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Mechanical, electrical, plumbing and tenant improvements over the building lifetime: Estimating material quantities and embodied carbon for climate change mitigation

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ABSTRACT

The building industry is expanding its ability to mitigate the environmental impacts of buildings through the application of life cycle assessment (LCA). Most building LCA studies focus on core and shell (C&S) and rarely assess mechanical, electrical, and plumbing (MEP) and tenant improvements (TI). However, C&S typologies in the commercial sector pose particular challenges to achieving net zero carbon due to the numerous renovations these building undergo through during their service life. MEP and TI are installed multiple times over the lifetime of commercial buildings leading to cumulative environmental impact caused by increasing material quantities and embodied carbon (EC). This study aimed to establish a preliminary range of material quantities and embodied carbon impacts for MEP and TI components, focusing on commercial office buildings in the Pacific Northwest. The first research stage involved quantifying material quantities while a second stage aimed to calculate Embodied Carbon Coefficients (ECC) and LCA impacts using different data sources. The embodied carbon estimates ranged from 40 to 75 kg CO_2e/m^2 for MEP and 45–135 kg CO_2e/m^2 for TI. However, with recurring instalments during a life span of 60 years the impacts become comparable to known impacts of core and shell systems.

1. Introduction

Policy efforts are increasing around the world to make all new buildings operate at net zero carbon by 2030, and all existing buildings operate at net zero carbon by 2050 [33]. Achieving these goals will require the reduction of whole building life carbon, which is the sum of operational carbon (OC) and embodied carbon (EC). EC encompasses the greenhouse gas (GHG) equivalent of producing, procuring, and installing the materials and components that make up a building and includes lifetime emissions from maintenance, repair, replacement and ultimately demolition and disposal [24]. Achieving a carbon-free environment requires the explicit incorporation of embodied impacts of construction products in all stages of its life and in its broader sustainability assessment [19]. According to several studies, the importance of embodied energy and EC has been increasingly recognized in the last decade because the percentage of relative OC is expected to decrease in the future due to the implementation of more efficient technologies [22], more advanced and effective insulation materials, and more energy-efficient equipment and appliances [13].

In this context, the most influential material-related parameters for environmental performance have been identified as material choice, building lifetime, and material service life [23]. Building material reuse stands as one of the most cost-efficient opportunities for mitigating EC while reducing landfilled material and conserving natural resources. According to a recent report, emissions from the material cycle of residential buildings in the G7 and China could be reduced by at least 80 per cent in 2050 through a series of material efficiency strategies [11]. Specific to the US, demolition waste from commercial renovation accounts for over 20% of the total construction and demolition waste stream [7]. The US Environmental Protection Agency (US EPA) employs a process called Sustainable Materials Management (SMM) to reduce material use. By examining how materials are used throughout their life cycle, an SMM approach seeks to use materials in the most productive way with an emphasis on using fewer materials and products, and reducing environmental impacts throughout the life cycle of a material [30].

Life cycle assessment (LCA) methods are still not commonly used in design practice, due in part to a lack of demand from

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building owners. The high cost of using LCA methods contributes to their low utilization at early design stages, and collaboration challenges between architects and engineers undermine the benefits of LCA [15].

In addition to these implementation constraints, most building LCAs focus solely on structure and enclosure (core and shell) but rarely assess interior work such as mechanical, electrical, and plumbing (MEP) and tenant improvements (TI). The manufacturing of building construction materials used in core and shell, such as steel, cement and glass accounts for 11% of process-related carbon dioxide (CO2) emissions in 2018 [9]. A recent review of LCA studies taking into account more than 1000 datapoints concluded that the building scope was not consistent and that most studies did not include MEP, TI, and sitework in the analysis [29].

However core and shell building typologies face particular challenges caused by the numerous upgrading these building undergo through during their service life. Tenant improvements (TI) refers to the customization done to a space to meet the needs of a new tenant and involves the upgrading of finishes, furniture and partitions. Mechanical, electrical and plumbing (MEP) systems can also be replaced as part of large energy retrofits in commercial office buildings [17]. Both TI and MEP upgrading should not be confused with typical maintenance and repair during the service life which typically involves the replacement of a particular equipment and may be done on a regular basis [26].

One critical source of uncertainty is related to and interior tenant improvement work. Currently, there exists very little data on the environmental impact of these components. However, these impacts may be significant because MEP and TI are often installed during building re-use and renovation, which may occur numerous times over the lifespan of a building. In retrofit schemes, the proportion of embodied carbon related to building services can be considerably higher [18].

This important omission of MEP and TI from LCA studies can be explained by two reasons. First, MEP and TI impacts can be difficult to quantify,. Some of the main problems that practitioners struggle with are time taken for the collection of data and the complexity of the LCA method [6]. This can be even more challenging in the case of MEP and TI where different equipment and material types are employed. In recent years, actions to overcome these barriers have emerged, including methods and tools that offer a simplified approach to conduct an LCA, reducing the time-consuming process of the life cycle inventory phase [10].

A second common explanation to omit MEP and TI from LCA studies is that the impacts from these systems appeared to be relatively low in earlier studies thus these systems are typically overlooked. A review developed by Tan and Nutter, indicated that the embodied energy in the heating, ventilation, air-conditioning, and refrigeration (HVAC + R) equipment from materials and manufacturing can be large in magnitude, yet small when compared to operational energy impact [14]. However, more recent LCA studies of HVAC + R equipment demonstrate that MEP can contribute anywhere from 11% [2] to 15% of the initial EC of a typical office building [5], while recurring EC of MEP from 30 years of maintenance and replacement may be six times the value of initial EC [20]. Another recent 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 [12].

MEP and TI impacts can be significant if differences in service life between equipment and whole building service life are considered. According to the Building Owners and Managers Association International (BOMA) most MEP equipment last no longer than 15 years, with only some plumbing materials having a maximum service life of 40 years [26]. The lifespans of different equipment and material types also vary. For example, small self-contained equipment, such as heat pumps and split units, typically have a lifespan of 10 to 15 years, while larger equipment such as air handling units (AHU), cooling towers, and boilers range between 20 and 25 years [16].

In addition to the short service life, products that experience rapid technological development, such as light-emitting diode (LED) lamps and fixtures, will be outdated by new products long before obsolescence. In other words, their actual lifetimes will be much shorter than they were designed to be (typically 50,000 h) because they will be eventually replaced by better LEDs (which overall will improve the customer experience but at a larger cost due to premature bulb replacement) [35]. The relative short lifespans of most MEP and TI equipment compared to the typical referenced service lifetime of buildings, which ranges between 50 and 60 years [31] in most whole-building LCAs (WBLCAs), should be taken into account, since in real-life applications, the recurring installments of these systems contribute to embodied carbon over time.

