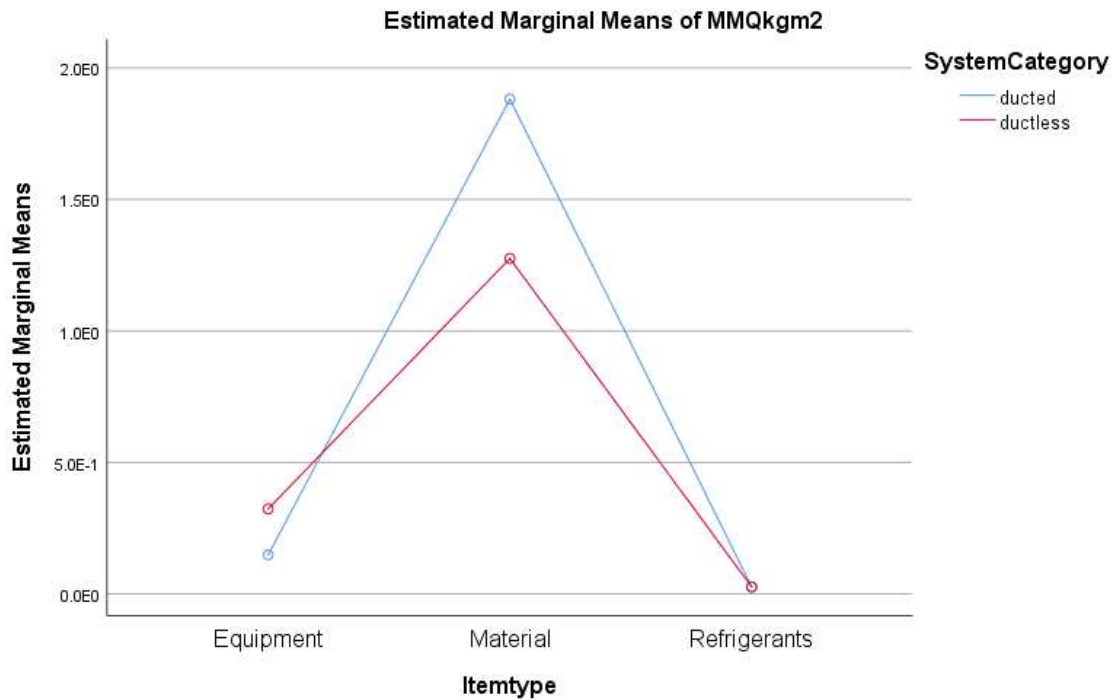


Figure 5.11 Interaction between system category and item type HVAC+R item type

5.4 Discussion and conclusion

This study analyzed the HVAC+R systems of twenty buildings registered under LEED v3. The twenty buildings are office buildings located in Washington State and registered under the LEED 2009 version 3.0 for either NC, CS and EB. Fifteen buildings have obtained some level of certification over the past two years. Buildings registered under LEED EB:OM (n=4) demonstrate energy performance using historical energy consumption data, buildings registered under LEED NC, CS, are modeled to estimate energy consumption via building energy simulation programs comparing the proposed to a baseline model designed following the parameters in ASHRAE 90.1 2007.

The results show that typical HVAC+R system selection is often a combination of different technologies for ventilation, heating and cooling, and that in general: smaller buildings tend to incorporate high efficiency packaged units while medium and large size buildings typically rely on High Performance Variable Air Volume (HPVAV) systems. Medium and large size buildings tend to incorporate more novel systems such as chilled beams and water source heat pumps (WSHP). Large buildings implement central

plants and typically incorporate Dedicated Outdoor Air System (DOAS), which contributes significantly to reduce energy consumption for ventilation.

The size of typical HVAC+R systems is based on the total heating and cooling load requirement of the building, this depends on various factors such as building use, occupancy, thermal envelope (Burdick 2011). Depending on the cooling and heating requirement of the building, the designer proposes a heating equipment to supply the capacity. This study demonstrate that the larger the capacity of the equipment, the larger is the larger the refrigerant quantities and thus the larger the emissions associated to GWP of the refrigerants.

From comparing the EC and OC results from HVAC+R systems, the results suggest that the operational carbon intensities during the 15 years of service life of the HVAC+R system can represent up to 6 times the embodied carbon of the systems including the refrigerant leakage during the fifteen years. It is worth noting, that with more stringent energy codes and cleaner energy grids this proportion may change. For instance, the data presented in this study was obtained from LEED templates using the Energy Star portfolio benchmark data, however the performance data for the same buildings reported to the Seattle Benchmark Portafolio shows that GHG emissions are half the magnitude of what was reported in LEED templates at the time of design. This differences are due to the fact that the Seattle emissions values reported use custom emissions factors provided by Seattle City Light and Enwave for electricity and steam, respectively. Seattle City Light (SCL) secures carbon offsets equal to the greenhouse gas emissions resulting from all aspects of SCL's operations, including those created by the generation of electricity the utility buys, employees' travel, and the trucks and other equipment used in its operations. Differences in schedules and peaks loads during operation may also explain this gap.

6. Case study of a VAV w PFP terminals: Understanding mechanical material quantities using an in depth analysis

This chapter provides a two building case studies with the objective to quantify mechanical material quantities in detail. This in depth analysis is framed within the context of a larger whole building life cycle assessment study LCA performed to understand total impact of a tenant improvement in an office building in San Jose, CA.

This chapter is organized according to the typical stages of a LCA as per ISO standards: Goal and scope: Defines the purpose and boundaries of the project; LCA methodology: the LCA results in detail: Discusses the implications of the LCA results

6.1 Introduction: Goal and Scope

This study was developed in the context of a life cycle assessment study developed with the aim to understand the environmental impacts of a typical tenant improvement. The present study, aims to perform a detailed LCA to the HVAC+R component of the original study, which used EIOLCA to identify which categories in the cost estimate were critical to include in a second stage using a detailed LCA. HVAC+R was considered, among other items, as a high-impact “priority” items that would require further analysis to determine the the top 90 - 95% of impacts.

The results of the original LCA study were expressed in terms of embodied carbon (GWP) acidification potential, eutrophication potential, smog formation potential, ozone depletion potential, primary energy use, and mass per unit floor area of office space., however this portion for the HVAC+R system only includes embodied carbon. The results of this study were intended to identify critical items that are particularly high-impact and also identify data needs that would improve the accuracy of the LCA, such as recommending the development of EPDs data for critical products. The intended audience of the original study is the internal team and other stakeholders.

The scope of the life cycle assessment refers to the HVAC+R system including the equipment, distribution types and refrigerants for the tenant improvement and also the core and shell portion of the building. The life cycle scope focuses on life cycle A and stage B.

6.2 Methodology

The LCA was performed using a detailed analysis approach to understanding material quantities of all equipment types, distribution material quantities, and refrigerants. This detailed approach is based on quantity take-offs (QTOs) from the project mechanical drawings and project documentation. The LCA data uses the ECC database developed in earlier stages of the research project.

6.2.1 Case study and description of the HVAC+R system

Building A is a tenant improvement project that involves four floors of an existing office building of size 79,000 GSF (7343 m²). According to the BOD documents, comfort cooling for the facility is provided by an air handler unit on every floor. Each air handler has a chilled water coil section in the air handler. This provides tempered conditioned air distributed throughout the floor. HVAC system is currently built-out for the previous tenants. The zonal systems and distribution ductwork and diffusers have been installed and are to be demolished back to the supply mains. Supplemental cooling and heating is possible through 2-1/2" valved condenser water taps located on each floor. According to the data provided, the total cooling load is 168 ton (42 ton per floor). Each floor is served by each air handler unit with chilled water from Chiller. Since we know the WSHP located in one provide 1 ton each, it is assumed that the remaining cooling tons (164 tons) are provided by the chiller.

6.2.2 Stage 1: Gathering Material Quantities

HVAC items were taken from the project mechanical schedules. The process for performing the take-offs (QTOs) consisted of the following steps:

Step 1) Measure or count items of interest in PDF plans using Bluebeam

Step 2) In performing the QTOs using bluebeam, marke-up item was categorized by "Layer", "Subject", and "Label" within Bluebeam. These terms were later renamed to "Category", "Subcategory", and "Items," respectively. This organizational structure of the QTO items uses Omniclass Table 21 Elements, which is based on Unifomat, to present the results in accordance with established building taxonomies, as shown in Table 6.1.

Step 3) Export QTO data from Bluebeam as a CSV file and import into Excel. Consolidate measurements by item by floor using Excel Pivot Tables.

Step 4) After exporting the data to Excel, measurements were consolidated by item and by floor to reduce the amount of unnecessary detail in the data.

Step 5) Export the consolidated QTO data to a master spreadsheet containing similar data from all projects. This final dataset would be used to analyze and compare the data from the different projects.

Table 6.1. Categories evaluated in detailed LCA, organized by cost estimate categories, CSI categories, and source of material quantity data.

