Material Selection and System Layout to Lower Embodied Carbon of Pipe in an Office Building

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ABSTRACT

The use of life cycle assessment (LCA) to evaluate the environmental impacts of buildings has largely ignored the embodied impacts of mechanical, electrical and plumbing (MEP) systems to date. MEP systems rely on significant proportions of metals and contain a multitude of complex components. A better understanding of the environmental impacts of MEP systems is needed to achieve a net-zero carbon future. LCA is used to determine the product [A1-A3] and transportation [A4] global warming potential (GWP_{100}) impacts for variable air volume (VAV) and radiant systems in a case study building. The study serves as an initial step in developing benchmarks and impact reduction strategies for MEP systems. The study considers the material substitution from standard practice to PEX pipe throughout (Radiant: PEX in slab, copper and steel elsewhere; VAV: steel and copper) and for both a typical single-riser pipe layout as well as a multi-riser layout for both HVAC system types. When assessed for a four-story office building, the A1-A4 GWP_{100} impacts for the pipe in the standard layout for the radiant and VAV systems are 1.1 $kgCO_2e/m^2$ and 0.8 $kgCO_2e/m^2$, respectively. Implementing a like-for-like material substitution to PEX with a single-riser layout led to 41% reduction for the pipe impacts in the radiant system and a 64% reduction for the VAV system. Employing a multi-riser layout with standard materials reduced the pipe impacts by 30% for the radiant system and 66% for the VAV system. To put this into perspective, the embodied impacts for the ductwork in the radiant and VAV systems in this building were 5.8 and 7.7 $kgCO_2e/m^2$, respectively. The use of PEX and/or a multi-riser layout represent relatively easy changes that lead to measurable GWP_{100} reductions for MEP systems.

INTRODUCTION

The built environment is in the process of playing catch-up to counteract the effects of climate change. Efforts are on-going to identify impact reduction strategies and determine how net-zero carbon buildings can be built and operated (Frischknecht et al., 2019; Röck et al., 2020; Satola et al., 2021). At the same time, there is a lack of understanding surrounding the scale and potential for environmental impact reductions in building elements that have been commonly excluded from building-scale life cycle assessments (LCAs). These elements include: mechanical, electrical, and plumbing (MEP) systems; interiors; sitework and landscaping (Nehasilova et al., 2016; Pomponi et al., 2018). These elements have been commonly excluded due to lack of information or preconceived notions that these elements do not contribute significant amounts to the environmental impacts of a building (Nehasilova et al., 2016; Pomponi et al., 2018; Rodriguez et al., 2020). However, as the built environment strives for greater levels of completeness within building-scale LCAs, more attention is being placed on these previously overlooked areas (Rodriguez et al., 2020). Additionally, as designers specify more technologies within buildings, to add resilience or lower operational impacts, and reuse and retrofit are being favored over new build, the environmental impacts of building services are of growing significance.

It is apparent that the environmental impacts of building services need to be further investigated to develop system specific benchmarks and identify impact reduction strategies. As such, this paper investigates the environmental impacts associated with the pipe materials required for variable air volume (VAV) and radiant systems within a non-residential building constructed in San Francisco, California. In addition, we present a comparison between a traditional single-riser and a multi-riser layout. This paper does not attempt to draw comparisons between the environmental impacts of VAV versus radiant systems but looks at the environmental impacts of pipe material selection within each system individually.

Background

Life cycle assessment (LCA) has seen increasing attention in recent years due to the need to measure and reduce environmental impacts in the fight against climate change (Roberts et al., 2020; Zeng and Chini, 2017). LCA is being used to quantify the environmental impacts across all stages of a building's life: product [A1-A3]; transportation [A4]; construction [A5]; use [B1-B7]; end-of-life [C1-C4]; and additional impacts or benefits that occur outside the boundary of the assessment [D] (BSI, 2012). Building services are seen as a means of reducing the operational energy use impacts for a building, but their embodied impacts have been largely overlooked (Rodriguez et al., 2020). Embodied impacts account for everything except the operational energy and operational water use, i.e. raw material extraction, transportation, manufacturing, installation, maintenance, refurbishment, waste processing and disposal (BSI, 2012; Roberts et al., 2020).