A better understanding of the material embodied carbon impact of MEP and TI can lead to innovative models in the building industry. As a vision of the future, the lighting industry, for instance, could have a paradigm shift and move towards circular economy, using artificial intelligence and new sensors, and rethink the luminaires, such as the "LED lighting leasing model" under which instead of selling luminaires and control systems, the lighting industry leases lighting systems or quality of lighting at a "pay-per-lux" model [34].

Commercial office buildings in the Pacific Northwest Region offer a unique sample of core and shell types and novel HVAC + R systems. Washington, in particular, is one of the states with the largest number of LEED certified projects in the United States [32]. Within Washington State, the city of Seattle has a large tradition of environmental stewardship which is reflected in innovative green building policy adoption. Since 2008, the city of Seattle is one of the leading cities around the world in developing outcome based energy code, focused on compliance through verified energy performance [8].

In the United States local 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) [25]. 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 [3]. The current 2015 Seattle Energy Code (SEC), is more stringent than the last version of ASHRAE Standard 90.1-2016 and came into full effect on Jan. 1, 2018.

The SEC requires the incorporation of current high efficiency mechanical systems such as dedicated outdoor air system (DOAS), variable refrigerant flow (VRF), and heat pumps. Under the SEC commercial code, the proposed building is compared to the energy model of a reference building with high efficiency Dedicated Outdoor Air Mechanical Systems [DOAS] and needs to be between 7 and 13% more efficient than the reference model depending on the amount of measures taken [27]. These additional requirements imposed on traditional HVAC + R design, would also contribute to embodied carbon as demonstrated in previous studies [18].

The present study aimed to establish a preliminary range of plausible embodied carbon impacts for MEP and TI components, focusing on commercial office buildings in the Pacific Northwest (PNW) region of the US. The objective is to contribute to a better understanding and provide estimates of the EC of MEP and TI systems in typical commercial buildings. In order to achieve this objective this study uses two sources of building data. The MEP and TI portions of the study used different types of data and methods to estimate material quantities for each type of system. While the MEP portion of the study followed a consultation process with local MEP engineers and contractors, the TI portion of the study estimated material quantities by performing quantity take-offs on architectural drawings of five office projects in the PNW.

This paper summarizes the study results, compares findings with other benchmark studies, and discusses their implications.

2. Materials and methods

2.1. Scope

The scope of this study was different for MEP and TI. Components of MEP in this study included:

- Mechanical: equipment and ductwork for heating, ventilation, and air-conditioning (HVAC) systems
- Electrical: generators, batteries, electrical service and distribution, wiring devices, and lighting fixtures for electrical systems
- Plumbing: domestic water piping and sanitary sewer piping for plumbing systems

It should be noted that MEP estimates did not include the impacts of refrigerants, which could be significant, nor plumbing fixtures and fittings.

The scope of TI included:

- Finishes: ceiling, flooring, painting, and interior glazing
- Furniture: chairs, cubicles, tables, private offices, sofas, and shelving
- Fixtures: cabinets, counters, doors, and partition walls (both fixed and operable)

2.2. Methodology

2.2.1. Calculating material quantities

The MEP and TI portions of the study used different methods to estimate material quantities. Generally, the MEP portion of the study estimated material quantities by developing eight hypothetical buildings in consultation with local MEP engineers and contractors. The TI portion of the study estimated material quantities by performing quantity take-offs on architectural drawings of five office projects in the PNW.

For the MEP portion of the study, an Advisory Committee was convened through personal invitations to well-known MEP contractor companies in the PNW. Once the advisory committee was established, the first step was to propose several hypothetical building models that would represent typical commercial office buildings in the PNW. Based on these hypothetical buildings, the advisory committee proposed a series of typical MEP systems and finally listed typical equipment and material types for each system as shown in Tables 1 and 2.

As the second step of the process, the advisory committee recommended to distinguish between standard and high-performance buildings. Within the PNW, the current 2015 Washington State Energy Code (WSEC) is more stringent than the 2014 Oregon Energy Efficiency Specialty Code (OEESC). Therefore

Table 1
Standard Performance Building (SPB) models to estimate quantities in MEP Systems categorized by building size as proposed by the advisory committee.

Performance Category	Area range (m^2)	Plumbing systems	HVAC systems	Electrical systems
Standard Large a	11,148–74,322	Water: Copper Waste & Vent: Cast Iron	VAV AHU w/PFP Terminals	Commercial LTG/PWR
Standard Large b	11,148–74,322	Water: Copper Waste & Vent: Cast Iron	WSHP	Commercial LTG/PWR
Standard Medium a	1858–27,870	Water: Copper Waste & Vent: Cast Iron	VAV AHU w/PFP Terminals	Commercial LTG/PWR
Standard Medium b	1858–27,870	Water: Copper Waste & Vent: Cast Iron	WSHP	Commercial LTG/PWR
Standard Small a	929–7432	Water: Copper Waste & Vent: Cast Iron	Packaged rooftop heat pump	Commercial LTG/PWR
Standard Small b	929–7432	Water: Copper Waste & Vent: Cast Iron	VAV AHU w/PFP Terminals	Commercial LTG/PWR
Standard XSmall a	185–232	Water: Copper Waste & Vent: Cast Iron	Packaged rooftop heat pump	Basic LTG & Power
Standard XSmall b	185–232	Water: Copper Waste & Vent: Cast Iron	Packaged rooftop AC + Furnace	Basic LTG & Power

Table 2
High-Performance Building (HPB) models to estimate typical in MEP Systems categorized by building size as proposed by the advisory committee.

Performance Category	Area range (m^2)	Plumbing systems	HVAC systems	Electrical systems
HP Large a	11,148–74,322	Water: Copper, Waste & Vent: Cast Iron	DOAS + Chilled Beam	Commercial LTG/PWR
HP Large b	11,148–74,322	Water: Copper, Waste & Vent: Cast Iron	DOAS + WSHP	Commercial LTG/PWR
HP Medium a	1858–27,870	Water: Copper Waste & Vent: Cast Iron	DOAS + VRF	Commercial LTG/PWR
HP Medium b	1858–27,870	Water: Copper Waste & Vent: Cast Iron	DOAS + WSHP	Commercial LTG/PWR
HP Small a	929–7432	Water: Copper Waste & Vent: Cast Iron	DOAS ERV + VRF	Commercial LTG/PWR
HP Small b	929–7432	Water: Copper Waste & Vent: Cast Iron	DOAS ERV + Packaged Rooftop Heat Pump	Commercial LTG/PWR
HP XSmall a	185–232	Water: Copper Waste & Vent: Cast Iron	DOAS ERV + VRF	Commercial LTG/PWR
HP XSmall b	185–232	Water: Copper Waste & Vent: Cast Iron	DOAS ERV + Packaged Rooftop Heat Pump	Commercial LTG/PWR

a "standard performance building" (SPB) is defined as a building designed under the OEESC compared to a "high-performance building" (HPB) built under the WSEC.