Cost estimate category	CSI category	Source of material quantity data
HVAC	23 21 00 - HVAC Hydronic Piping and Pumps	Mechanical schedules
	23 31 00 - HVAC Casing and Distribution	
	23 31 13 - Metal Ducts	
	23 31 16 - Nonmetal Ducts	
	23 36 00 - HVAC Terminal Units	

3. Simplify and combine similar QTO items

To simplify the analysis to a level of work that could be completed within the desired timeline, similar items were combined into a generic item type. The results of this simplification for all items are presented in Table 6.2. The “Original item description” refers to the original name of the item from the data source – the QTO, Master Schedule, project drawings, etc.

Table 6.2. Consolidation of original QTO items into simplified QTO items, for TI.

Cost estimate category	Original item description	QTO item (simplified name)
HVAC	Double deflection adjustable sidewall supply air diffuser (front blades vertical, all steel construction, with OBD, U.O.N)	Grille
	Double deflection radius mount sidewall supply air diffuser (front blades vertical, all steel construction, with OBD, U.O.N)	
	QTY (1) 1" SLOT, picture frame borders, insulated boot plenum, concealed mounting hardware, all aluminum construction, white border, black inside	
	Round neck perforated return for grille with plaster fast frame for hard lid ceiling, all steel construction	
	Round Neck Square Plaque Air Diffuse with plaster fast frame for hard lid ceiling	

Sidewall return grille, 45 degree fixed deflection blades, all steel construction-install with blades facing up	
Surface -mounted exhaust grille (egg crate). 1/2"x1/2" cube cores, aluminium construction, with OBD for balancing	
Surface mounted makeup grille, 45 degree fixed deflection blades, all steel construction-install with blades facing away from door	
VAV box exterior	VAV Terminals w/ electric heat
VAV boxes interior	
AHU per floor	VAV AHU w/ DX
Water Source Heat Pump per floor	WSHP

4. Collect LCA data for QTO items

The method for choosing the LCA data and the final data selection for each QTO item is discussed in this section.

About the LCA data

The research team searched for best-fit LCA data from building-specific LCA databases and EPDs, prioritizing North American sources then European sources where no other alternatives were available. European sources were least preferred because they were less geographically relevant and they used CML impact characterization methodology, which characterizes some impact measures using different units than TRACI 2.1. TRACI 2.1 is the preferred impact characterization methodology in North America, and most commonly used in the North American databases and EPDs. A characterization methodology is the framework for expressing the environmental effects of emissions into impact measures, such as global warming potential, acidification potential, etc.

The research team's selection of database data vs EPD data depended on the QTO item in question. Generally, database data was preferred because it was more generic and representative of the industry. The databases considered in this project were Athena and Quartz. Quartz was prioritized over Athena because Quartz was open-access while Athena was somewhat proprietary (though Athena can be downloaded for free and the impacts per unit measurement can be derived). Since the results were going to be shared in the form of a spreadsheet tool, the research team needed to identify open source LCA data, so Quartz was prioritized over Athena. If a QTO item was not available in Quartz, the research team searched for an appropriate EPD. If an appropriate EPD could not be found, the closest substitute was made, either using another EPD that was a similar product, or by estimating quantities with database data using unit

conversions. Two important European LCA data sources for MEP items were the German Oekobaumat database and the PEP Ecopassport program, which is the french EPD program for electronics and mechanical systems.

Final data selection

The selected LCA data for each QTO item are shown in Table 6.3.

Table 6.3. LCA data selections for QTO items. Data source’s marked with a * were characterized per CML, not TRACI 2.1.

Cost estimate category	QTO item	Data type	Data source name	Data item description
HVAC	Galv sheet metal	Database	Quartz	Galvanized Steel Ducts
	Grille	EPD	Oekobaumat*	Air Ventilation Duct (zinc coated steel plate)
	HVAC ducting	Database	Quartz	Galv sheet metal
	Insulation - duct wrap	EPD	UL*	Armaflex® Class 1
	Insulation - hydronic water insulation	EPD	UL*	FIBERGLAS™ PIPE INSULATION
	Refrigerants	EPD	USGBC	R-410A
	VAV AHU w/ DX	EPD	PEP*	"Bidirectional ventilation unit for tertiary buildings
	VAV Terminals w/ electric heat	EPD	PEP*	Caisson de ventilation simple flux collective ou tertiaire
	WSHP	Database	Oekobaumat*	Electric heat pump (water-water) 10 kW; 1 piece (en

5. Apply LCA data to QTO items / make assumptions

Certain assumptions had to be made about the LCA data and QTO data. For example, certain dimensional units had to be assumed in order to make the units match. Table 6.4 describes the assumptions for each QTO item.

Table 6.4. Calculation assumptions for simplified QTO items.

Cost estimate category	QTO item	Units	Assumptions
HVAC	Grille	These were calculated from mechanical schedule lists.	
	VAV Terminals w/ electric heat		
	VAV AHU w/ DX		
	WSHP		

6.3 Results

This subsection presents the detailed LCA results, including background information and estimates of variability.

6.3.1 Results of the original study

The results for the detailed LCA in the original study are shown in Table 6. The total mass of the project was estimated to be 88 kg/m² while the overall results of the detailed LCA for life cycle stages A and C are shown in Table 6.5. For GWP, HVAC+R was the second highest-impact category.

Table 6.5. Total detailed LCA results, life cycle stages A and C.

Measurement	Life cycle stage	GWP (kg CO ₂ e/m ²)	Primary energy (MJ/ m ²)
Detailed LCA	A	195	8954
	C	-15.7	9.5

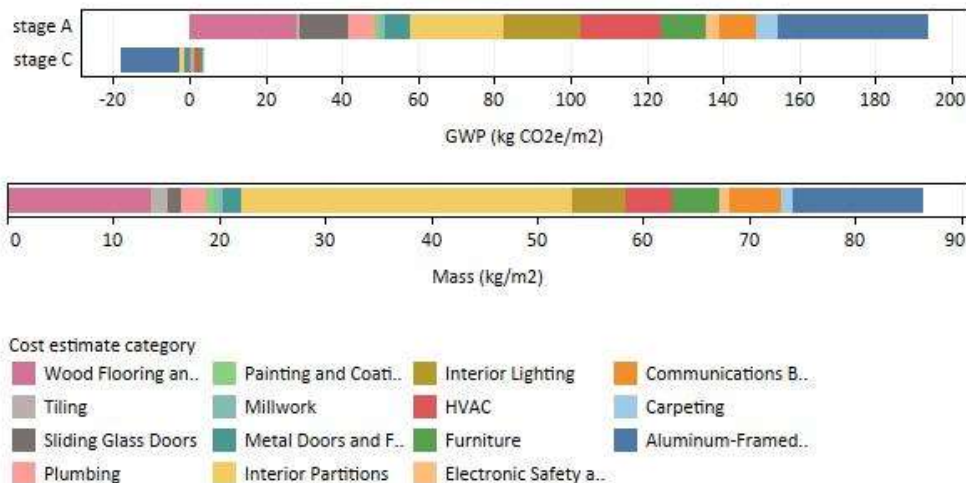


Figure 6.1. Contribution of cost estimate categories to overall results of the detailed LCA (M. Huang, Rodriguez, and Simonen 2019).

6.3.2 HVAC +R GWP detailed contribution analysis

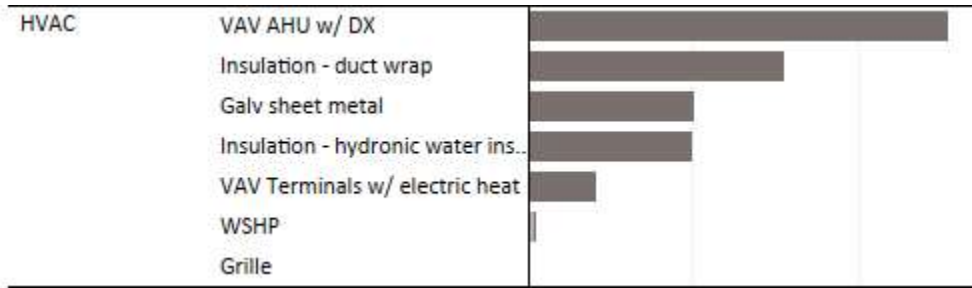


Figure 6.2 Embodied Carbon of HVAC+R

6.4 Discussion

This section discussing critical items in the results, data needs, a comparison of the results to another study, and limitations of this study.

Based on the results of the detailed LCA, the highest-GWP are Air handling units (VAV AHU w/ DX). AHUs are self-contained units and generally require the specific materials that they are made of, therefore have limited possibilities to reduce their GWP. However, it is more efficient in terms of minimizing embodied carbon to have fewer large AHUs than many small AHUs.

6.4.1 Refrigerants

Although refrigerants were not included in the overall results, they were evaluated in this study and estimated to be very high-impact.

The refrigerant calculations for this HVAC system were developed using the equipment described in mechanical schedule documentation. Water source heat pumps in each of the floors are described as DAIKIN CCH/CCW-R410-012 model, which uses a R-410 refrigerant. R-410A is a non-ozone-depleting blend of two refrigerants, HFC-125 and HFC-32, in a fifty percent mixture. R-410A exhibits a higher operating pressure and refrigeration capacity than R-22. R-410A is intended for use in new air conditioning applications that have traditionally been used HCFC-22 (R-22).

