LCA for Low Carbon Construction

Life Cycle Assessment of Tenant Improvement in Commercial Office Buildings

Final Report

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A group of industry advisors provided project plans to form the basis of this project. We appreciate their interest and involvement in this study. The members of the advisory committee are listed as follows:

Advisory Member	**Company**
Stacy Smedley	Skanska
Meghan Lewis and Nathaniel Smith	Mithun
Ericka Colvin	Yost Grube Hall Architects
Farleigh Winters	LSW Architects
Tracey Olson	Hacker Architects

The research team also received assistance from student Aiwen Xie in compiling data for the project.

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Executive Summary

This study is an extension of the Life Cycle Assessment (LCA) for Low Carbon Construction Project, initiated in 2016 and funded by the Charles Pankow Foundation, the Oregon Department of Environmental Quality, and Skanska. The goal of the Low Carbon Construction Project is to provide accessible guidance to industry professionals looking to integrate carbon into life cycle based decision-making. Mechanical, electrical, and plumbing (MEP) and tenant improvement (TI) were selected by the Oregon Department of Environmental Quality as a relevant research topics to investigate. Currently, there exist very little data on the environmental impacts of these components, but they may be significant because MEP and TI are often installed numerous times over the lifespan of a building. The goal of this study is to present estimates of material quantities and environmental impacts for commercial office buildings in the Pacific Northwest.

This report focuses on the TI portion of the study. It presents the methodology, resulting estimates of material quantities and environmental impacts, and a discussion of the results. The scope of the study was limited to embodied (cradle-to-gate) environmental impacts. Material quantities were collected by performing material quantity take-offs (QTOs) on plans from four sample projects collected from local industry advisors. LCA data were sourced from North American building industry LCA databases (Quartz and Athena) and from EPDs for products not found in the databases. Impacts were characterized per TRACI 2.1. This report is accompanied by a calculation spreadsheet that provides more information on the background data, and allows a user to input custom quantities to estimate TI impacts for their own projects.

TI encompassed the following items:

- Finishes, which included:
    - Ceiling
    - Flooring
    - Painting
    - Interior glazing
- Furniture, which included:
    - Office furniture (e.g. chairs, cubicles, tables)
    - Shelving (e.g. server racks)
- Fixtures, which included anything that was permanently screwed or glued in, such as:
    - Casework (e.g. cabinets, counters)
    - Ceiling suspension systems
    - Doors
    - Partition walls

Five case study buildings were selected to provide material quantities for the LCA. The resulting overall environmental impacts, averaged across case study buildings and normalized by total floor area of the projects, ranged approximately as follows:

- GWP: 45 – 135 kg CO_2eq/m^2
- AP: 0.2 – 0.6 kg SO_2eq/m^2
- EP: 0.02 – 0.30 kg Neq/m2
- ODP: $7.6x10^{-7}$ – $5.4x10^{-6}$ kg CFC11eq/m^2
- SFP: 2.2 – 7.4 kg O_3/m^2
- Energy: 820 – 2750 MJ/m^2, or approximately 73 – 242 kBTU/sf
- Mass: 17 – 43 kg/m^2

These results were judged to be significant, given that typical recurrence interval of TI is every 10 – 20 years over a building's lifetime.

The study also identified several items that were particularly high impact, taking into consideration their typical quantities in a building. These items were: office furniture or compartments (basic office, cubicles, chairs, tables), doors, ceiling panel suspension system, carpet, glazing, acoustical panels, metal ceiling panels, and partition walls.

Limitations to this study are:

- **Limited number of sample projects**: Having only five projects limited the strength of the findings from this study. Furthermore, the projects were not ensured to be statistically representative of the building stock of interest.
- **Environmental data with differing units**: For some items in the study, some of the available LCA data did not have units matching TRACI 2.1. To avoid distorting the results, the LCA values with mismatching units were assumed to be zero. Thus, the concerned items and impact categories should be assumed to have a higher level of uncertainty than those with units consistent with TRACI 2.1.
- **Representativeness of data**: The LCA data did not exactly reflect the specific products used in the sample projects. This level of detail would have been outside the study scope, and product-specific data was not available for the products in question. Some data were highly general (from databases) while others were more specific (from EPDs).
- **End-of-life impacts**: End-of-life impacts would have been important to consider due to the recurring nature of TI work, but was outside the scope of this study and was thus not included. Note that many EPD sources do not provide end-of-life impacts.
- **Not all projects were from office buildings**: The research team endeavored to collect projects from "commercial office spaces," assuming they would come from commercial office buildings, but the project advisors provided plans of office spaces from a variety of building types. Since research team did not have a wide selection of projects to choose from, the selected projects came from a variety of building types.
- **Comparison to other studies**: With more time or budget, this study could have been enriched by comparison to other similar studies or a literature review.

Due to these sources of uncertainty, the true impact of TI is likely to be somewhat higher than results shown in this study.