Next, the advisory committee recommended to use building size as a key variable to classify different MEP systems. Building sizes expressed in total area (gross square footage) determined design requirements and types of MEP systems. These eight hypothetical buildings were classified into four size categories (Large, Medium, Small, and XSmall) and two energy performance categories.

Lastly, MEP systems were inherently different and have diverse levels of equipment complexity and material selection. Plumbing was the least complex of the three systems and was defined primarily by the selection of piping material rather than particular equipment. HVAC and electrical systems were much more complex systems with many intricate components. For this study, only one of the most representative HVAC systems was considered for each one of the four building size categories.

As a result, sixteen building models were established, eight SPB and eight HPB as shown in Tables 1 and 2. Descriptors "a" and "b" under "Performance Category" refer to two different HVAC types per building size. Acronyms used in the table are as follows:

- VAV AHU: Variable air volume air handling unit
- PFP: parallel fan terminals
- LTG/PWR: Lighting/power
- WSHP: Water-source heat pump
- HP: High-performance
- DOAS: dedicated outdoor air system
- VRF: variable refrigerant flow

Table 3
Description of building projects to estimate TI material quantities.

Project ID	Total floor area		Number of floors	Average area per floor		TI intensity	Number of occupants	Occupant density (people/sf)	Geographic location
	(sf)	(m^2)		(sf)	(m^2)				
1	94,208	8757	4	23,552	2189	Unknown	399	0.0037	Washington
2	136,986	12,733	7	19,569	1819	Unknown	103	0.0027	Washington
3	2865	266	2	1433	133	Low	60	0.0209	Oregon
4	25,842	2402	1	25,842	2402	Medium	257	0.0080	Washington
5	75,000	6971	2	37,500	3486	Low	656	0.0087	Oregon

Table 4
Data sources for TI items considered in this study. * indicates items or measures that excluded data with inconsistent units. "N.A." = "North America."

Relevant item from QTO	Product name	Source name	Type of source	Year	Region
acoustical panel	Acoustical Ceiling Panels (mineral fiber)	Quartz	Database	2015	N.A.
basic office	Cadence® Desking (approx. floor area 120 sf)	Allsteel	EPD	2016	N.A.
carpet	Carpet Tile	Quartz	Database	2015	N.A.
ceiling panel suspension system	Suprafine® XL® Suspension System – Steel	Armstrong	EPD	2014	N.A.
chair (average of 3 products)	• New Aeron® Chair • Mirra® 2 Chair • Caper ® Stacking Chair	Herman Miller Herman Miller Herman Miller	EPD EPD EPD	2016 2014 2014	N.A. N.A. N.A.
concrete sealant	Concrete Sealant	Quartz	Database	2015	N.A.
cubicle	Terrace® Open Plan Workstation(approx. floor area 45 sf)	Allsteel	EPD	2016	N.A.
door types 1–5 (wood door)	Wood door leaf, production-weighted average	Masonite Architectural	EPD	2016	N.A.
door type 6 (hollow metal door)	Metal door leaf, hollow core, production-weighted average	Steel Door Institute	EPD	2017	N.A.
doors, all types	Steel Door Frame	Ambico	EPD	2017	N.A.
GWB ceiling	5/8″ Fire-Rated Type X Gypsum Board	Athena	Database	2018	N.A.
interior glazing, doors	Laminated Glass	Quartz	Database	2015	N.A.
interior glazing	Anodized Aluminum Curtainwall Extrusion	Quartz	Database	2015	N.A.
laminate casework* (sum of 2 products)	• High pressure laminate (HPL compact) • Particleboard	Formica AWC, CWC	EPD industry average EPD industry average	2017 2013	Europe N.A.
linoleum	Linoleum Flooring	Quartz	Database	2015	N.A.
metal ceiling panels (average of 2 products)	• Aluminum specialty products • Galvanized Steel Ducts	CISCA Quartz	EPD industry average Database	2014 2015	N.A. N.A.
operable partition*	MOVEO Fullwall Element	Dorma	EPD	2012	Europe
paint	Low VOC Eggshell Acrylic Paint	Quartz	Database	2015	N.A.
partition wall (sum of 3 products)	• Steel Studs • Drywall (Natural Gypsum) • Thermafiber® Mineral Wool Insulation Light Density (without facing material)	Quartz Quartz Thermafiber	Database Database EPD	2013 2015 2014	N.A. N.A. N.A.
server racks	Steel Plate	Athena	Database	2018	N.A.
sheet vinyl*	Heterogeneous Vinyl Sheet	Armstrong	EPD	2014	N.A.
sofa	UP 3 seat sofa with backrest	Fora Form	EPD	2017	Europe
solid surface countertop*	Richlite Countertops	Richlite	EPD	2012	N.A.
table*	Desk Nova U (approx. surface area 11 sf)	Narbutas	EPD	2017	Europe
tile*	Ceramic Tile	Tile of Council of N. America	EPD industry average	2014	N.A.
VCT*	Vinyl Composition Tile	Armstrong	EPD	2014	N.A.
wall rubber base*	Rubber Wall Base (4″ high)	Roppe	EPD	2018	N.A.
wood flooring*	New hardwood flooring	USDA [4]	Research paper	2013	N.A.
wood slat ceiling*	WoodWorks® Tegular, Vector® and Concealed Ceiling Panels (includes metal suspension system)	Armstrong	EPD	2017	N.A.