In this study, the GWP of refrigerants in the HVAC system is calculated separately from the rest of the equipment, due to the differences in their physical nature. Additionally the direct emissions provoked by refrigerants are typically considered a use stage impact. HFCs in traditional commercial refrigerants are powerful GHGs, with GWPs hundred to thousands of times more damaging to the climate than CO₂. For

example just 1 kg of R-410A leaking into the atmosphere equates to the climate impact of two tonnes of CO₂.

It is worth noting that this is the GWP of the HFC gases in the refrigerant and does not consider initial 'embodied' impact in manufacturing these refrigerants.

Refrigerant charge in HVAC system varies depending on equipment type (i.e. VRF, VAV AHU), cooling capacity (i.e. number of cooling tons) and piping. Estimates for refrigerant charge range from a low of 0.8kg (1.74lb) per cooling ton (from manufacturer data sheets) to 3.6 kg (8 lb) per cooling ton (from a mechanical contractor who considers total refrigerant charge in the building including refrigerant in the piping (B.X. Rodriguez et al. 2019)).

Given that the case study project has 4 tons of cooling served by 4 water source heat pumps (WSHP) (according to mechanical schedules), and 1 chiller that serves 164 ton of cooling capacity and 7343 sqm (18890 sqf) of area, we can estimate that the amount of refrigerants used will be between 0.02 (CO₂e kg/sqm) and 0.1 (CO₂e kg/sqm).

Refrigerant leakages due to general use can be estimated between 2% per year and 10% at the end of life of the equipment or even up to 100% in the case when the equipment is sent to landfill and all refrigerant is released to the atmosphere. UNEP TEAP.

In this study, in order to calculate the leakages and therefore the GWP impact of refrigerant, we used the industry standard for refrigerant quantity calculation, the formula provided for enhanced refrigeration management in LEED v4 2009 (USGBC 2013) (please see below to learn more about this approach). Leakage GWP impacts are calculated based on the chemical composition of the refrigerants as converted to greenhouse gases. LEED recommends assumptions of leakage of 2% per year and 10% at the EOL, therefore 40% for equipment with a 15 year lifespan.

Due to the different potential paths of refrigerants and orders of magnitude, we developed two case calculations using a case a) standard and a case b) Low-GWP refrigerant and three different EOL pathways for case A.

Case a) Calculation 0.8-3.6 kg per TON range (spec sheets- mechanical contractor) using R410 w 2% leakage per year **Results in 13.68-62.90 (kg CO₂e /m²)-total for a 15 year lifespan.**

Case b) Calculation 0.8-3.6kg per TON (spec sheets- mechanical contractor) using ammonia R717 w 2% leakage per year **Results in 0 (kg CO₂e /m²)-total for a 15 year lifespan.**

EOL Scenario 1) Total refrigerant recovery, recycle and reuse at the end of life= 0% leakage at the end of life, but w 2% leakage per year **Results in 12.24-47.17 (kg CO₂e /m²)-total for a 15 year lifespan.**

EOL Scenario 2) Total destruction of refrigerant bank at the EOL=0% leakage at the end of life, w 2% leakage per year **Results in 12.24-47.17 ((kg CO₂e /m²)-total for a 15 year lifespan.**

EOL Scenario 3) Total release of refrigerant bank =70% leakage at the end of life w 2% leakage per year **Results in 34.2-157.24 (kg CO₂e /m²)-total for a 15 year lifespan.**

The refrigerant calculations for this HVAC system are developed using the equipment as described in mechanical schedule documentation. In particular, water source heat pumps in each of the floors are described as DAIKIN CCH/CCW-R410-012 model, which uses a R-410 refrigerant. R-410A is a non-ozone depleting blend of two refrigerants - HFC-125 and HFC-32 in a fifty percent mixture. R-410A exhibits higher operating pressure and refrigeration capacity than R-22. R-410A is intended for use in new air conditioning applications that have traditionally been used HCFC-22 (R-22) (Daikin 2015).

Among the different Low-GWP alternatives the most promising are natural refrigerants. Natural refrigerant such as CO₂ (R744) and ammonia (R717) seems to be the most promising. CO₂ has many excellent advantages in engineering applications, such as no toxicity, inflammability, high volumetric capacity (with a possibility to make the system compact), lower pressure ratio, superior heat transfer. Ammonia is an efficient and popular refrigerant due to its superior thermodynamic properties and low cost. Ammonia is environmentally benign, having zero GWP and zero ODP. It is hazardous when released in large quantities due to its toxicity (ASHRAE, 2017).

6.5 Conclusion

An in depth material quantities calculation of an HVAC+R system in Building A office space, which estimated the impacts based on detailed material quantity take-offs. The detailed method assessed life cycle stages A (A1 through A3-A5, depending on the data sources) and C. This study shows that air handling equipment contributes significantly to the overall EC. However, refrigerants can represent one of the most important items to consider if there is no refrigerant management.

7. Conclusion, summary of findings and future research

7.1 Contributions of this dissertation

This dissertation provides a new simplified method to assess the embodied carbon (EC) across the life cycle of Heating, ventilation, air conditioning and refrigerant systems that can assist design teams to assess the overall EC impact of HVAC+R systems in early stages of design. A method such as this one would contribute to reduce four important barriers in WBLCA practice that prevent a better understanding of embodied carbon in buildings: 1) the time consuming process behind most LCA methods; (2) limited availability of building LCA data; (3) limited availability of material quantity data, and (4) a focus on structural, foundation and enclosure systems in the building scope of most WBLCA studies.

This simplified method builds on existing methods proposed in the past to assess the embodied carbon of other building systems such as structure (Wolf 2017) and envelope. In such methods the total EC (GWP) is normalized by floor area in order to provide a new metric for EC that can be aggregated across different building systems, just like Energy Use Intensity (EUI) is aggregated for operational energy of different energy systems (i.e. lighting, HVAC, etc). The simplified method to assess the EC of HVAC+R is calculated by using three independent types of calculation for each one of the system components; mechanical equipment, distribution systems and refrigerants, as shown in Equation 1.

$$\text{Total GWP}_{\text{HVAC+R}} [\text{kgCO}_2\text{e}/\text{m}^2] = \text{GWP}_{\text{equipment}} + \text{GWP}_{\text{distribution}} + \text{GWP}_{\text{Refrigerant}} \quad (1)$$

$$\text{GWP}_{\text{equipment}} [\text{kgCO}_2\text{e}/\text{m}^2] = \text{MEQ} [\text{kg}_\text{m}/\text{m}^2] * \text{ECCe} [\text{kgCO}_2\text{e}/\text{kg}_\text{m}] \quad (2)$$

$$\text{GWP}_{\text{distribution}} [\text{kgCO}_2\text{e}/\text{m}^2] = \text{DMQ} [\text{kg}_\text{m}/\text{m}^2] * \text{ECCd} [\text{kgCO}_2\text{e}/\text{kg}_\text{m}] \quad (3)$$

$$\text{GWP}_{\text{refrigerant}} [\text{kgCO}_2\text{e}/\text{m}^2] = \text{Rc} [\text{kg}_\text{r}/\text{TON}] * \text{Cooling capacity} [\text{TON}] * \text{ECCr} [\text{kgCO}_2\text{e}/\text{kg}_\text{r}] \quad (4)$$

This method is based on three independent calculations due to different material nature of each one of the HVAC+R components: equipment, distribution and refrigerants. The statistical analysis of the twenty LEED registered buildings dataset in Chapter 5 proved that the difference between the means of three groups is significant. Equation 2 shows the model for GWP of equipment, where mechanical equipment quantities (MEQs) represent the total weight of unitary equipment such as boilers or chillers, that are typically a composite of different materials, while in equation 3 distribution material quantities (DMQs) represents a single material that can be quantified individually (copper piping, galvanized sheet metal). HFC gases, refrigerants are quantified separately as shown in equation 4.

In order to reduce the effort and time to assess material quantities and embodied carbon of equipment distribution material types, design teams can use the following default values presented in Table 7.1 and Table 7.2. These values from the hypothetical building study presented in chapter 4 indicate that for most HVAC+R systems the material quantities range from 12/25/35 kg/m² (+/-20%) (min likely/most likely/high likely) and 35/70/129 kgCO₂/m² for embodied carbon. In all cases refrigerant emissions will depend on the cooling tons and specific refrigerant charges as demonstrated in Chapter 6.