MEP systems are composed of many different components of varying sizes, materials and purposes. The complexity of these systems makes performing an assessment and comparing between different assessments a challenge. DeMarco and Fortier (2022) highlighted that comparability issues stemmed from inconsistencies in function unit for LCAs of space conditioning systems. When MEP systems are included in a building LCA, they are often reported as a single value without much consideration, nor discussion, surrounding the leading contributors to the MEP impact or any alternatives that could lead to an equivalent system. However, the environmental impacts of MEP systems is of growing importance as these systems are replaced numerous times throughout a building's life cycle and are often upgraded when buildings are retrofitted (Rabani et al., 2021; Rodriguez et al., 2020). Rodriguez et al. (2020) identified high-impact items for MEP systems, including galvanized steel ductwork and cast-iron wastewater pipes, but did not investigate the capacity to reduce the environmental impacts of these elements through material substitution nor layout optimization.

Focusing specifically on the environmental impacts of pipe within MEP systems, Asadi et al. (2016) and Xiong et al. (2020) are relevant. Asadi et al. (2016) compared the environmental performance of cross-linked polyethylene (PEX) pipe to copper pipe for a residential plumbing system in a student dormitory in Pennsylvania. Asadi et al. (2016) indicate a 42% reduction in GWP_{100} over a 40-year service life when copper pipe is switched to PEX but did not include the fittings and did not breakdown the environmental impacts based on life cycle stages for a building. Xiong et al. (2020) compared the environmental impacts of unplasticized polyvinyl chloride (PVC-u) piping system in a residential building to copper and galvanized steel. However, the method used to characterize the environmental impacts limits comparability with other studies. Xiong et al. (2020) looked at the relative contribution of the different pipe materials to the total impact but did not consider direct material substitutions for the entire water distribution system considered.