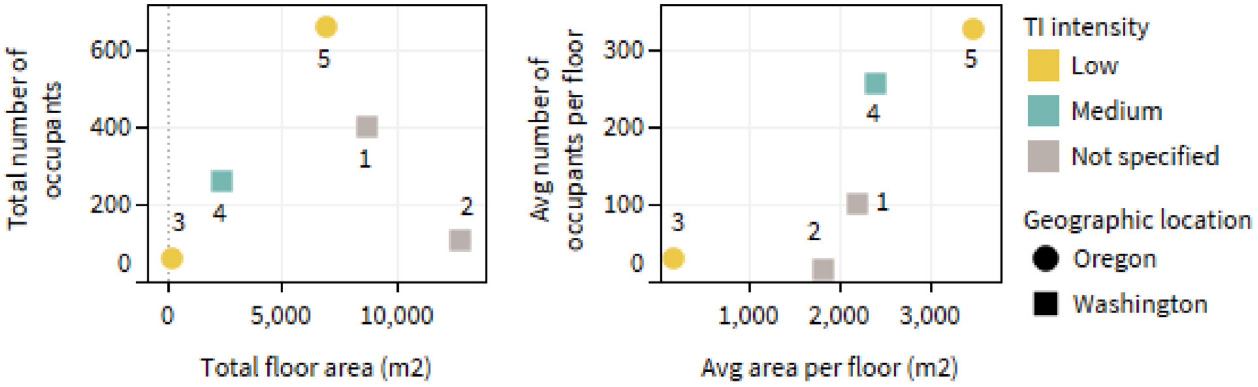

Fig. 1. Number of occupants vs floor area for overall project (left) and average per floor (right) for projects in this study, labeled by project ID.

- ERV: energy recovery ventilator
- Waste & Vent: wastewater and ventilation

The TI portion of the study estimated material quantities by performing quantity take-offs (QTOs) on architectural drawings of five office projects in the PNW. In order to obtain the architectural drawings, the research team contacted industry professionals to request architectural drawings or bills of materials. Responders to this query, or industry participants, agreed to provide sample projects under the condition that the identities and details of their projects would not be published, and that the project plans and data would not be shared outside of the research team.

The collected projects considered in this study are shown in Table 3. Projects 1, 2, and 5 were conventional office spaces in the form of traditional "cubicle farms" or open offices. Project 3 was a small office area within a larger non-office complex, while Project 4 was a medical office. These last two projects were not traditional commercial office spaces, but the research team decided to include them to expand the number of projects in this study (Table 4).

The project sizes in terms of floor area and number of occupants are shown in Fig. 1.

The process for performing QTOs consisted of the following steps. First, the team measured items of interest in the building plans, which were presented in PDF files, using Bluebeam and supplemented with Revit if available. The team exported QTO data from Bluebeam as a CSV file, then imported the data into Excel. In Excel, measurements were consolidated by item and by floor to reduce the amount of unnecessary details in the data. The team also added additional miscellaneous items; for example, if a floor plan was repeated multiple times throughout a project, this repetition was calculated and appended to the data. Then, the team consolidated measurements by items using Excel Pivot Tables to reduce the amount of unnecessary information in the final dataset. Finally, the research team exported 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 5).

Table 5
Initial embodied carbon impacts at low, medium, and high estimate levels in kg CO_2e/m^2.

	Initial construction	MEP	TI	MEP + TI
Low	300	40	45	85
Medium	400	60	90	150
High	500	75	135	210

2.2.2. Collecting LCA data

In order to calculate the EC of each system, this study used publicly-available data sources and environmental product declarations (EPDs) to gather LCA. Generally, the selection of available and geographically-appropriate LCA data for MEP and TI products was limited.

The TI study used LCA data sources from EPDs (mostly from North America with a few from Europe) and North American building industry databases, Athena and Quartz.

For the MEP material and equipment types, many sources were European because there were very few North American EPDs for the MEP products of interest. LCA results of manufacturing typical HVAC equipment and material are commonly available through open databases and journal articles. The ÖKOBAUDAT, the German mandatory data source within the Bewertungssystem Nachhaltiges Bauen (BNB), offers the largest amount of data for mechanical components [21]. There are only a few valid EPD for HVAC equipment in existing EPD programs. The PEP Ecopassport program, the International EPD System, and the Institut Bauen & Umwelt e.V. (IBU) have the largest number of English EPDs for HVAC equipment. In the US, the Underwriters Laboratories (UL) EPD program holds two EPDs for centrifugal chillers and 39 EPDs for insulation types.

The life cycle scope of this study was limited to A1–A3 (product stage), or A1–A5 (product and construction process stages) if available. A1 = Raw material supply, A2 = Transportation, A3 = Manufacturing, A4 = Transportation, A5 = Construction-installation. In the data sources, these stages were also variously referred to as "c2g" (for "cradle-to-gate"), "Raw material extraction & processing, production (manufacturing & assembly)", etc.

3. Results

3.1. Material assessment

The resulting mass across all buildings considered in the study ranged from 16 – 23 kg/m^2 for MEP and 17–43 kg/m^2 for TI. Fig. 1 presents the low, medium, and high mass estimates.

For the MEP component, the analysis revealed that mass are higher in high performance buildings (HPBs) compared to standard performance buildings (SPBs) across all building size categories as shown in Fig. 2. The total material quantity for MEP of typical commercial office buildings in the PNW ranged from 14.6 to 19.9 kg/m^2 for SPB, and 17.1 to 22.7 kg/m^2 for HPB across sixteen typical building size models. The analysis also revealed that material quantities of mechanical systems are significantly higher than material quantities of electrical and plumbing systems across all building size categories for both SPB and HPB buildings. Mechanical items can

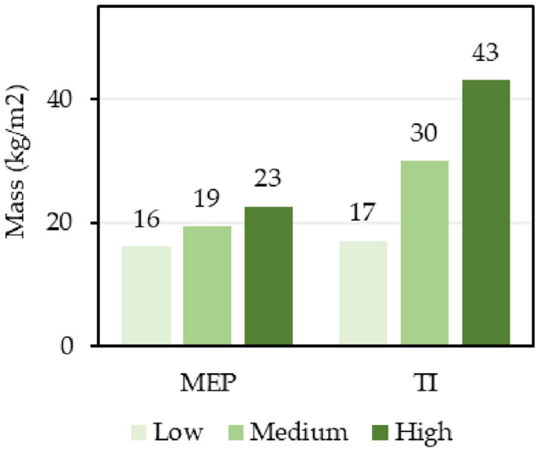

Fig. 2. Mass estimates for MEP and TI at low, medium, and high estimates levels.

have up to four times the overall mass as electrical and plumbing, as shown in Fig. 2.

In the TI portion of the study, the relative material quantities per unit of total floor area varied between projects, and not all projects had all of the same items. An example of this variation is shown in Fig. 3 for items that were quantified per unit area. Fig. 3 shows that the projects varied widely in quantities and types of materials or items used, suggesting that the corresponding environmental impacts for TI would vary widely as well.