Table 7.1 Material quantity estimates for equipment and distribution systems according to each HVAC+R system type

Building type	System type	Equipment	Distribution	Total (kgm/m ²)
Standard	Packaged rooftop AC + Furnace	3.1	9.6	12.8
	Packaged rooftop heat pump	5.7	14.4	20.1
	VAV AHU w/ PFP Terminals	10.9	22.4	33.3
	WSHP	9.8	17.0	26.8
High performance	DOAS + Chilled Beam	6.3	8.1	14.5
	DOAS + VRF	5.7	6.4	12.1
	DOAS + WSHP	15.8	19.6	35.4
	DOAS ERV + Packaged Rooftop Heat Pump	7.4	17.7	25.2
	DOAS ERV + VRF	11.2	14.6	25.7

Table 7.2 Embodied carbon estimates for equipment and distribution systems according to each HVAC+R system type

Building type	System type	Equipment	Distribution	Total (kgCO ₂ e/m ²)
Standard	Packaged rooftop AC + Furnace	9.8	25.6	35.4
	Packaged rooftop heat pump	18.0	39.2	57.3
	VAV AHU w/ PFP Terminals	66.8	61.0	127.8
	WSHP	40.1	44.8	85.0
High performance	DOAS + Chilled Beam	38.7	21.3	60.0
	DOAS + VRF	22.2	17.6	39.8
	DOAS + WSHP	64.7	51.2	115.9
	DOAS ERV + Packaged Rooftop Heat Pump	30.2	52.0	82.3
	DOAS ERV + VRF	48.2	39.3	87.5

7.2 Results and estimation of impacts

In order to respond to the main research question of the dissertation: 1) What is the relative contribution of the single equipment and material types of typical Heating Ventilation and Air Conditioning and Refrigerants (HVAC+R) systems in commercial office buildings of the Pacific Northwest, this research first provided a review stage where a framework to describe the Goal and Scope by reviewing current Whole Building Life Cycle Assessment (WBLCA) methods available for the AEC industry, and identified the embodied carbon coefficients (ECC) and equipment lifespan for typical HVAC+R equipment in existing LCA studies.

In a second stage a triangulation approach using a mixed method research design was completed. Under such method the three studies to assess material quantities and embodied carbon were designed as three independent approaches to respond to the same research question. Once the results are compared these can be convergent or divergent. Chapter 4, 5 and 6 describe the three independent study. In Chapter 4, a simplified method is proposed and implemented to assess embodied carbon (EC) in HVAC+R systems of commercial office buildings. In this stage the method is used to assess distribution material quantities (DMQs) and mechanical equipment quantities (MEQs) and EC of HVAC building systems in a sample of sixteen hypothetical building models (standard and high-performance) in the Pacific Northwest. In a fourth stage, the simplified method is used to assess the embodied carbon of HVAC building systems in a sample of 20 case study buildings in the State of Washington, and finally an independent case study is completed to provide an alternative standard method for material quantity take offs. The data collection method for each study is described in Table 7.3.

Table 7.3 Data gathering method for the material quantities in each study

Exercise	Material quantities for Equipment MEQ [kg/m ²]	Material quantities for distribution DMQ [kg/m ²]	Refrigerant Charge Rc [kg/m ²]
Ch 4 Advisory Committee	Based on historical data from each contractor	Based on historical data from each contractor. Midpoint calculated	Data not provided. Only one contractor provided an estimate equal for all systems from a low of 0.8kg (1.74lb)) to 3.6 kg (8 lb) per cooling ton
Ch 5 LEED Data	Equipment description in LEED documentation	Based on the estimates from Advisory Committee study	Refrigerant charge recorded in LEED template for Refrigerant Management Credit
Ch 6 In depth case study	Equipment description in project documentation	Accurate estimation using mechanical drawings for each case study using bluebeam.	Refrigerant charge for each equipment described in project documentation.

Using the building as the unit of analysis, this study contributes to the body of knowledge by integrating three different datasets and data collection methods to respond to the same research question: input from an advisory committee based on historical data from mechanical contractor projects; existing data documentation in the LEED certification platform and an in depth case study to explore typical HVAC+R system. The contribution of this study adds to the field of WBLCA where the focus has been the analysis of structural and envelope systems. In the following sections a summary of research findings and a discussion of the implications of each one is presented.

7.2.1 A taxonomy for WBLCA and review of methods

WBLCA is currently a well-established method used to assist building designers in reducing environmental impacts of a building. Different tools are currently available to provide guidance to practitioners on how to carry out the assessment. The proliferation of tools brings numerous challenges to the accuracy and comparability of the studies since the results can vary with regards to which parts of the building were included and the parameter used to describe the study. The first stage of this dissertation presented a systematic review of 16 WBLCA tools. This study found significant differences in key parameter names in each tool to define the goal and scope stage of the assessment (G&S). The G&S phase includes the description of the object of assessment- a building in the case of WBLCA- and is therefore critical in performing WBLCA. Current WBLCA studies do not describe the G&S consistently, hence the results are not comparable. This is due, in part, because the tools used for WBLCA guidance do not provide a consistent list of parameters for the definition of G&S. Given the lack of standardization in WBLCA methods, this research proposes a taxonomy of parameters which could be used in WBLCA reports in the future. This taxonomy serves as the basic list of parameters used to build the database of the research samples in the subsequent stages of the research.

7.2.2 Embodied Carbon Coefficients (ECC) for HVAC+R equipment and distribution material types.

Chapter three discusses how LCA data for HVAC+R for equipment and distribution types presents the same challenges of variation and lack of standardization that have been discussed in the literature in the last two decades. LCA data for HVAC+R systems can be found in published studies, EPD and open databases, however not all of these types of sources present the data in a way that can be integrated into a WBLCA due to several discrepancies. For instance, EPD programs and LCA databases model the data according to ISO standard 15978 or EN 15804 illustrating the results in modules that allow for the structured expression of results over the entire life cycle. Modular presentation of the data enables aggregation with data from other sources and thus enables the use of LCA data into future WBLCA. Data

presented in modular form is available through EPD programs PEP, UL and open databases OKEBAUDAT, INIES and QUARTZ database.

As in most WBLCA studies, LCA data for HVAC+R the largest discrepancies are defined in the G&S stage, specifically in the use of different standards that serve as reference. This leads to important differences in system scope definition, life cycle boundaries, selection of functional units, reference flows lifespans and impact results.

The embodied carbon coefficients (ECC) for HVAC+R equipment and distribution types that are available across the different EPD programs, databases and publishes articles are not always consistent. For instance, In general, life cycle stage A has the best data coverage across all LCA data sources, and represents the largest impact when compared to C, in most cases. LCA data for stages B, C, and D are not available for all types of equipment and distribution types. When data for stage B is included, B is the stage with the highest GWP impact. For the purpose of this study, the results are only presented for life cycle stage A.

The lifespan of the different equipment and material types also varies, small self-contained equipment such as heat pumps, split units typically have a lifespan between 10-15 years, while larger equipment such as AHU, cooling tower and boiler range between 20-25 years. Chillers are the items with the largest lifespan with typically 25-30 years of operational life. No HVAC+R item reported a lifespan larger than 35 years in any of the sources analyzed. The relative short lifespan of HVAC+R equipment compared to the typical referenced service of buildings life ranging between 50 and 60 years (USGBC 2013) in most WBLCA, as seen in Appendix A should be taken into account, since in real life application, the recurring instalments of these systems add up embodied carbon overtime.

For HVAC+R equipment, the capacity of the equipment is a key variable in embodied carbon. In HVAC+R, the cooling or heating capacity of the equipment is calculated with a load calculation of the total cooling and heating requirements of the zone that the system serves. In general, the larger the heating and cooling loads of each zone in the building, the larger the capacity of HVAC+R equipment, the larger the overall weight of the equipment. Since embodied carbon is associated to the total material quantity (weight), HVAC+R equipment with larger capacities have larger embodied carbon per unit of equipment.

7.1.3 HVAC+R systems in existing and new commercial office buildings

In order to understand the different HVAC+R systems types across the commercial building stock in the PNW, this study identifies systems in standard performance buildings (SPB) as different from the ones in high performance buildings (HPB). In the framework of this study a SPB is defined as a building designed under the requirements of the Oregon State Energy Code, while a HPB is defined as a building design

under the requirements of the Washington State Energy Code (WSEC). Chapter 4 characterized the HVAC+R systems for both SPB and HPB, while Chapter 5 describes only systems in HPB, and Chapter 6 analyzes the material quantities of a HPB building in more detail.

In Chapter 5, the sample of twenty LEED registered buildings in Washington State, shows that for most small buildings, the most common type of HVAC+R system are self-contained systems, such as packaged rooftop units (RTUs). In most cases, these RTUs are packaged rooftop heat pumps serving each individual zone in the building. Another type of system used in small buildings is Variable Refrigerant Flow (VRF) systems including heat recovery ventilators. In mid-size and large buildings in the same sample, the most common type of system are High Performance Variable Air Volume Systems (HPVAV). In various buildings in the sample, the centralized system consists of a cooler supporting office by office air handling units (AHU). Each AHU provides conditioned air to all occupied spaces using parallel fan powered terminal units (PFP). Ventilation in primary office space of medium buildings is also provided by roof top units (RTUs).

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7.1.4 Mechanical material quantity estimates (QTOs) in typical HVAC+R Systems

At the core of the simplified method to estimate the embodied carbon of HVAC+R presented in this dissertation is the assessment of the material quantities of each type of HVAC+R system. Table 8.1 shows the results for material quantities across the three exercises presented in this dissertation. This comparison suggests that the results of the in-depth case study is not comparable to other projects. Chapter 4 and 5 provide ranges of material quantities for a sample of hypothetical and LEED registered buildings, respectively. Chapter 4 revealed that material quantities are slightly higher in HPB buildings using Dedicated outdoor systems (DOAS) for energy efficiency compared to SPB buildings across all building size categories, however with no statistical significance. Chapter 5 presented a detailed analysis of the equipment quantities in HPB and show that equipment material quantities were actually significantly lower than equipment quantities in both studies. The results of the studies indicate that the material quantity estimate is sensitive to the method used, therefore this should be taken into account in future validation studies of these results.