Table of Contents

1 Project Overview

This project is an extension of the Life Cycle Assessment (LCA) for Low Carbon Construction Project, initiated in 2016 and funded by the Charles Pankow Foundation, the Oregon Department of Environmental Quality, and Skanska. The goal of the Low Carbon Construction Project is to provide accessible guidance to industry professionals looking to integrate carbon into life cycle based decision-making. To date, the project has produced a benchmarking study titled *The Embodied Carbon Benchmark (ECB) Study* and a user-friendly practice guide titled *Life Cycle Assessment of Buildings: A Practice Guide*. The benchmarking study had identified numerous sources of uncertainty in the building industry's current understanding of the total embodied carbon in buildings. One critical source of uncertainty was related to mechanical, electrical and plumbing (MEP) and interior tenant improvement (TI) 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. Thus, MEP and TI were selected as the next research topics to be funded by the Oregon Department of Environmental Quality based on a refined internal Research Opportunity report V3 dated July 2017. The purpose of this project is to advance the building industry's understanding of the environmental impacts of MEP and TI.

This report addresses the TI portion of this project. This report provides the following:

- A description of the research methodology
- The results for material quantities and environmental impacts
- A discussion of the results and sources of uncertainty, with pathways and strategies to reduce uncertainty in our current knowledge about the material quantities and environmental impacts of TI fit-out

1.1 Goal

The goal of this project is to establish estimates of the typical ranges of material quantities and environmental impacts associated with TI.

1.2 Scope

"Tenant improvement" or "TI" is a broad term that describes the work of furnishing an office space over the bare structure. A literature review was conducted to find a common definition for "tenant improvements," but no official definition was found. One source described it as "changes made to the interior of a commercial or industrial property by its owner to accommodate the needs of a tenant such as floor and wall coverings, ceilings, partitions, air conditioning, fire protection, and security."[1] For the purposes of this project, the scope of TI was established based on the professional opinion of the project investigator (PI), Kate Simonen.

[1] http://www.businessdictionary.com/definition/tenant-improvements-TI.html

TI was specified to include:

- Finishes, which include:
    - Ceiling
    - Flooring
    - Painting
    - Interior glazing
- Furniture, which include:
    - Office furniture (e.g. chairs, cubicles, tables, private offices)
    - Shelving (e.g. server racks)
- Fixtures, which include anything that is screwed or glued in, such as:
    - Casework (e.g. cabinets, counters, fixed desks)
    - Ceiling suspension systems
    - Doors
    - Partition walls, both fixed and operable

The following items were excluded from the scope of this project:

- Air conditioning or heating (because this fell under the scope of the mechanical portion of the MEP project)
- Lighting fixtures (because this fell under the scope of the electrical portion of the MEP project)
- Plumbing fixtures, such as sinks and toilets (because this fell under the scope of the plumbing portion of the MEP project, and was typically excluded from the TI plans)
- Art and decorative embellishments
- Window dressings
- Stairs (because the quantities were difficult to obtain from the plans, being prefabricated or custom-made)
- Electrical equipment such as computers, printers etc.

The environmental impact data -- mostly from building-industry specific environmental impact databases and EPDs -- were limited to the five most common environmental impact categories in the building industry, which are: global warming, acidification, eutrophication, ozone depletion, and smog formation. Embodied energy and mass were also evaluated. The life cycle scope was limited to cradle-to-gate impacts (modules A1 - A5).

The geographic location was limited to the Pacific Northwest (Washington, Oregon).

2 Methodology

2.1 Projects

Material quantity data were based on architectural TI plans of real buildings. In order to obtain sample building plans, the research team reached out to industry professionals to request architectural drawings or bills of materials. Those who agreed to participate in this research study are referred to as *industry advisors* in this report. They provided the data upon which this project was based. The advisors agreed to participate in this study under the condition that identities and details of their projects would not be published, and that the project plans and data would not be shared outside of the project team. Thus, the buildings are not identified in this rpeort.

The industry advisors were asked to:

1. Provide sample sets of TI architectural plans OR bills of materials
2. Participate in 2-3 optional phone calls to offer input on the project. In the end, only one phone call was conducted per advisor as an introductory "kick-off" phone call.

The participating industry advisors and their respective firms are listed as follows:

1. Stacy Smedley, Skanska
2. Meghan Lewis and Nathaniel Smith, Mithun
3. Ericka Colvin, Yost Grube Hall Architecture
4. Farleigh Winters, LSW Architects
5. Tracey Olson, Hacker Architects

The following information was requested from each industry advisor:

- For a commercial office space in the Pacific Northwest (Washington, Oregon):
    - TI data: Bill of materials OR full set of tenant improvement plans
    - MEP data: Bill of materials OR full set of MEP plans, including equipment schedule (this was requested to supplement the MEP project)
    - Quick description of work (if not included in plans)
        - TI intensity (low, medium, or high level of work?)
        - Number of occupants for scope of work (typical, not maximum)
        - Geographic location
        - New construction or renovation?

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.

All projects were renovations. None were new tenant fit-outs.

The responses regarding "TI intensity" were either not answered or ambiguous because most advisors were not sure how to differentiate between the different levels of TI intensity. The research team was not able to find any established descriptions of TI intensity for the project advisors to reference. Therefore, this parameter should be considered highly uncertain, and thus was not explored in the analysis of results. Towards the end of the study, the research team realized the cost could have been a useful indicator for "TI intensity," but by this point it was too late to collect this information and revise the analysis in terms of cost.