3.2. Embodied carbon impact assessment

During the final stage of this project, the EC results were calculated by multiplying the life cycle impact data found in the literature by the material quantities estimation from the first stage. Fig. 4 shows the Global Warming Potential (GWP) EC results for MEP and TI. The EC estimates ranged from 40 – 75 kg CO_2e/m^2 for MEP and 45–135 kg CO_2e/m^2 for TI. Fig. 4 presents the low, medium, and high EC estimates, where "Low" represents the minimum value, "High" represents the maximum value, and "Medium" represents the average of the "Low" and "High" values.

For the MEP component, the results of this stage illustrate that mechanical adds the largest contribution to the total EC of each building due to the high level of material weight and the great GWP of some of the mechanical components, as shown in Fig. 5. The second largest contribution to GWP are electrical systems, followed by plumbing across all building size categories. In conclusion, the trends of embodied carbon for both SPB and HPB in descending order are: mechanical, electrical, then plumbing.

Fig. 6 presents the total GWP impacts per square meter for each project in the TI portion of the study, and Fig. 7 presents the results per occupant. From these two figures, it can be observed that normalizing the results by unit area can produce a very different picture than normalization by occupant. Some advisors did not provide responses regarding work intensity or number of occupants. The research team estimated number of occupants based on number of cubicles and/or offices, or plumbing fixture calculations if shown on the plans. It would have been valuable to normalize the results to the number occupants in each project, but this value was not clearly nor consistently defined for the projects.

The results indicated in Figs. 4–7 use different LCA databases indicated earlier. The TI study used LCA data sources from EPDs (mostly from North America with a few from Europe) and North American building industry databases, Athena and Quartz. For the MEP material and equipment types, the data sources come from the European EPDs programs; ÖKOBAUDAT, PEP Ecopassport program, the International EPD System, and the Institut Bauen & Umwelt e.V. (IBU) and UL EPD programs.

It can be observed that overall environmental impacts are roughly correlated with mass, which is logical. It is also worth noting that impacts were typically correlated with mass in the context of an overall building, but not necessarily on an individual item level.

3.3. High-impact items

Some MEP and TI items were associated with high EC values due to the combined effects of their carbon intensities and their

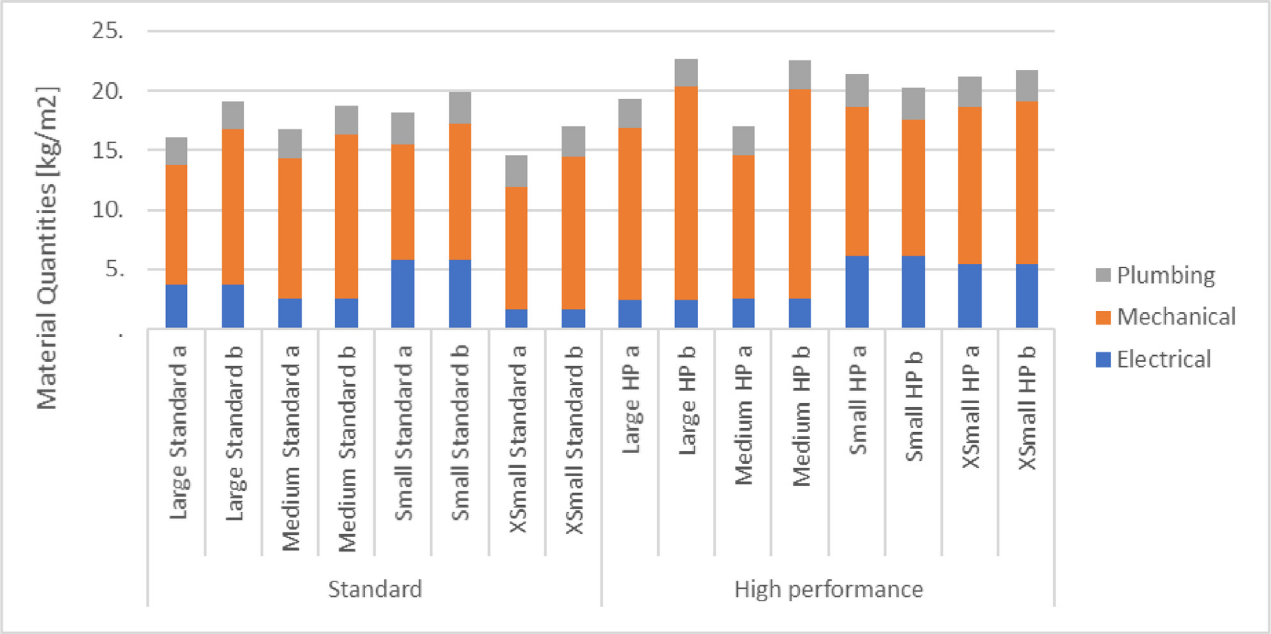

Fig. 3. Mass estimates for MEP systems in standard and high performance buildings..