Table 7.4 Comparison between the total material quantity results [kg/m²] without refrigerants for the three exercises in this study

Exercise	Sample size	QTOs in SPB [kg/m ²]	QTOs in HPB [kg/m ²]
Ch 4 Advisory Committee	N=16	9.8 - 13.8	11.5 – 17.9
Ch 5 LEED Data	N=20	Not considered	7.19 – 12.7
Ch 6 In depth case study	N=1	Not considered	4.56

In both studies in Chapter 4 and 5, the data is analyzed using a two way ANOVA using material quantities as the dependant variable. The results show that there is no significant difference between the different building sizes. This is not the case for item types, where the test shows that there is a significant difference between refrigerants, equipment and distribution materials. In Chapter 5, the results indicate that there is no significant difference between ductless and ducted systems. There is no significant interaction between building size and HVAC+R item.

Table 7.5 Comparison between the material quantity results [kg/m²] in HPB for equipment, distribution and refrigerant for the three exercises in this study

Exercise	MEQ [kg/m ²]	DMQ [kg/m ²]	Rc [kg/m ²]
Ch 4 Advisory Committee	3.7 - 9.9	6.4 - 9.9	0.02-0.9
Ch 5 LEED Data	0.1- 3.4	6.4 – 9.6	0.01-0.05
Ch 6 In depth case study	2.0	2.6	0.02-0.9

7.1.5 Embodied Carbon (EC) in typical HVAC+R Systems

As indicated in Chapters 4, 5 and 6 the total HVAC+R equipment and distribution sizing is determined by the internal heating and cooling loads. The typical criteria for system sizing include: lighting and equipment loads, occupation density, and wall and envelope glass u-values. In general, the larger the heating and cooling loads are, the larger the capacity of HVAC+R equipment that is required, and thus the larger the overall weight of the equipment, and thus the larger the embodied carbon of the total system. This study demonstrates that the total embodied carbon in HVAC+R depends on total cooling capacity of the building in cooling tons in contrast to the embodied carbon structural systems where there is a direct correlation between building size and the embodied carbon of concrete and steel (De Wolf 2014).

Table 7.6 Comparison between the total embodied carbon results [CO₂e kg/m²] stage A without refrigerants for the three exercises

Exercise	Sample size	EC in SPB [CO ₂ e kg/m ²]	EC in HPB [CO ₂ e kg/m ²]
Ch 4 Advisory Committee	N=16	27.8 – 48.2	35.8 - 60
Ch 5 LEED Data	N=20	Not considered	20.31 – 50.41
Ch 6 In depth case study	N=1	Not considered	21.07

The different studies presented also show that refrigerants play a critical role in whole building life carbon. As shown in Table 8.2, the initial refrigerant charge at the time of instalment is relatively small compared to other material quantities, however the GWP of HFC can account for a large share of the total whole life cycle carbon depending on the leakage rate, as shown in Table 7.4.

Table 7.7 Comparison between the embodied carbon results [CO₂e kg/m²] stage A for equipment, distribution and refrigerant in HPB in three exercises

Exercise	GWP equipment [CO ₂ e kg/m ²]	GWP distribution [CO ₂ e kg/m ²]	GWP refrigerants [CO ₂ e kg/m ²]
Ch 4 Advisory Committee	15.5 -38.7	17.6-30.9	40.45 – 95.23
Ch 5 LEED Data	3.78 - 22.03	18.13 – 32.52	5.7 – 48.5
Ch 6 In depth case study	2.0	2.6	12.24 -157.24

7.1.5 Embodied Carbon (EC) vs Operational Carbon in HVAC+R Systems

Chapter 5 compares the EC and OC results from HVAC+R systems reported in LEED documentation, the results suggest that the operational carbon intensities during the 15 years of service life of the HVAC+R system can represent up to six times the embodied carbon of the systems including the refrigerant leakage as seen in figures 8.1 and 8.2. It is worth noting, that with more stringent energy codes and cleaner energy grids this proportion may change. For instance, the data presented in this study was obtained from LEED templates using the Energy Star portafolio benchmark data, however the performance data for the same buildings reported to the Seattle Benchmark Portafolio show that GHG emissions are half the magnitude compared to the values recorded in LEED templates at the time of design. This differences are due to Seattle emissions using custom emissions factors provided by Seattle City Light and Enwave for electricity and steam, respectively. Seattle City Light (SCL) secures carbon offsets equal to the greenhouse gas emissions resulting from all aspects of SCL’s operations, including those created by the generation of electricity the utility buys, employees’ travel, and the trucks and other equipment used in its operations. Differences in schedules and peaks loads during building operation may also explain this performance gap.

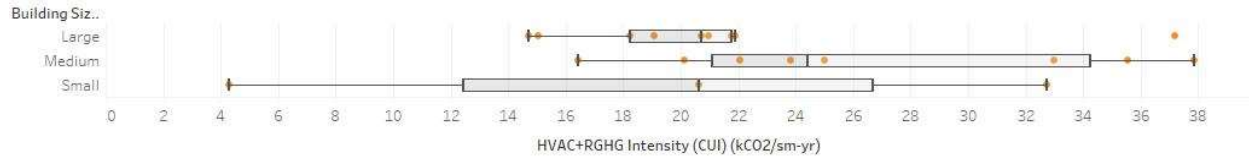


Figure 7.1 HVAC+R Total Carbon Intensity [CO₂e/m²-year] according to each building size category

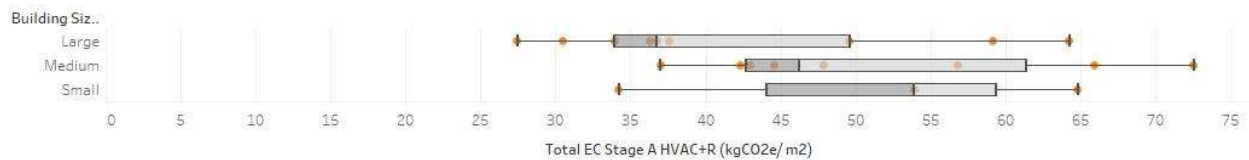


Figure 7.2 HVAC+R Embodied Carbon Intensity [CO₂e/m²] in 15 years according to each building size category

This large contribution of the operational carbon compared to EC found in this study is in line with past studies that indicate that the embodied energy in the HVAC+R equipment from material and manufacture can be large in magnitude, yet small when compared to operational energy impact (Jong Tan and Nutter 2011). Nevertheless, when the different impacts of initial EC in HVAC+R are added over time, the impacts can be significant. More recent LCA studies of HVAC+R equipment demonstrate that building services can represent anywhere from 11% (Bagenal George, Hamot, and Levey 2019) to 15% of initial EC of a typical office building (Cheshire 2014), while recurring EC of building services from 30 years of maintenance and replacement may be six times the value of initial EC (Medas M. et al. 2015).

In line with these findings, this study exemplifies that while HVAC+R system represent a relatively small share compared to other systems (i.e structural), with recurring instalments and lack of refrigerant management across the typical 60 year lifespan of the building, this initial impact can add up overtime and surpass the embodied carbon of other systems as shown in Table 7.8 and Figure 7.3 .

Table 7.8 Embodied Carbon (EC) vs Operational Carbon in HVAC+R Systems for different scenarios

Level	Initial construction	Equip	Distribution	Refrigerants	Operational carbon per year
Low	300	15	17	6	12
Medium	400	20	25	45	24
High	500	39	31	157	36

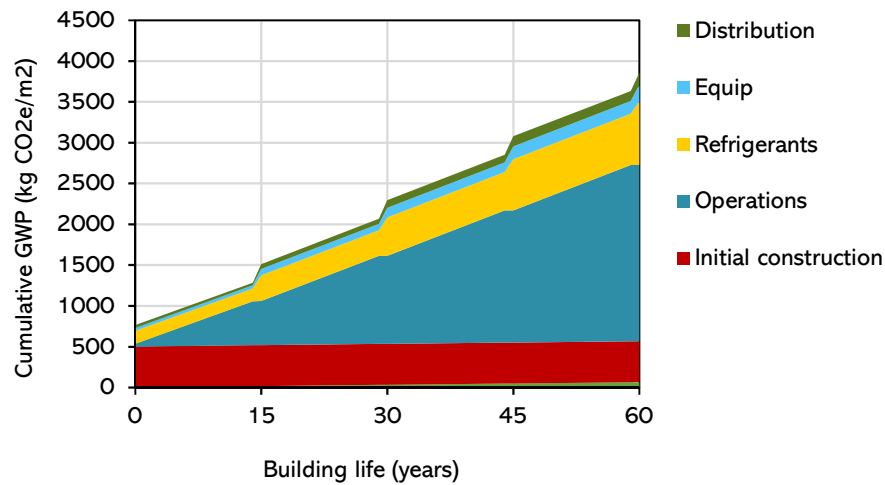


Figure 7.3 Embodied Carbon (EC) vs Operational Carbon in HVAC+R Systems a high impact worst-case scenario (no refrigerant management)

As mentioned throughout the development of the different exercises in this study, in the case of HVAC+R systems, the total equipment and distribution sizing is determined by the internal heating and cooling loads. In general, the larger the heating and cooling loads are, the larger the capacity of HVAC+R equipment that is required, and thus the larger the overall weight of the equipment. This has been discussed in the literature comparing different systems in commercial office buildings where large heating loads also can increase refrigerant charge (Mead 2018).