The collected projects considered in this study are shown in Table 1. Projects 1, 2, and 5 were conventional office spaces in the form of traditional "cubicle farms," open offices, or a mix of both. Project 4 was a medical office, and Project 3 was a small office area within a larger non-office complex.

Table 1. Project characteristics.

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	8,757	4	23,552	2,189	Unknown	399	0.0037	Washington
2	136,986	12,733	7	19,569	1,819	Unknown	103	0.0027	Washington
3	2,865	266	2	1,433	133	Low	60	0.0209	Oregon
4	25,842	2,402	1	25,842	2,402	Medium	257	0.0080	Washington
5	75,000	6,971	2	37,500	3,486	Low	656	0.0087	Oregon

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

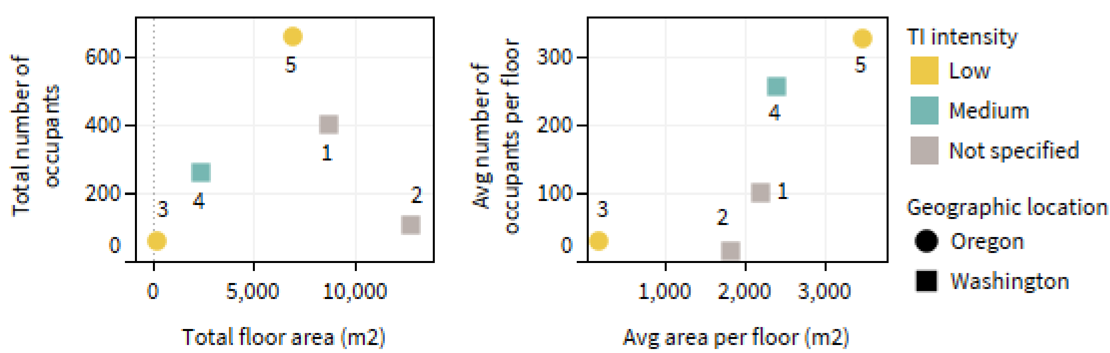

Figure 1. Number of occupants vs floor area for overall project (left) and average per floor (right) for projects in this study, labeled by project ID.

2.2 Quantity take-offs

The process for performing the take-offs (QTOs) consisted of the following steps:

1. *Measure or count items of interest in PDF plans using Bluebeam (and supplemented with Revit if available).*
    - In performing the QTOs, a number of measures were taken to simplify and expedite the process. These measures were taken out of concern for the project scope and budget. An example of this simplification / expedition process was: If eight types of partition walls were specified for Project 1, and five other types were specified for Project 2, we assumed that all were the same type of partition wall. This also allowed a single source of environmental impact data to be used for all partition walls across all projects.
    - A marked-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 is shown in Table 2. The QTO items were also later categorized per Omniclass Table 21 Elements, which is based on Uniformat, to present the results in accordance with established building taxonomies. This classification of the QTO items per Omniclass is shown in Table 3.
    - See Figure 2 for a sample screenshot of QTO work in Bluebeam.
2. *Export QTO data from Bluebeam as a CSV file and import into Excel. Consolidate measurements by item by floor using Excel Pivot Tables.*
    - After exporting the data to Excel, measurements were consolidated by item and by floor to reduce the amount of unnecessary detail in the data. For example, if there were twenty measurements of "partition wall" on one floor, the twenty measurements were summed into a single value for that floor.
3. *Add additional miscellaneous items.*
    - If a floor was repeated multiple times throughout a project, this repetition was calculated and appended to the data. For example, if a model floor was repeated five additional times in a project, the values from the model floor were multiplied by five and added to the dataset.
    - Doors: It was more expedient to count doors using door schedules from the plans, so this data were collected separately then appended to the exported Bluebeam data.
    - Additional items such as ceiling painting or wall painting were added by utilizing similar areas previously collected in Bluebeam. For example, the area of "ceiling painting" was taken to be equal to that of "GWB ceiling."
4. *Consolidate measurements by item (removing floor information) using Excel Pivot Tables.*
    - These measurements were consolidated to remove floor-specific information, which was no longer needed for additional calculations, to reduce the amount of unnecessary information in the final dataset.
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.*