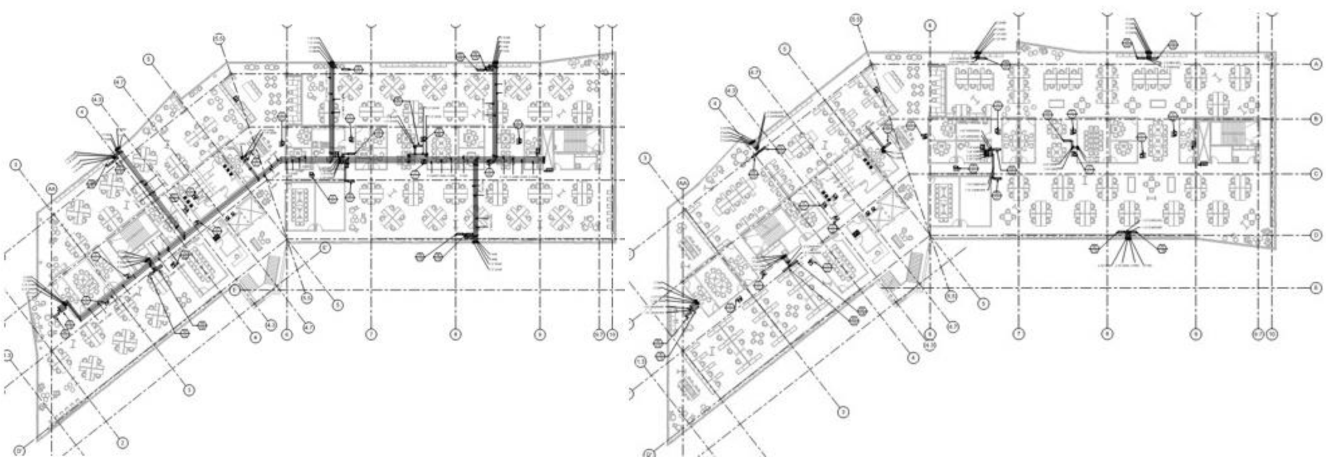
METHODS

We used LCA to investigate the global warming potential (GWP_{100}) impacts of the pipe and ductwork used within radiant and VAV systems for a 112,000 gross square foot (gsf) (10405 m^2) 4-story office building located in San Francisco, California. The material quantity inventory was developed based on the Revit model. LCA was not used to influence the design of the building. As such, the presented assessment is retrospective and provides an indication of the magnitude of these systems' impacts based on standard design procedures. The functional equivalence for the assessments is based on the design parameters (including the design temperatures and internal loads) from the cost analysis completed by Feng and Cheng (2018). Fittings have not been included within the scope of this study due to availability of information. Environmental product declarations (EPDs) have been used to conduct the LCA. Results are presented for the product [A1-A3] and transportation [A4] life cycle stages, whereas end-of-life is discussed qualitatively.

Two layouts with two material selections have been considered for both the radiant and VAV systems. Table 1 provides the material inventory for the pipe used in each of the scenarios. The standard layout represents current industry practice with a single riser: for the radiant system PEX is used in the slab with copper an steel pipe being used elsewhere; the VAV system uses copper or steel pipe throughout. For this study steel is used for all standard-material selection with nominal diameter sizes greater than two inches. The multi-riser and PEX multi-riser scenarios estimate the material needed if the standard single-riser layout is substituted with multiple risers located at the key distribution locations for the VAV and radiant systems. Figure 1 illustrates a typical floor for the standard single-riser and the multi-riser pipe layouts. The multi-riser layout calculations include the floor level distribution piping on one of the 4 floors. The PEX single-riser and PEX multi-riser substitutes all pipe materials for PEX in the standard and multi-riser layouts, respectively.

Table 1. Total Amounts of Pipe for System Layouts

System	Layout	Material Quantities [kg (lbs)]		
		Steel	Copper	PEX
Radiant	Standard	3490 (7695)	1350 (2970)	375 (825)
	Multi-riser	2505 (5525)	945 (2080)	260 (575)
	PEX single-riser	0	0	2250 (4965)
	PEX multi-riser	0	0	1575 (3475)
VAV	Standard	845 (1860)	2285 (5040)	0
	Multi-riser	0	890 (1960)	0
	PEX single-riser	0	0	1095 (2410)
	PEX multi-riser	0	0	320 (705)



(a) (b)

Figure 1 Typical floorplan (a) Standard single-riser layout; (b) Multi-riser layout.

Relevant information from selected EPDs is presented in Table 2. The pedigree matrix, presented in Ciroth et al., (2016), has been used to calculate data quality scores for each EPD. The pedigree matrix uses qualitative aspects of an EPD to determine an uncertainty based on how closely the EPD corresponds with its desired use. The data quality scores are presented as values (from 1-5) based on reliability, completeness, temporal correlation, geographical correlation, and further technological correlation, respectively, as described in (Ciroth et al., 2016). These data quality scores have been combined to get a total uncertainty, representing the square of the geometric standard deviation, for each EPD following the method presented by Ciroth et al. (2016).

Table 2. Environmental Product Declaration Information for Materials

Information from EPD	PEX-China	PEX-Europe	Copper	Steel
A1-A3 GWP_{100} [$kgCO_2e$]	3.05	2.76	3.4	1686
A4 GWP_{100} [$kgCO_2e$]	Not reported	0.28	Not reported	41.1
A5 GWP_{100} [$kgCO_2e$]	Not reported	0.09	Not reported	Not reported
Functional Unit	1 kg of pipe	1 kg of pipe	1 kg of pipe	1 ton of pipe
Geography	China	Europe	North America	Europe
Standard	EN 15804+A1:2013	EN 15804+A2:2019	Not Specified	EN 15804+A2:2019
Publication Date	07/29/2019	01/25/2022	06/25/2019	09/08/2023
EPD type	Product Specific	Product Specific	Industry Average	Product Specific
Data Quality Score	(1,1,2,5,2)	(1,1,1,4,2)	(2,1,2,2,2)	(1,1,1,4,2)
Total Uncertainty	1.23	1.22	1.60	1.22
Reference	(Rifeng, 2019)	(Uponor Corporation, 2022)	(thinkstep, 2019)	(Noksel, 2023)