Larger embodied carbon intensities due to larger heating and cooling loads may also add evidence to the importance on more accurate estimations of heating and cooling loads. As discussed extensively in the literature, historically, HVAC+R sizing has relied on rules of thumb that have worked in construction in past decades, however with more energy stringent energy codes, these rules of thumb have not changed (Burdick 2011). An oversized HVAC+R system increases initial cost, increase OC due to increased energy consumption, and increases initial EC and refrigerant emissions with recurring installments as demonstrated through this study.

In order to meet the 2050 carbon reduction targets to stop and reverse global warming it is critical to address the embodied carbon in buildings. While HVAC+R system represent a relatively small share compared to other systems (i.e structural), with recurring instalments and lack of refrigerant management across the typical 60 year lifespan of the building, this initial impact can add up overtime.

8.2 Limitations of the study

The inherent limitations of this dissertation should be acknowledged in all publications of the data, including the online tool. A summary of the limitations per research stage are as follows:

8.2.1 Limitations on compiling LCA data for HVAC+R equipment and distribution components

As demonstrated in chapter 2, the available LCA data for HVAC+R systems is scarce and comes from different geographical regions; therefore it is not directly comparable. The available LCA data is limited to only some types of HVAC+R equipment and distribution component. Therefore, in order to complete this study, EPD and openly available LCA data from standard equipment was used to represent other equipment of similar material composition and weight.

In order to integrate the existing LCA data more effectively, this study uses only LCA data for HVAC+R for life cycle stage A. Most LCA data offer LCA results for different modules and can not directly aggregated. This study uses only LCA data available in EPD, databases and published journals that can be accessed online.

8.3 Identifying knowledge gaps in the simplified method proposed

The simplified method presented in this study encompasses different component where different types of knowledge gaps and sources of uncertainty are identified. It should be noted that knowledge gaps in material quantity estimations are different from the knowledge gaps in the LCA data for buildings as these are estimated with different methods and have different levels of uncertainty

8.3.2 Knowledge gaps on calculating material quantities of typical HVAC+R systems

In Chapter 2, the material quantities estimation method performed by the Advisory Committee presents several sources of uncertainties. In order to obtain pounds of equipment per square foot of building, several assumptions were made. Some of these assumptions include considering equal capacity of HVAC+R equipment across all building scales. For example, in a 2,000 to 25,000 sf office, the equipment list includes two packaged rooftop heat pumps, each of which weighs 2,000 lb/unit. Those exact same units (also 2,000 lb/unit) would be used for a 10,000-80,000 sf office, but ten units total. This method assumes that the packaged rooftop heat pumps are identical across building sizes, while in reality, mechanical equipment varies in size and capacity, depending on the design requirements.

8.3.3 Knowledge gaps on compiling LCA data of typical HVAC+R systems

The LCA data used for this study in Chapter 3, 4, and 6 are not aligned since different background data software, and assumptions are used across all different sources. LCA methods used for different LCA data may not be consistent since different life cycle stages and calculation methodologies are used. In MEP systems, in particular, functional/declared units and reference flows contain significant variability. For example, under ÖKOBAUDAT database (German), reference flows for mechanical equipment are typically described ‘per unit’ or ‘piece of equipment’, while EPD use ‘one ton of cooling capacity’ (based on an average case 1000-ton centrifugal chiller mode). The conversion of cooling capacity units to kg, adds a significant level of uncertainty to the impact calculation since different number of equipment units with varying levels of capacity and operational weight can serve the same purpose.

HVAC+R equipment uses different names and description across geographical regions. Using and aggregating LCA data from different geographical locations adds uncertainty.

8.4 Future development and future research questions

8.4.1 Validating the results of this study: Material quantities estimates

The simplified method presented in this study encompasses different estimations that could benefit from internal and external validation. At the core of the estimations in the simplified method is the process of calculating the material quantities for both distribution and equipment types in HVAC+R systems. This study proposed three different methods to estimate material quantities: consultation with an advisory committee using historical data from past projects, project data from LEED templates and in-depth material quantity estimation (QTOs) using mechanical drawings. The results of these three approaches proved to be divergent. In the future, additional methods could include for instance the incorporation of more individuals carrying out the QTOs estimation from mechanical drawings in order to cross-check data from at least three sources and confirming it is correct or not.

In order to carry out external validation of the model proposed, a third separate data set can be used, however this data could be reviewed to account for larger similarities with the data set used to develop the simplified method. For instance, buildings should be classified according to the total cooling capacity, which was proven to be a large predictor of the HVAC+R equipment size. The complete method can be replicated using this new data set, or new ‘validation’ data.

8.4.2 LCA data for HVAC+R equipment and distribution components.

With the objective of integrating the impact of HVAC+R systems into WBLCA studies in the future, teams would greatly benefit from more complete LCA data for HVAC+R equipment and distribution components and a more accurate assessment of total refrigerant use for each building type. Future LCA studies for HVAC+R should address the gaps identified in this research summarized in using the same: standards as reference, system scopes definition, life cycle boundaries, selection of functional units, reference flows and lifespans. More comprehensive LCA data for material types and equipment specific for the North America industry is urgently needed.

8.4.3 Accurate estimations of refrigerant charge overtime in HVAC+R in commercial buildings.

Refrigerant quantities throughout the reference service life of a typical buildings are not currently accounted for. The data currently available are based on estimations of initial refrigerant charges for each type of equipment, as shown in Chapter 4. In practice, however, evidence shows that leakages occur both in equipment and distribution around the building. The refrigerant replacement and use after end of life of the equipment could be more accurately quantified with surveys for building managers and commissioners.

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Appendix A WBLCA Method matrix comparison

Appendix B HVAC+R Systems Descriptions

Appendix C Lifespan of typical HVAC+R equipment and distribution types

APPENDIX B HVAC+R Systems Descriptions

This section contains a brief description of each HVAC system described by the Advisory Committee (Table 1) and the different equipment typically used for each one of the systems.

Table 1 Typical HVAC Systems described in the scope of the study

Building Size Category	HVAC system (Standard Performance)	HVAC system (High performance)
XSmall a	Packaged rooftop heat pump	DOAS ERV + VRF
XSmall b	Packaged rooftop AC + Furnace	DOAS ERV + Packaged Rooftop Heat Pump
Small a	Packaged rooftop heat pump	DOAS ERV + VRF
Small b	VAV AHU w/ PFP Terminals	DOAS ERV + Packaged Rooftop Heat Pump
Medium a	VAV AHU w/ PFP Terminals	DOAS + VRF
Medium b	WSHP	DOAS + WSHP
Large a	VAV AHU w/ PFP Terminals	DOAS + Chilled Beam
Large b	WSHP	DOAS + WSHP

1.0 HVAC Systems *_Ducted Solutions*

HVAC Systems for commercial applications are often classified in ducted and ductless solutions (AMCA 2017). Ducted systems have been used in office buildings for decades and are also known as ‘centralized’ solutions. Ductless solutions have been introduced in recent years and encompass a broad myriad of technologies.

1.1 Packaged Rooftop Units (RTUs)

Packaged systems are all-in-one solutions, that can provide heating and cooling in certain regions and small office space where there is limited space for a traditional VAV System. Typically RTUs are further classified in Packaged Rooftop Heat Pump (PRHP)



Fig. 1 Packaged Rooftop Units (image source: <http://www.valentair.com>)

1.1.1 Packaged Rooftop Heat Pump (PRHP)

Packaged heat pump incorporates heat pump technology to provide cooling and heating in the same solution. The heat pump transfers heat by reversing the refrigeration cycle used by a typical air conditioner. Through a cycle of evaporation and condensation, air is heated and pushed over warm coils, is blown through the ductwork to increase the temperature in the interior rooms of each zone (GOODMAN 2018).

1.1.2 Packaged rooftop AC + Furnace (PRAC)

In this type of system, the typical cooling feature associated with an air conditioner uses electricity as its power source and the unit's internal components cycle the refrigerant. Warm air is pulled in by a fan and then passes over the cold evaporator coil, the cooled, dehumidified air is pushed through the ductwork to the various spaces inside each zone (GOODMAN 2018). Packaged rooftop units for light commercial applications typically have capacities between 18– 88 kWth (5 and 25 tons), while larger units range in capacity from 263– 703 kWth (75 to 150 tons) (Goetzler et al. 2016).

1.2 High Performance Variable Air Volume Systems (HPVAV)

HPVAV are systems that perform significantly better than minimally compliant VAV systems (AMCA 2017). HPVAV are characterized by the use of typical VAV equipment with the addition of optimized system control strategies and fan-pressure optimization (Murphy 2011). HPVAV also called High Performance Air Systems (HPAS) typically include heat recovery and efficient fans and capacity control (Smith 2013) .