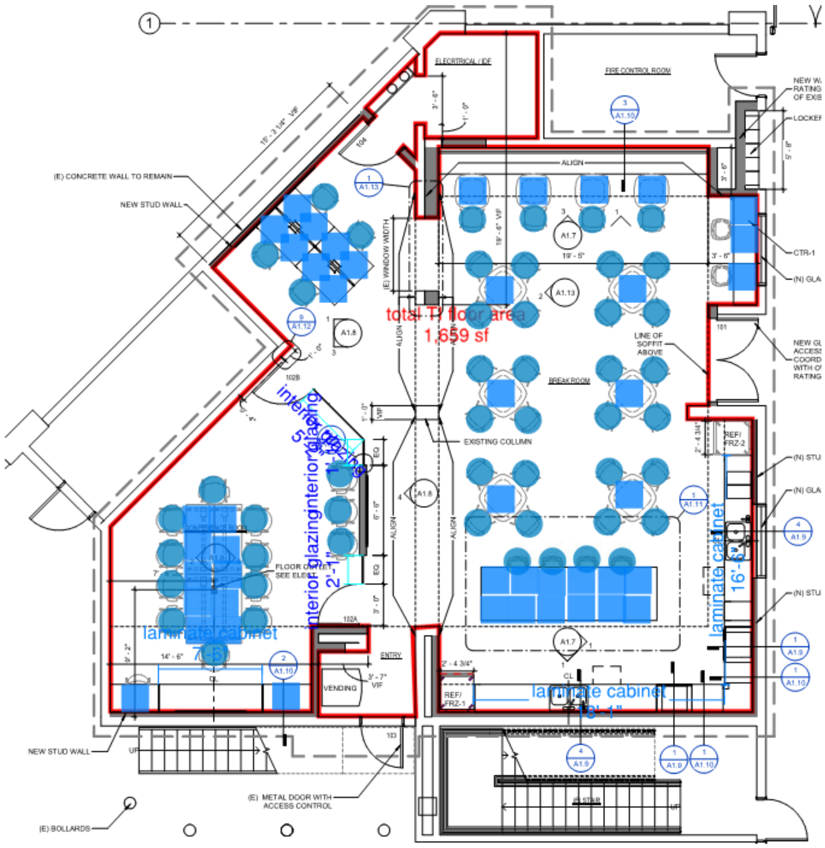

Figure 2. Example QTO mark-up from Bluebeam.

Table 2. Organizational structure of QTO information.

Category	Sub-category	Item
Finish	Ceiling	acoustical panel
		ceiling painting
		GWB ceiling
		metal ceiling panel
		wood slat ceiling
	Flooring	carpet
		concrete sealant
		linoleum
		sheet vinyl
		tile
		VCT (vinyl composition tile)
		wood flooring
	Wall	interior glazing
		wall painting
Furniture	Office Furniture	basic office (private office)
		chair
		cubicle (small work station)
		sofa
		table
	Shelving	server racks
Fixture	Casework	laminate casework
		solid surface countertop
	Ceiling	ceiling panel suspension system
	Door	door type 1 (wood door, no windows)
		door type 2 (wood door with large window)
		door type 3 (wood door with small window)
		door type 4 (glass door)
		door type 5 (wood door with medium-sized window)
		door type 6 (hollow metal door with two medium-sized windows)
	Wall	operable partition
		partition wall
		wall rubber base

Table 3. Organization of QTO items per Omniclass Table 21 (Uniformat).

Omniclass Level 1 Title	Omniclass Level 2 Title	Omniclass Level 3 Title	Omniclass Level 4 Title	Item
Equipment and Furnishings	Furnishings	Fixed Furnishings	Casework	laminate casework
				solid surface countertop
		Movable Furnishings	Furniture	chair
				sofa
				server racks
				table
Interiors	Interior Construction	Interior Doors	Interior Swinging Doors	door type 1
				door type 2
				door type 3
				door type 4
				door type 5
				door type 6
		Interior Partitions	Interior Fixed Partitions	partition wall
			Interior Operable Partitions	operable partition
		Interior Specialties	Compartments and Cubicles	basic office
				cubicle
		Interior Windows	Interior Fixed Windows	interior glazing
		Suspended Ceiling Construction	Acoustical Suspended Ceilings	acoustical panel
				acoustical panel 30%
			Ceiling Suspension Components	ceiling panel suspension system
			Suspended Plaster and Gypsum Board Ceilings	GWB ceiling
			Special Function Suspended Ceilings	metal ceiling panel
	Interior Finishes	Ceiling Finishes	Ceiling Painting and Coating	ceiling painting
			Ceiling Paneling	wood slat ceiling
		Flooring	Carpeting	carpet
			Flooring Treatment	concrete sealant
			Wood Flooring	wood flooring
			Tile Flooring	tile
			Resilient Flooring	linoleum
				sheet vinyl
				VCT
		Wall Finishes	Wall Painting and Coating	wall painting

2.3 Environmental impact data

The environmental impact data for the materials and products from the TI sample projects were taken from North American building industry LCA databases (Quartz or Athena) and EPDs. Generally, the Quartz database was first consulted, then Athena, before seeking out individual EPDs. Building industry databases were prioritized over EPDs because they could represent a wider range of products for a particular product type.

Each project may have specified a manufacturer for each item in the project, but this study assumed the same set of environmental impacts for the same type of item across all projects. This was done in order to ensure consistency in LCA data between projects. For example, although Project 1 and Project 2 may have specified different brands of acoustical ceiling tile, the project team assumed that the same brand was used for both projects. Additionally, if Project 1 had used multiple types of acoustical ceiling tile, it was assumed that they were all of a single type unless the material differed greatly (e.g. mineral fiber vs wood slat ceilings).