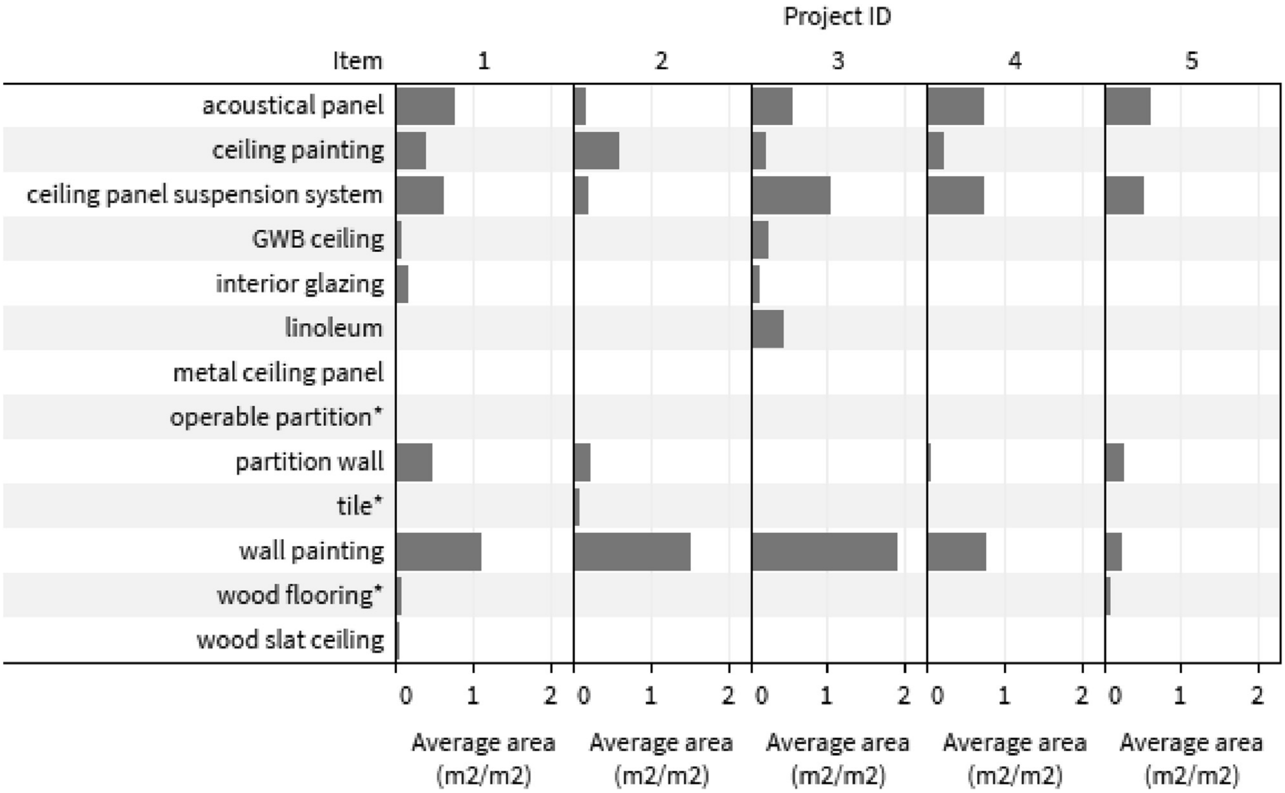

Fig. 4. Quantities of items measured per unit area (m2) normalized by total floor area (m2) for TI projects. * indicates items or measures that excluded data with inconsistent units due to CML vs TRACI.

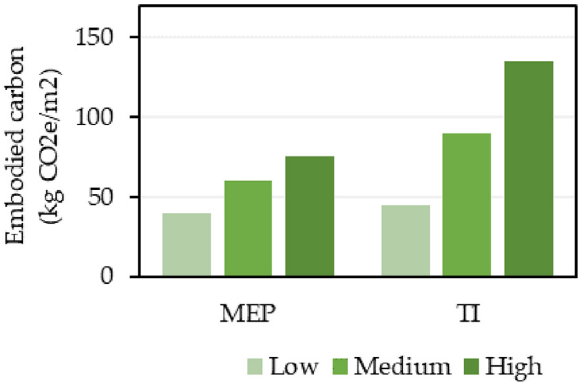

Fig. 5. Embodied carbon estimates for MEP and TI at low, medium, and high estimate levels.

quantities assessed in buildings. Based on the data collected in this preliminary study, high-impact items (per unit floor area) included:

- For the MEP components: AHUs and other large, heavy units, galvanized sheet metal for ductwork, light fixtures, cast iron piping for wastewater and ventilation.
- For the TI components: cubicles and furniture, some types of flooring, which depended on the flooring type, and ceiling panel suspension systems, as shown in Fig. 8.

The material quantities of some high-impact items varied significantly. For MEP, highly variable items were those that were either present or absent depending on the building model (e.g. batteries were included some electrical systems and not in others) and ductwork (the quantity of ductwork varied by a factor of 2 depending on the building size and system). For TI, highly variable items included flooring and ceiling finishes (because design choices affected the material types and quantities) and furniture, especially cubicles (because furniture quantities depended on the number of occupants).

4. Discussion and recomendations

Overall, the results of this study suggest that the environmental impacts of TI and MEP are significant, especially when the full building lifespan is considered. The recurring nature of MEP and TI installments are important to consider, especially in the context of the full building lifespan. MEP and TI are often replaced every 10 to 20 years [26], and the accumulated impacts can be significant.

The MEP and TI results can be compared to benchmark data from The Carbon Leadership Forum's Embodied Carbon Benchmark (ECB) Study [28]. The ECB study collected EC data for life cycle stage A (cradle-to-gate and/or cradle-to-construction) for office buildings with building scopes limited to structure, foundation, and enclosure. The central 50% of values ranged from approximately 300 to 500 kg CO_2e/m^2 [28].

Fig. 9 presents the results of adding the low and high estimates for MEP and TI to the results from the ECB study, using three scenarios showing the combined impacts of initial construction, MEP, and TI accumulated over a building lifespan of 60 years. Each scenario reflects the low, medium, and high estimates of each contribution, assuming a recurrence interval of 15 years. Initial construction impacts are shown as 300, 400, and 500 kg CO_2e/m^2, approximating the 25th, 50th, and 75th percentile values of office buildings from the ECB study, respectively. During the first 15 years of a building's lifespan, MEP and TI impacts are a small fraction of the initial construction estimates. However, when