HPVAV and ductless technologies have been compared extensively in the literature. In response to exotic alternatives that are gaining popularity as high-efficiency systems, a study demonstrated that if air systems such as High Performance Rooftop (HPVAV) are correctly installed, these typically cost less than piped systems such as Variable Refrigerant Volume (VRF), and consume up to 20% less energy (Smith 2013).

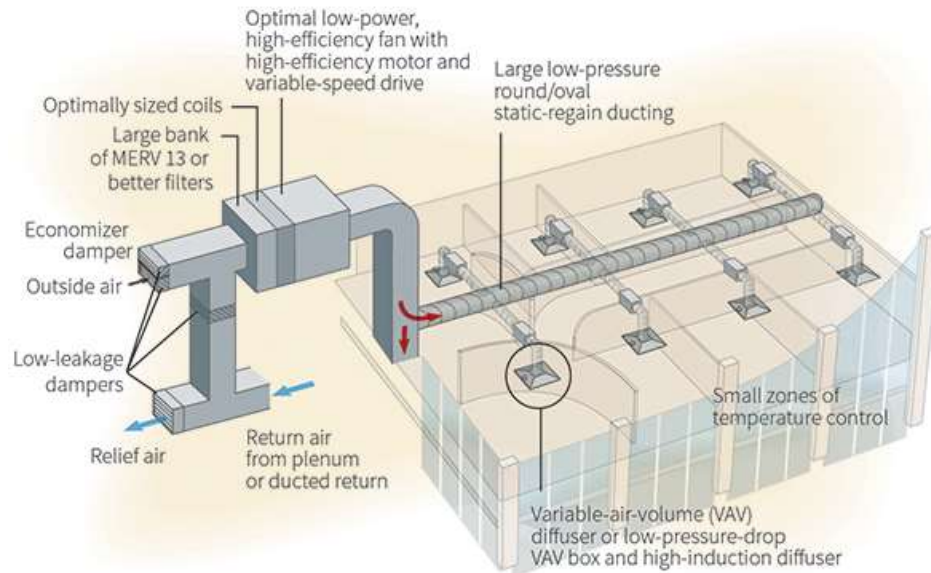


Figure 2: High-performance variable-air-volume (VAV) system (AMCA 2017)

1.2.1 VAV AHU w/ PFP Terminals

Variable air volume (VAV) systems are air systems that vary their supply air volume flow rate. This mechanism satisfies different space heating/cooling loads, maintains predetermined space air temperature and humidity for thermal comfort, and conserves fan power (Yao et al. 2007). There are two types of VAV systems, namely packaged VAV using direct-expansion cooling coils, and central VAV using chilled-water cooling coils (Yu et al. 2016). Many VAV systems supply air with a constant temperature and recirculate a portion of the returned air (Engdahl and Johansson 2004).

2.0 HVAC Systems _Ductless Solutions

Ductless systems pipe a refrigerant or chilled water into occupied spaces for zone heating and cooling without requiring the ductwork of typical ducted systems, typically these systems use a secondary ventilation system to meet outside air needs(AMCA 2017).

2.1 Variable Refrigerant - Multi Split Systems (VRF)

VRF is a ductless refrigerant system that varies the refrigerant flow rate with the help of the variable speed compressor and electronic expansion valves (EEVs) located in each indoor unit to meet the space cooling or heating load in order to maintain the indoor set temperature (Aynur 2010). The VRF system is an outgrowth of the “multi-split” systems used in residential applications. The big difference between VRF systems and conventional HVAC systems is that they adjust cooling/heating output by modulating the refrigerant flow continuously with the variable speed compressor (Liu and Hong 2016). It is worth noting that VRF is also commonly known as VRV, however this is a trademark of Daikin, a leading VRF manufacturer. VRF is a generic term used by the construction industry.

A multi-split air VRF conditioning system, consists of one outdoor and multiple indoor units, and can therefore satisfy the same needs for the installation of several individual units with less space (Wu, Xingxi, and Shiming 2005). Fig. 3 displays a typical multi-split VRF system that has multiple indoor units, where the indoor units (located in each zone) are connected to the outdoor unit in parallel with the refrigerant pipes.

The multi-split VRF system can be used for both air conditioning (cooling mode) and heat pumping (heating mode) according to the season (Aynur 2010). There are two types of VRF systems available, heat pump (HP) and heat recovery (HR). HP VRF provides either all heating or all cooling to multiple zones at a time. HR VRF provides heating and cooling simultaneously to multiple zones with various cooling or heating demand. The VRF system is further categorized into air-source VRF and water-source VRF depending on what heat sink/source is used for the outdoor unit (Liu and Hong 2016).

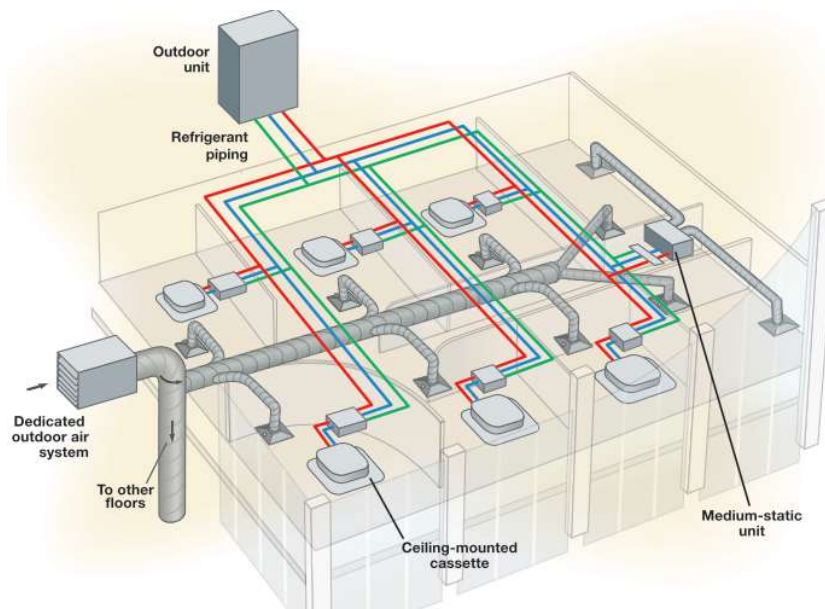


Figure 3: VRF system (AMCA 2017)

Studies comparing the cooling energy used between VAV and VRF indicate that the cooling energy consumed by VRF systems was up to 70% lower than that consumed by VAV systems (Yu et al. 2016).

2.2 Water Source Heat Pump (WSHP)

WSHP systems rely on a large piping loop that moves water used to reject the heat. The large piping loop combines water-source heat pumps with a heat rejector and a boiler. WSHP are used to provide comfort in a wide range of climates. The system utilizes energy-conserving, heat-recovery capabilities to transfer heat from one area to another to meet individual zone requirements. If used with system design and control strategies, the systems is one of the most energy efficient for commercial spaces.

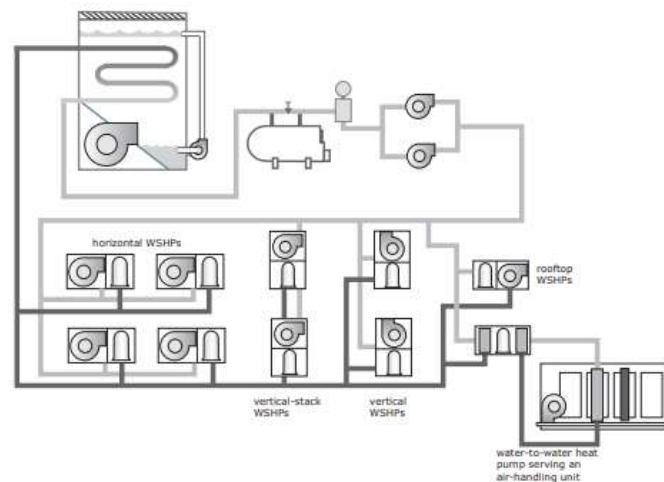


Figure 1: Water Source Heat Pumps (WSHP) (TRANE 2018)

2.3 Fan coil Units (FCUs)

FCUs can serve the function of cooling, heating or both through a water coil contained in a factory made-cabinet assembly located directly in the room or hidden behind a wall or ceiling (Wujek and Dagostino 2010). FCUs are relatively simple and inexpensive systems commonly used in commercial, institutional and multifamily residential buildings(Pourarian et al. 2017). FCUs are widely used in central air-conditioning systems, especially in office buildings around the world, therefore most studies or patents related to FCUs have been presented in recent years (Tianyi et al., 2011).

2.4 Chilled Beams

Chilled beams are modern terminal devices designed to be mounted in the ceiling that have room air circulate through coil fed by chilled or hot water (Wujek and Dagostino 2010). Chilled beams differ


from radiant chilled ceilings in that they transfer heat primarily via convection instead of radiation. Similar to radiant chilled ceilings, to date, chilled beams have been used primarily in Europe and, to some extent, Australia. Chilled beams come in two distinct architectures: passive and active (Roth et al., 2007).