The following measures of environmental impact were collected, units specified per TRACI 2.1:

- Global warming potential (GWP) in kilograms of carbon dioxide equivalent (kg CO_2eq). Note that biogenic carbon was not credited with a negative value for wood products.
- Acidification potential (AP) in kilograms of sulfur dioxide equivalent (kg SO_2eq)
- Eutrophication potential (EP) in kilograms of nitrogen equivalent (kg Neq)
- Ozone depletion potential (ODP) in kilograms of CFC11 equivalent (kg CFC11eq)
- Smog formation potential (SFP) in kilograms of ozone equivalent (kg O_3eq)

Additionally, the following measures were collected:

- Embodied energy in megajoules (MJ), later to be compared with operating energy data. In some cases, this was referred to as "primary energy," while in other cases this was taken as the sum of PERT (total use of renewable primary energy resources) and PENRT (total use of non-renewable primary energy resources).
- Mass in kilograms (kg). This included the mass of packaging if available from the data source (typically in EPDs but not databases), but excludes the impact of waste disposal.

The life cycle scope 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.

The research team endeavored to collect data sources that had impact measure units consistent with TRACI 2.1. For a handful of items, the research team was unable to find satisfactory data sources that both matched the item description and matched units with TRACI 2.1. Some sources had impact units based on an older version of TRACI, while others were based on CML (typical for European data). In these cases, the team chose to select data sources that best matched the item description. This choice was made in order to enhance the accuracy of the three most prominent measures in building LCA studies (which always had consistent units across data sources): GWP, embodied energy, and mass. Thus, some of the EPDs were European instead of North American. Values that had mismatching units were set to zero to avoid inflating the data. Items and measures that had conflicting units in the dataset are indicated with an asterisk (*) in the remaining tables and figures in this report.

Another challenge in applying the environmental data to the quantity take-offs resided in the discrepancy between the units of the quantity take-off estimation and the units of the environmental source data. Some assumptions had to be made to make the conversions. Unit weights were obtained from online sources, which were documented along with all other assumptions in the calculations. For example, in the quantity take-offs, paint was measured by linear foot of wall surface painted, but in the Quartz database, environmental impacts for "Low VOC Eggshell Acrylic Paint" were provided per kg of paint. Therefore, it was assumed that paint covered 350 square feet per gallon[2] and weighed 11.5 lbs/gallon[3]. With the assumption that the walls were 12 ft high (per typical project plans), the conversion from linear foot of wall surface to kilogram of paint could be performed, and the environmental impacts per linear foot of wall could be calculated.

2.3.1 Notes on specific items

Some building components did not have established environmental impact data, meaning that they could not be found in databases or in EPDs. These were usually building components that varied greatly in construction (e.g. partition walls, interior glazing, chairs, doors), or were too obscure to have dedicated environmental data (e.g. server racks). For these items, the research team estimated their environmental impacts as follows:

- Chairs: The environmental impact of chairs was obtained by averaging the EPD data of three different office chairs (two rolling chairs, one stacking chair).
- Doors: Nine door types from the first plan set were simplified down to three types based upon percentages of wood and glass in the door. Additional door types from other plans were later added (a full glass door, a wood door with medium-sized windows, and a hollow metal door). The percentages were obtained by modeling the doors in Rhino (see the Appendix for screenshots). For door types consisting of larger than average or double doors, multipliers were used to account for the increase in materials and resulting increase in impacts. Thus a double door such as type D3 was considered type D1 with a multiplier of 2. Ultimately, doors were designated as the following across all projects:
    - Door type 1: Wood door with no windows
    - Door type 2: Wood door with large window
    - Door type 3: Wood door with small window
    - Door type 4: Glass door
    - Door type 5: Wood door with medium-sized window
    - Door type 6: Hollow metal door with two medium-sized windows

[2] https://www.lowes.com/cd_paint+calculator_1352225126183_
[3] https://bhs.econ.census.gov/bhs/cfs/weightConversion.html

Note that all doors include the impacts of a steel door frame. The door types are depicted in Figure 3.

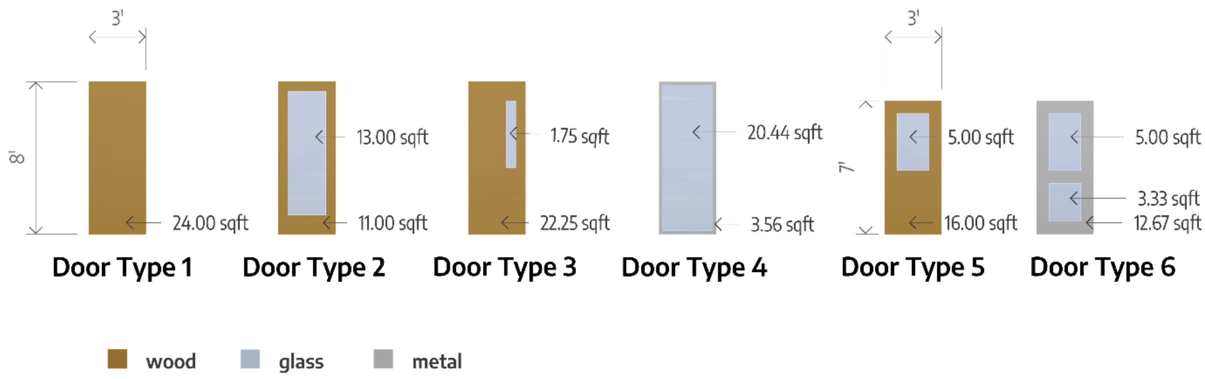

Figure 3. Door types.