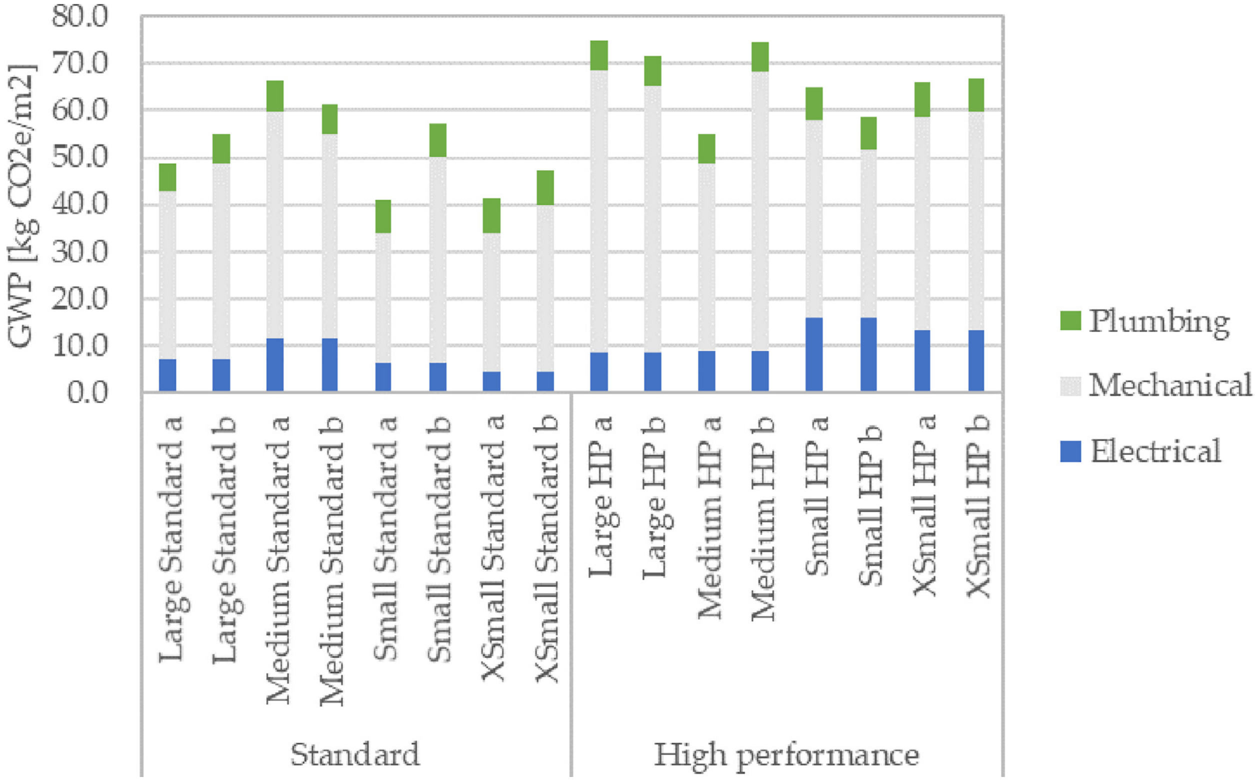

Fig. 6. Global Warming Potential (GWP) for Mechanical (excluding refrigerants) Electrical and Plumbing System Types in Standard Buildings and High-Performance Buildings (kg CO_2eq/m^2).

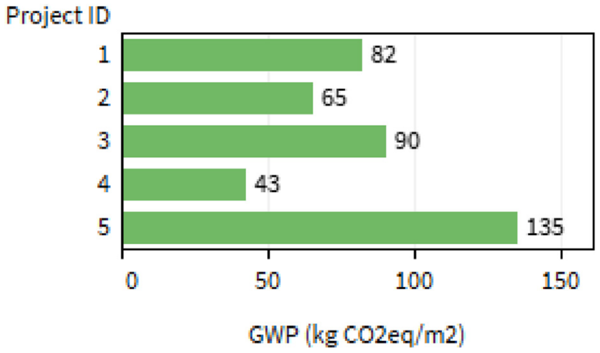

Fig. 7. Total impacts per square meter.

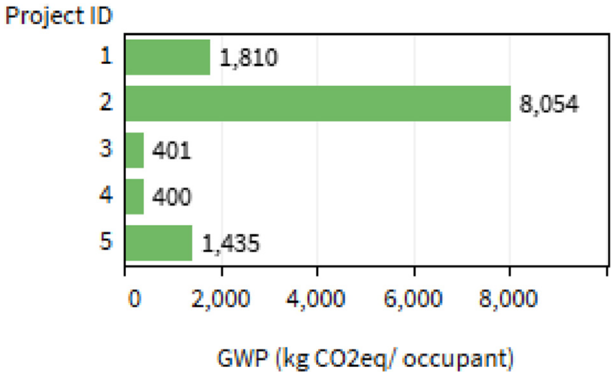

Fig. 8. Total impacts per occupant.

replacements of MEP and TI begin to accumulate, the combined impacts can exceed the initial construction impacts, depending on the estimate level. For example, after 60 years in the 'high estimate' scenario, the combined impacts of MEP and TI exceed the initial construction impacts. This figure shows how significant MEP and TI can be when their recurring installations are considered over the lifetime of a building (Fig. 10).

Table 3 summarizes the values used in Fig. 9.

4.1. Impact of recurrence

In order to understand the EC impact of MEP and TI during the lifespan of the building, an important consideration is the frequency of typical renovations. For the MEP component, this study used both BOMA [26] and ASHRAE's life expectancy chart [1]. According to industry advisors, TI fit-out typically occurs every 10 to 20 years. If one assumes this rate of occurrence for a building with a life span of 60 years, then the total impact of TI could range from 130 to 810 kg CO_2e/m^2, using the GWP results estimated from this study.

The level of accuracy of these results should be limited to their order of magnitude. The variation in values within the order of magnitude should be considered uncertain, given the limited sample of buildings used in the data procurement for the TI component and the hypothetical buildings used in the MEP portion of the study. These samples are not statistically representative of the building stock

Additional sources of uncertainty in this study include the representativeness of data. The LCA data for TI and MEP items in this study were taken from generalized databases (Quartz, Athena) or EPDs, which could be product specific or industry average. In this study, a TI item (e.g. chairs) used the same LCA data across all pro-