2.5 Dedicated Outside Air Systems with Energy Recovery (DOAS + ERV)

A DOAS is a system where the ventilation is managed independently of the primary heating and cooling system. DOAS optimizes the operational energy efficiency, by separating ventilation from space conditioning, mechanical systems, and it has been included in the most recent energy efficiency standards. For instance, under the WSEC 2015, a DOAS is required for every HVAC system. An energy recovery ventilator (ERV) is employed to make mechanical ventilation most efficient by transferring energy between the outdoor air and the building exhaust air.

3.0 Typical Equipment and Material types

3.1 Typical Equipment and Material Types for HVAC

Equipment	Description	Image
Packaged Units AC	<p>Casing: Unit casing shall be constructed of zinc coated, heavy gauge, galvanized steel</p> <p>Compressors: All 3 ton standard units shall have direct drive, hermetic, reciprocating type compressors</p> <p>Refrigerant Circuits: Each circuit offers a choice of independent fixed orifice expansion devices or thermal expansion valve.</p> <p>Evaporator and Condenser Coils</p> <p>Internally finned, 5/16” copper tubes mechanically bonded to a configured aluminum plate fin shall be standard</p> <p>3-10Tons – 60 Hz (W: 480- 1060lbs.)</p> <p>Source: Trane</p>	

Packaged
Units Pump

Casing: Unit casing shall be constructed of zinc

coated, heavy gauge, galvanized steel.

Refrigerant Circuits: Each refrigerant circuit has independent fixed orifice or thermostatic expansion devices.

Evaporator and Condenser Coils:

Internally finned, 3/8" copper tubes mechanically bonded to a configured aluminum plate fin shall be standard.

3-10Tons – 60 Hz (W: 589- 1431lbs.)

Source: Trane



DOAS ERV
w/ electric
heat

Energy Recovery Unit Ventilator (ERS)

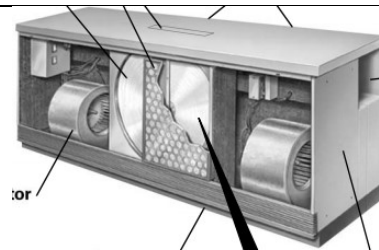
Cabinet: The unit cabinet is a durable, furniture quality steel with exposed edges rounded. Cabinet insulation is a foil faced, acoustically and thermally lined insulation.

Motor: is a permanent split capacitor type, 3-speed motor, resiliently mounted with integral thermal overload protection and permanently lubricated ball.

Fans: Centrifugal forward-curved, double-width, double-inlet corrosion resistant wheels, statically and dynamically balanced, direct driven.

Heat Exchanger: The total energy recovery wheel is constructed of two separate air streams flowing in a counter flow configuration. 500 CFM W: 331 lbs.

Source: Trane



VRF outdoor units Factory-assembled, single-piece, air-cooled outdoor unit. Contained within the unit enclosure shall be all factory wiring, piping, controls, and the multiple inverter-driven twin rotary compressors.

W: 882 lbs.

Source: Toshiba Carrier



VRF cassettes Zinc hot dipping steel plate

W: 42-48lb

Source: Toshiba Carrier



VAV AHU w/ DX Central equipment that regulate and handles air (thermal, humidity and IAQ treatment) that is supplied to the building ductwork. AHU can be compact, modular, DX, packaged or rooftop.

Commercial Packaged Air Handling Unit with Direct Expansion 2,400 to 6,000 Cfm (1150 to 5650 L/s), Nominal Airflow, 6 to 25 Tons (21 to 105 kW), Nominal Cooling

Cabinet: Indoor mounted, draw-thru, packaged air-handling unit that can be used in a suspended horizontal configuration or a vertical configuration. Unit shall consist of forward-curved belt-driven centrifugal fan(s), motor and drive assembly, pre-wired fan motor contactor, factory-installed refrigerant metering devices (direct-expansion coil units), cooling coil, 2-in. (51-mm) disposable air filters, and condensate drain pans for vertical or horizontal configurations.

Cabinet: shall be constructed of mill-galvanized steel.



DX coil is 4-row and consists of copper tubes with sine-wave aluminum fins bonded to the tubes by mechanical expansion. DX coils feature factory installed thermostatic expansion valves (TXVs) for refrigerant control. The TXVs are Puron R-410A compatible.

W: 730-1062lbs

Source: Toshiba Carrier

VAV Terminals w/ electric heat Terminal Units (ATU) regulate the quantity and temperature of air delivered to a zone. Single duct VAV electric heater design product label includes tagging, airflow and electrical information 2) Mechanical lock construction ensures lowest possible casing leakage 3) Roll formed inlet collar with integral stiffening ribs adds strength and rigidity 4) Electrical devices installed within a electric control box enclosure, with single point power connection



W: 0.65kg (1.45lb)

Source: Johnsons controls

Cooling tower Stainless Steel towers are factory assembled, crossflow cooling towers, designed to serve air conditioning and refrigeration systems as well as industrial process loads and power applications on clean water.



W: 226 kgs.

Source: Marley

Boiler	<p>Commercial gas boiler sections are made of durable cast iron for long life</p> <p>W:1100-6500 lbs</p>	
DOAS w/ heat recovery	<p>Indoor and rooftop • 100% outside air packaged units • Single or 2 panel two tunnel with exhaust air • Energy recovery systems • EC motors for energy savings • Programmable microprocessor controls • Custom factory assembled, full thermal break enclosures</p> <p>Sizes from 1,000 to 25,000 cfm •</p>	
Single duct VAVs or CAVs	<p>Model TSS terminals provide variable air volume (VAV) control beyond the typical single duct box</p> <p>W: 0.65kg (1.45lb)</p> <p>Source: Johnsons controls</p>	
VRF fan coils	<p>The unit includes a chassis, coil, fan wheel(s), fan casing(s), fan board, and motor(s). The chassis construction is 18-gauge galvanized steel, and continuous throughout the unit. The unit is acoustically and thermally insulated with closed-cell insulation. All panels are made rigid by channel forming. All panels are 18-gauge galvanized steel, including the bottom panel.</p>	

The hinged access door is flush with front panel. Bottom panels ship with tamperproof screw fasteners and safety chain.

Source: Trane

Distributed Zone WSHP 24 to 60 MBtuh - 60 Hz

Distributed Pumping System A distributed pumping system contains a single pump module connected directly to the unit's supply and return. This module is typically field installed and piped to the unit. This design requires individual pump modules specifically sized for the flow requirement of the water-source heat pump. When the heat pump compressor turns off, the individual pump also turns off.

W: 323-546 lb

Source: Trane

Air Cooled Chiller or Water Cooled Chiller + Cooling tower 350–570 to 1470–1720 NTON (60 hz)

Casing: close-grained cast iron are used on the centrifugal compressor.

Compressor motors: are hermetically sealed two-pole, squirrel cage induction-type (except for model CVHS chillers, which use a permanent magnet motor—a specially designed, eight-pole motor suitable for unit inputs of low voltage 60 or 50 Hz, three phase current).

W: 19319 to 63486 lb

Source: Trane



Cooper Pipe For water plumbing across all building size categories



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APPENDIX B Lifespan of typical HVAC+R equipment and distribution types

According to the Building Owners and Managers Association International (BOMA) the following Tables 10 and 11 average useful life years of the equipment considered for this study:

Table 12: Average Useful Life Years per Type of HVAC Equipment (Schoen 2010)

Equipment	Average Useful Life Years
1. Packaged units	18
2. DOAS ERV w/ electric heat *	25
3. VRF outdoor units *	15
4. VRF cassettes*	17
5. VAV AHU w/ DX	25
6. VAV Terminals w/ electric heat*	17
7. Cooling tower	10
8. Boiler	18
9. DOAS w/ heat recovery*	12
10. Single duct VAVs or CAVs*	25
11. VRF fan coils	20
12. Distributed zone WSHP	15
13. Air Cooled Chiller or Water Cooled Chiller + Cooling tower	20
14. Pumps	15

Table 13: Average Useful Life Years per Type of Electrical Equipment (Schoen 2010)

Equipment	Average Useful Life Years
1. Non-metallic boxes	NA
2. LED fixtures	20
3. Fixtures	20
4. Battery 20W Unit	5
5. Battery	5
6. Occupancy sensors	10
7. Daylight sensors	10
8. MC Cable (metallic cable)	40

9. Copper feeders	40
10. Metal boxes	20
11. Code minimum time clock, 0.68 lbs/EA	NA
12. Data/WAP (Wireless)	NA
13. DATA/AV/Access CNTRL	NA
14. Feeder Wire	40
15. Aluminum feeders 100amp and over	NA
16. FA	NA
17. Basic Service Switchgear	25
18. D-Rings 0.15 lbs/EA	NA
19. Transformer	30
20. Transformer Vault	30
21. Backup Generator	20
22. Non-Metallic Cable	40
23. EMT Conduit	40
24. Energy meters, 0.59 lbs/EA	20

Table 14.- Average Useful Life Years per Type of Plumbing Materials (Schoen 2010)

Material Type	Average Useful Life Years
1. Cast iron pipe	30
2. PEX water pipe	30
3. PVC	30
4. Cooper pipe	30
5. Stainless Steel	NA