- Similarly, some projects had tables of multiple sizes. The tables were multiplied by an approximate size factor to reflect the size of the table assumed for the EPD data.
- Interior glazing: A base unit of glazing was established and modeled in Rhino, comprising of an aluminum mullion frame and laminated glass panels. The cross sectional area for the aluminum, from which the volume and weight were derived, was determined using CAD drawings based on a plan detail modeled in Rhino. See the Appendix for a drawing.
- Laminate casework: The "average" casework item was assumed to be a cabinet that was 2 feet tall, 1.5 feet deep, with 2 inner shelves, and a vertical panel every 3 feet. Cabinets were assumed to have a back panel, and 50% of the front of the cabinet was assumed to have a door (assuming 50% of cabinets had doors while the remaining 50% had open shelves), per the typical plan notes. Particleboard was assumed to be 0.75" thick. Laminate was assumed to be applied to one side of the particleboard only. See the Appendix for a drawing. There were a few other casework items that were assumed to have a similar material density per linear foot, such as fixed desks and counters.
- Server racks: The amount of steel used in a server rack was estimated by averaging the weights of three large server racks found on Amazon.com, assuming that the server racks were made entirely out of steel.
- Solid surface countertop: Countertops were taken as 2 ft wide and made from Richlite per the applicable project plans.
- Partition wall: A base unit of wall was established and modeled in Rhino. The wall was comprised of a steel stud frame spaced at 16" on center, mineral wool insulation (4" thick), and a single layer gypsum wall board (GWB) (thickness unknown, per Quartz) mounted on both sides of each wall. The quantities of these materials were extracted from Rhino and converted to the units of their respective environmental impact data. The impacts were then calculated using the respective data sources, and converted to the unit measurements in the quantity take-offs. See the Appendix for a drawing. Some partition walls in the projects had more than one layer of gypsum, but this was a small quantity (less than 10%), usually located around the core of the building for fire protection purposes. Since multiple layers of gypsum served non-TI purposes, it was deemed acceptable that these additional layers were not quantified.

- Metal ceiling panel: Metal ceiling panels represented what were originally "perforated metal ceiling panels" and "suspended ceiling grids." These two items were combined for simplicity, and also because they may have been ornamental, which would have categorized them outside the scope of this study. The impacts were taken as the average of an EPD for aluminum specialty ceiling products and galvanized steel from Quartz.

Cubicles and offices were counted per each in the quantity take-offs, but the environmental impact data in the EPDs were provided per square meter. The EPDs assumed that cubicles occupied a total floor space of 12 m^2 and offices occupied 23.3 m^2, which seemed inappropriately large. Therefore, the cubicle and office floor areas were estimated per typical areas shown in the project plans (45 sf / 4.2 m^2 and 120 sf / 11.2 m^2, respectively), and the environmental impacts per each item were calculated based on those areas.

Some items, such as glass display cabinets, wool acoustical ceiling panels, rope hanging screens, and marker boards (white boards), could not be accounted for because there were no satisfactory environmental data for these products. There was a relatively small quantity of these items in the projects, therefore it was deemed acceptable to omit them from the final QTO accounting. Inter-story stairs were also omitted because the material quantities were difficult to estimate from the project plans (often being prefabricated or custom made).

See Table 1 for a complete list of TI items and data sources used in this study.

*Table 1. 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	GWP [kg CO_2eq]	ODP [kg CFC11eq]*	AP [kg SO_2eq]*	EP [kg Neq]*	SFP [kg O_3eq]*	Energy [MJ]	Mass [kg]
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	Herman Miller	EPD	2016	N.A.							
	• Mirra® 2 Chair	Herman Miller	EPD	2014	N.A.							
	• Caper ® Stacking Chair	Herman Miller	EPD	2014	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*	• High pressure laminate (HPL compact)	Formica	EPD industry average	2017	Europe				X	X		

Relevant item from QTO	Product name	Source name	Type of source	Year	Region	GWP [kg CO_2eq]	ODP [kg CFC11eq]*	AP [kg SO_2eq]*	EP [kg Neq]*	SFP [kg O_3eq]*	Energy [MJ]	Mass [kg]
(sum of 2 products)	• Particleboard	AWC, CWC	EPD industry average	2013	N.A.		X	X				
linoleum	Linoleum Flooring	Quartz	Database	2015	N.A.							
metal ceiling panels (average of 2 products)	• Aluminum specialty products	CISCA	EPD industry average	2014	N.A.							
	• Galvanized Steel Ducts	Quartz	Database	2015	N.A.							
operable partition*	MOVEO Fullwall Element	Dorma	EPD	2012	Europe				X	X		
paint	Low VOC Eggshell Acrylic Paint	Quartz	Database	2015	N.A.							
partition wall (sum of 3 products)	• Steel Studs	Quartz	Database	2013	N.A.							
	• Drywall (Natural Gypsum)	Quartz	Database	2015	N.A.							
	• Thermafiber® Mineral Wool Insulation Light Density (without facing material)	Thermafiber	EPD	2014	N.A.							
server racks	Steel Plate	Athena	Database	2018	N.A.							
sheet vinyl*	Heterogeneous Vinyl Sheet	Armstrong	EPD	2014	N.A.			X	X			
sofa	UP 3 seat sofa with backrest	Fora Form	EPD	2017	Europe		X		X	X		
solid surface countertop*	Richlite Countertops	Richlite	EPD	2012	N.A.			X		X		
table*	Desk Nova U (approx. surface area 11 sf)	Narbutas	EPD	2017	Europe				X	X		
tile*	Ceramic Tile	Tile of Council of N. America	EPD industry average	2014	N.A.		X		X	X		
VCT*	Vinyl Composition Tile	Armstrong	EPD	2014	N.A.			X	X			
wall rubber base*	Rubber Wall Base (4" high)	Roppe	EPD	2018	N.A.				X	X		
wood flooring*	New hardwood flooring	USDA [1]	Research paper	2013	N.A.		X	X	X	X		
wood slat ceiling*	WoodWorks® Tegular, Vector® and Concealed Ceiling Panels (includes metal suspension system)	Armstrong	EPD	2017	N.A.		X					