The transportation [A4] impacts have been calculated to simulate the products being manufactured in the USA. Three transportation scenarios are used to calculate the transport impacts. The EPD transport scenario uses the assumed transportation distances reported within the respective EPDs for PEX (1000 miles (1600 kilometers)), steel and copper (100 miles (160 kilometers)). The breakdown of transportation type by weight for different distances, as reported by the US Department of Transportation (DoT) (U.S. DoT, 2023), forms the second scenario. These mode compositions have been used with ecoinvent version 3.9 (Wernet et al., 2016) to formulate transportation mix impact factors for each distance classification. The US DoT reports that 73.5% by weight of freight is transported less than 250 miles (400 kilometers) (U.S. DoT, 2023). As such, the DoT transportation scenario has been calculated using 250 miles. The truck scenario assumes all materials are transported 250 miles (400 kilometers) by a freight truck.

RESULTS

The results are reported in two sections corresponding with the respective life cycle stages considered. The first subsection reports the product stage [A1-A3] GWP_{100} impacts for the different system layouts considered for both the radiant and VAV systems. The second subsection presents the GWP_{100} impacts for the transportation [A4] of the materials from the manufacturing facility to the construction site.

Product Stage [A1-A3] GWP_{100} Impacts

The A1-A3 GWP_{100} impacts for the various pipe materials per unit length are presented in Figure 2. Overall, PEX has a lower A1-A3 GWP_{100} impact per unit length when compared to the same nominal diameter pipe for steel and copper. Figure 3 presents the A1-A3 GWP_{100} impacts for the pipe and ductwork within VAV and Radiant systems. The ductwork has been assumed to be the same in all four piping scenarios for each HVAC system type and has been calculated based on the GWP_{100} impacts reported by (Veltek, 2023).

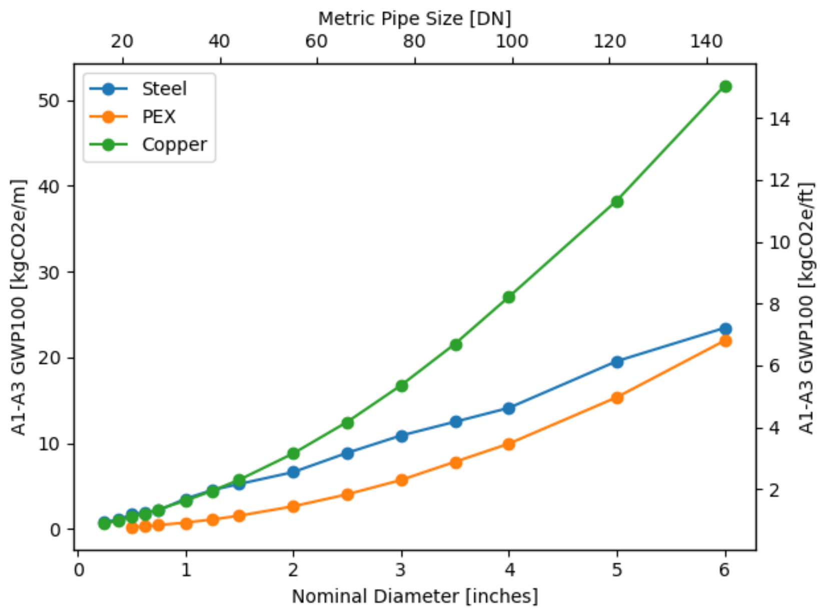
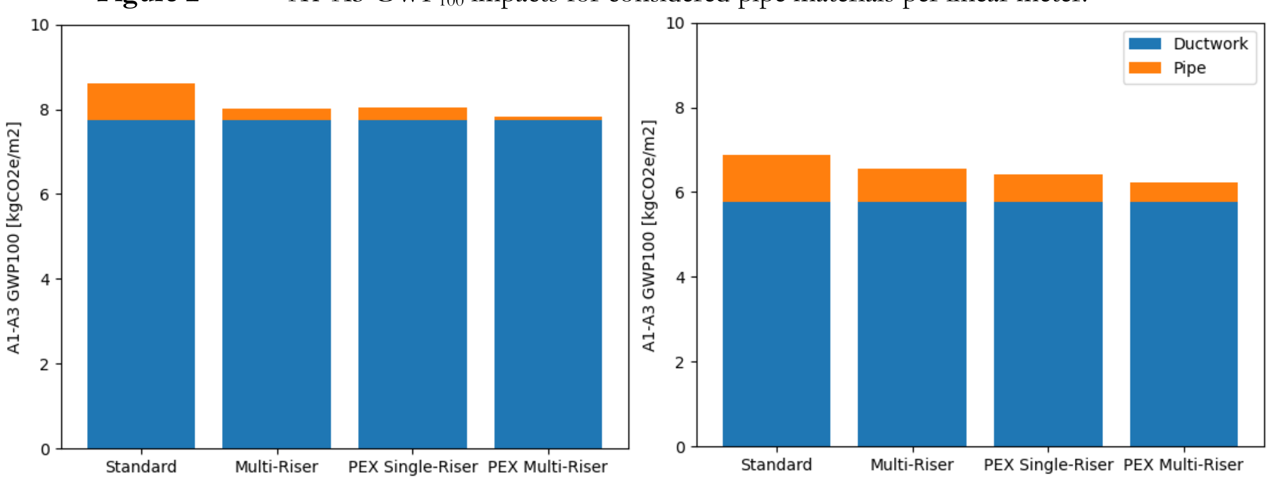