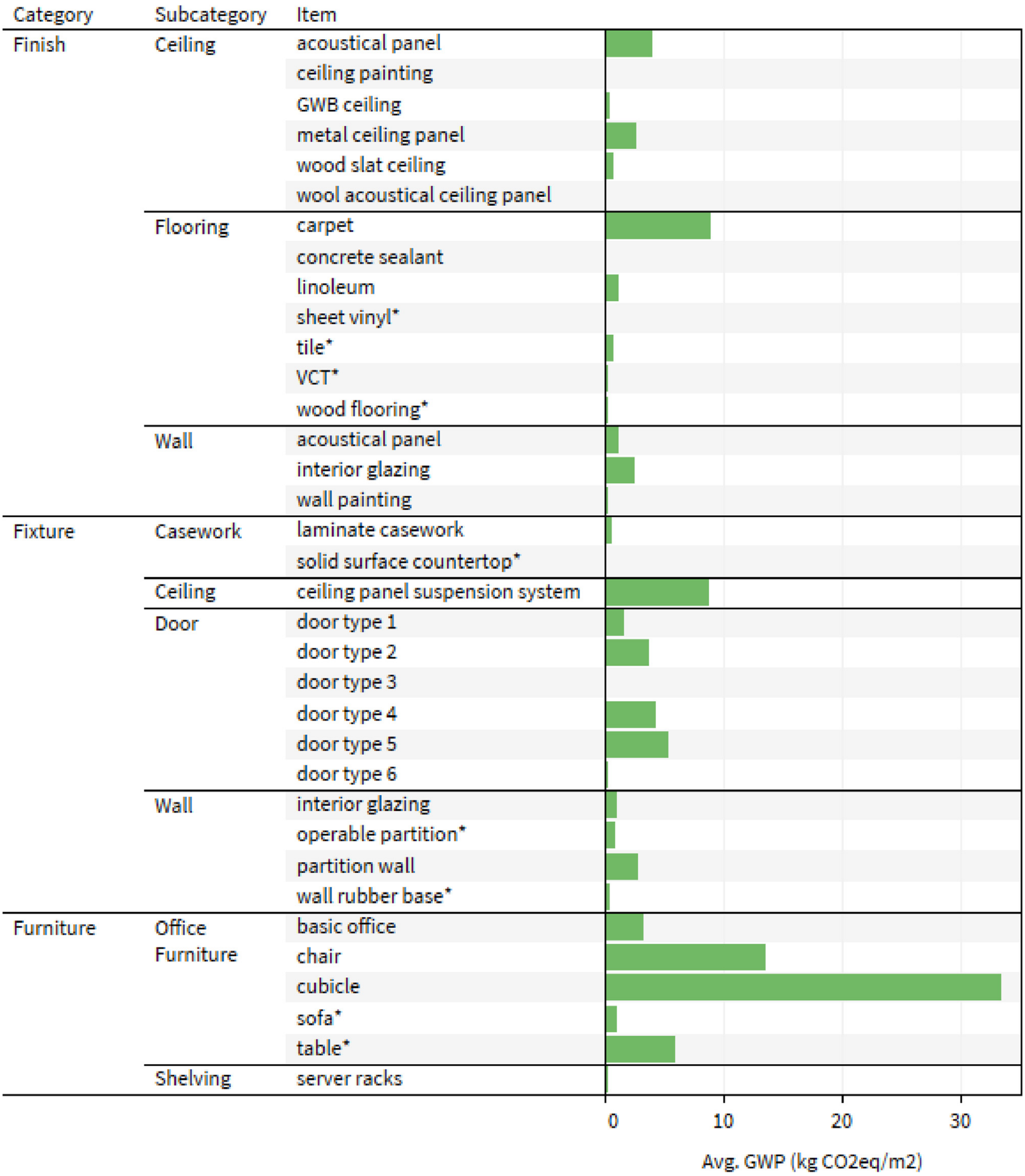

Fig. 9. Breakdown of GWP impacts, average of projects.

ject, ignoring individual variations within projects and between projects. In other words, a single EPD does properly reflect all similar products, and generalized databases do not reflect project-specific products.

In practice, several strategies can be employed to reduce the EC impacts of MEP and TI. In order to reduce TI impacts design teams can re-use office furniture, including cubicles and private offices, as these items were observed to have the highest impacts in the context of a building. It is also suggested to avoid using carpet, tile, and ceiling panels; expose floors and ceilings instead, or source low-impact products for these components. One can also limit use of interior glass, doors, metal items, such as metal ceiling panels and server racks. In general, strategies to reduce, re-use, or recycle carpet, ceiling panels, or any product as much as possible should be considered.

For the reduction of EC of MEP, the main recommendations are related to the efficient design of HVAC systems that adds the largest contribution to the total GWP of each building due to the high

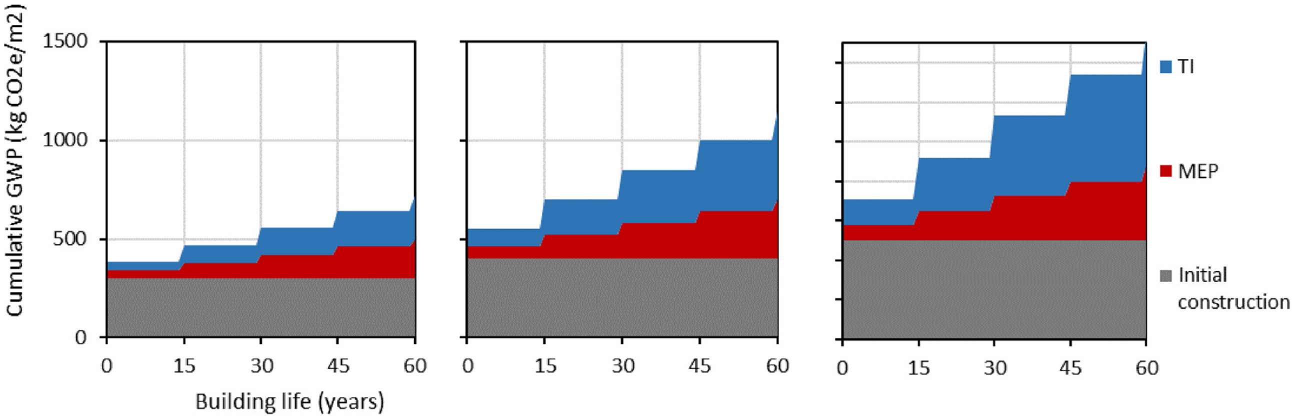

Fig. 10. Cumulative embodied carbon impacts of initial construction, MEP, TI, at low, medium, and high estimate levels over 60 years.

material weight and the great GWP of some of the HVAC components. In the case of HVAC 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 the larger the overall weight of the equipment. Therefore, EC will add an additional justification to the right-sizing of HVAC systems.

5. Conclusions

This study characterized material quantities and environmental impacts of TI and MEP in office buildings in the PNW. This was done by collecting material quantity data from five actual projects (three in Washington, two in Oregon) for the TI portion of the study, and for 16 hypothetical building models for the MEP portion of the study. Environmental impact data were taken primarily from European and North American building industry databases and EPDs where needed. The results identified high-impact TI components as: office furniture (offices, cubicles, chairs, tables), ceiling panel suspension systems, carpet, doors, glazing, and acoustical panels. High-impact MEP components included: AHUs and other large, heavy units, galvanized sheet metal for ductwork, light fixtures, cast iron piping for wastewater and ventilation. To reduce the impacts of MEP and TI, these findings suggest that the environmental impacts of TI and MEP can be mitigated by re-using or recycling these high-impact and sometimes high-quantity components.

This preliminary study provides evidence that initial EC of TI and MEP components is smaller than that of core and shell components. But, with recurring installments, the impacts of TI and MEP over a typical building lifetime can become significant. From a theoretical perspective, this paper contributes to the current body of knowledge on WBLCA which is mostly focused on assessing the impact of core and shell and envelope of buildings. This study shows that including MEP and TI estimates in initial construction estimates could increase life cycle stage A impacts by 30% or more. However, a WBLCA that considers other life cycle stages, including operational impacts, would provide a more comprehensive understanding of MEP and TI impacts.

This preliminary study provides a basis for future work that will be needed to advance the state of knowledge on MEP and TI environmental impacts. Some of the future data need and research need are: More EPDs specific to MEP and TI in the North American building industry; Building case studies to compare actual embodied carbon estimates to the generic models created for this study; Quantification of refrigerant use in buildings for different HVAC systems; Accurate estimations on refrigerant charges, leakages, and recovery during end-of-life.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2020.110324.

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