3 Results

The environmental impact results were calculated by multiplying the material quantity data with the relevant environmental impact data. As noted previously, if an item had environmental data that had inconsistent units with TRACI 2.1, the impact value was assumed to be zero to avoid inflating the data. This only applied to acidification, eutrophication, smog formation, and ozone depletion. Global warming, energy, and mass all had consistent units.

3.1 Variation in material quantities

First of all, the relative material quantities per unit of total floor area varied between projects, and not all projects had all of the same items. This variation is shown in Figure 4 for items measured per each, Figure 5 for items measured per linear foot, and Figure 6 for items measured per square foot.

From these figures, it can be observed that TI projects varied widely in quantities and types of materials or items used. This suggests that the corresponding environmental impacts for TI will vary widely as well. It should be noted that:

- Project 4 did not provide furniture plans, so no furniture was counted for this project.
- Some quantities appear to be zero because 1) not all QTO items appeared in all projects, or 2) the quantities are so small that they do not appear on the graph. For example, server racks appeared only in Projects 1 and 5, while solid surface countertops appeared only in Projects 1, 4, and 5, but they all appear to be zero in Figure 5 because the quantities are all relatively low.
- Wall painting quantities may seem high, but it should be noted that both sides of all walls were assumed to be painted.
- The relative quantities of walls compared to floor areas affected the normalized values shown in the figures. For example, in the Project 3, the wall painting quantity per unit area was relatively high because the project had a very small footprint area compared its quantity of wall. However, the project had a small quantity of internal partition walls, so wall painting on the perimeter walls was significant.

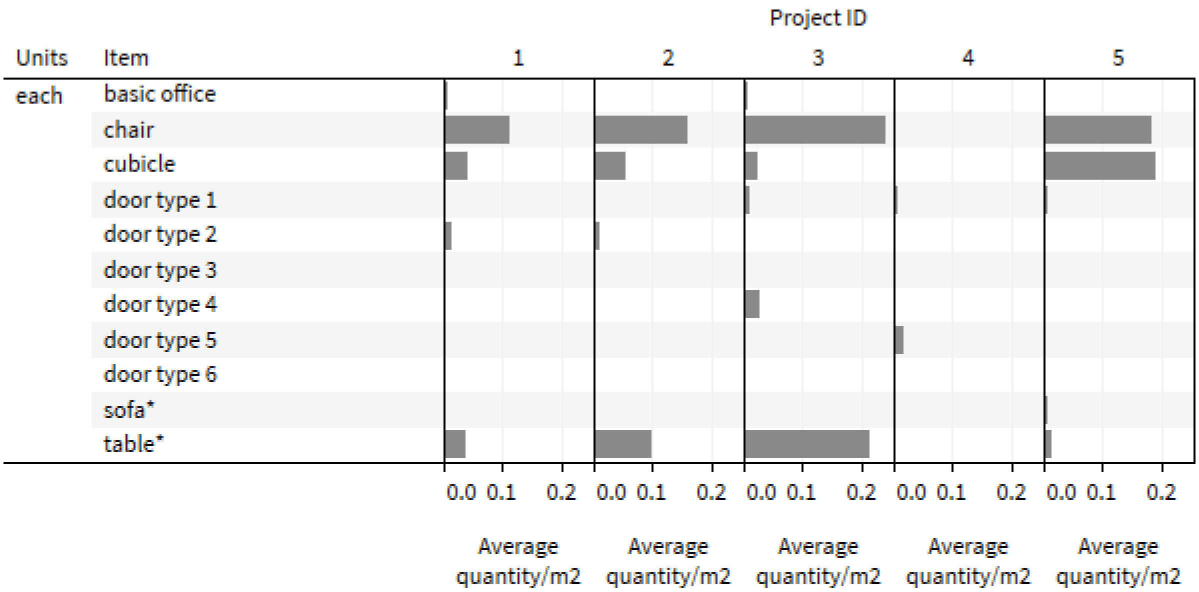

Figure 4. Relative variation in quantities between projects for QTO measured per each.