Figure 2 A1-A3 GWP_{100} impacts for considered pipe materials per linear meter.



(a) (b)

Figure 3 A1-A3 GWP_{100} impacts for (a) VAV system and (b) Radiant system.

The pipe represents 10% of the A1-A3 GWP_{100} impacts using a standard layout and 1.2% with the PEX multi-riser layout for the VAV system. For the radiant system, the pipe represents 16% of the A1-A3 GWP_{100} impacts with a standard layout and 7.4% with a PEX multi-riser layout. Substituting all pipe materials to PEX led to a 41% reduction in the A1-A3 GWP_{100} impacts for the pipe in the radiant system and a 64% reduction for the pipe in the VAV system. The results demonstrate how simple material substitutions and pipe layouts can lead to net-reductions in upfront embodied carbon impacts for these systems.

Transportation [A4] GWP_{100} Impacts - Pipe

Table 3 summarizes the GWP_{100} impacts for the three transportation scenarios used in this study. The three scenarios act as a sensitivity analysis as the mode and distance for travel is unknown. Additionally, the three scenarios demonstrate how the transportation [A4] impacts compare to the product stage [A1-A3] impacts reported earlier.

Table 3. A4 GWP_{100} Impacts [$kgCO_2e$]

System Scenario	Radiant System			VAV System		
	US DoT	Truck	EPD	US DoT	Truck	EPD
Standard Single-Riser	231	477	170	138	283	53
Multi-Riser	162	334	119	39	80	15
PEX Single-Riser	98	202	529	48	98	257
PEX Multi-Riser	69	141	371	14	29	75

The switch to PEX pipe leads to a significant increase in the transportation impacts associated with the EPD transport scenario for both the Radiant and VAV systems. However, the transportation impacts represent at most 7% of the total A1-A4 impacts for the pipe in the scenarios considered. The transportation impacts contribute the largest proportion to the A1-A4 impacts under the PEX multi-riser scenarios for both systems under the EPD transportation scenario. The increased transportation impacts do not overcome the lower A1-A3 impacts incurred when PEX is used in the all-PEX or PEX multi-riser layouts. Therefore, PEX provides the lowest impact when compared to steel and copper for both radiant and VAV systems in this building.

DISCUSSION

The results indicate that ductwork contributes 5.8 $kgCO_2e/m^2$ for the radiant system and 7.7 $kgCO_2e/m^2$ for the VAV system, with the pipe contributing 0.5-1.1 $kgCO_2e/m^2$ and 0.1-0.9 $kgCO_2e/m^2$ for the radiant and VAV systems, respectively, depending on the layout and material selection. The results indicate that the pipe impacts are significantly higher than those reported by Asadi et al. (2016). Therefore, more work is needed to ensure adequate completeness is achieved when assessing the environmental impacts of these systems. Additionally, Rodriguez et al. (2020) report the A1-A3 embodied GWP_{100} impacts of MEP systems to be 40-75 $kgCO_2e/m^2$. However, these impacts are not broken down to the individual systems and components. Comparing the presented results to Rodriguez et al. (2020) would indicate that the runs of ductwork and pipe represent 10-20% of the A1-A3 impacts for MEP systems given a standard layout. However, larger sample sizes are needed to make generalizable comparisons.

Achieving impact reductions via material substitution is of critical importance for climate change mitigation. However, the responsible sourcing of materials and considerations for end-of-life treatments of materials are important to consider when addressing climate change.

Responsible Sourcing of Materials

The analysis presented within this study focused on achieving impact reductions via material substitution. However, impact reductions can also be achieved by the substitution of products within the same material classification. The environmental impacts of a product are influenced by countless factors, including: amount of recycled content; type of energy used to power the manufacturing facility; amounts of waste generated during the production process; transportation and intermediate processes within the production process, among others (Cascione et al., 2022). Wherever possible, materials should be sourced from manufacturers who use renewable energy to power their production facilities and do not rely on fossil fuels. In addition to fuel source, materials with higher recycled content can be more favorable as they will rely less on raw material extraction. However, certain materials can incur larger impacts to include recycled content than to be produced from virgin sources.

End-of-life

Table 4 compares the end-of-life treatments for PEX based on the considered EPDs. Unfortunately, there is no consensus regarding end-of-life treatment of PEX pipe. The Uponor and the European Plastics Pipes and Fittings (TEPPFA) EPDs from Europe indicate vastly different end-of-life scenarios and the EPD from China negates end-of-life for the product until the building is demolished, at which point the PEX pipe will become inert waste.

Table 4. PEX End-of-Life Impacts

End-of-Life Treatment	Rifeng EPD	Uponor EPD	TEPPFA EPD
Landfill	n/a	1%	85%
Recycled	n/a	63%	0%
Incinerated	n/a	36%	15%
Reference	(Rifeng, 2019)	(Uponor Corporation, 2022)	(teppfa, 2018)

The steel and copper pipes are both considered to have 90% recycled rates at end-of-life as reported by thinkstep (2019) and the American Iron and Steel Institute (AISI) (2023, p.11). Therefore, if material substitutions are being encouraged to drive impact reductions for the A1-A5 impacts, these impact reductions need to be evaluated against the potential increased amounts of plastics being sent to landfill or incineration at end-of-life. Metals, although higher impact, are seen to be more recyclable and therefore better fit the context of a circular economy. When impact reduction strategies are promoted for buildings, they need to be evaluated in a holistic perspective to ensure real reductions occur across the entire life instead of shifting the environmental impacts to a life cycle stage not being considered in the assessment scope. If material substitutions are promoted for pipe products, these substitutions need to be balanced with greater efforts to advance the recycling and reuse of these components at end-of-life.

CONCLUSION

This paper demonstrates an initial step in the development of system specific benchmarks and impact reduction strategies for building services. The limitations of this study stem from the limited sample size and representativeness of the background data used to characterize the presented environmental impact results. Larger scale studies need to be conducted to identify trends across different building typologies; geographies; and/or systems. These trends can be used to develop benchmarks and impact reduction strategies for the studied systems. Further work should also look at of the influence of system layout efficiency on the overall environmental impact.

Availability of data is another limitation of this study. The EPDs used in this study represent the environmental impacts of products manufactured in specific geographies (China and Europe). As such, their reported environmental impacts may not accurately reflect those for equivalent products manufactured domestically. More effort is needed to promote the development and use of EPDs across the US.

Although significant reductions have been demonstrated for the pipe within the radiant and VAV systems considered in this study, the ductwork presents a considerably larger A1-A3 GWP_{100} impact. Reducing the environmental impacts for the ductwork was not included in the scope of work for this study and should therefore be the focus of future research. The results presented in this paper demonstrated how designers can achieve tangible, actionable impact reductions via material substitution and layout configuration.

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