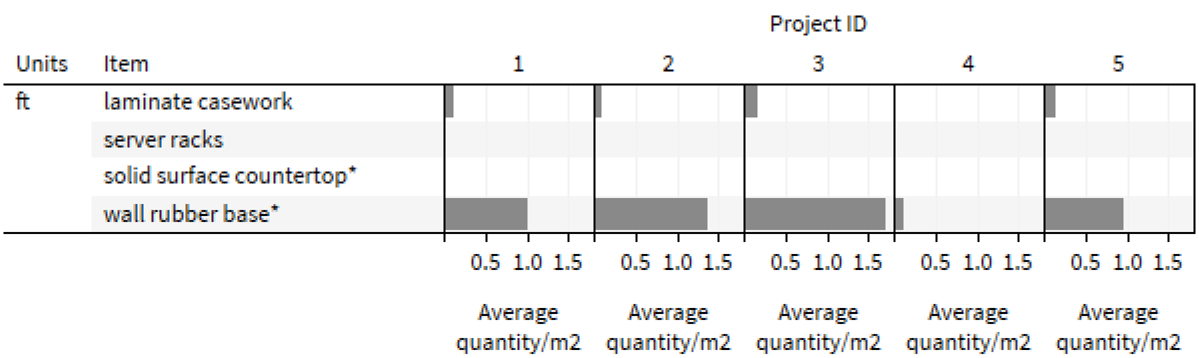

Figure 5. Relative variation in quantities between projects for QTO measured per linear ft.

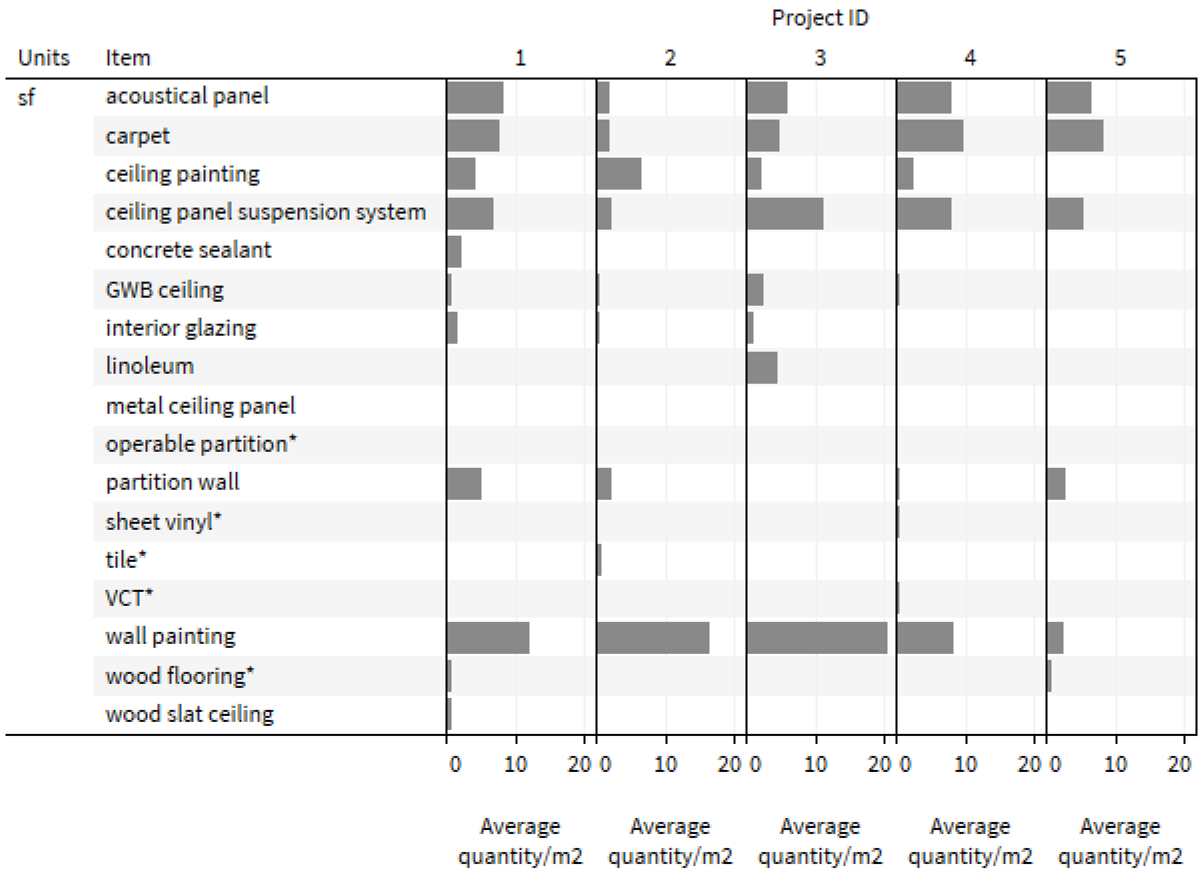

Figure 6. Relative variation in quantities between projects for QTO measured per square foot.

3.2 Impacts per item

The resulting environmental impacts of each item are shown in Figure 7, Figure 8, and Figure 9 for units of measurement per each, per linear foot, and per square foot respectively. From these figures, it can be observed which items are high-impact per unit of measurement. For "per each" items, offices, cubicles, and doors, especially the metal door are high-impact. For "per linear foot" items, server racks stand out. For "per square foot" items, high impact items include metal ceiling panels, operable partitions, and glazing. Later subsections explore which items are high-impact with consideration for their quantities in a building.

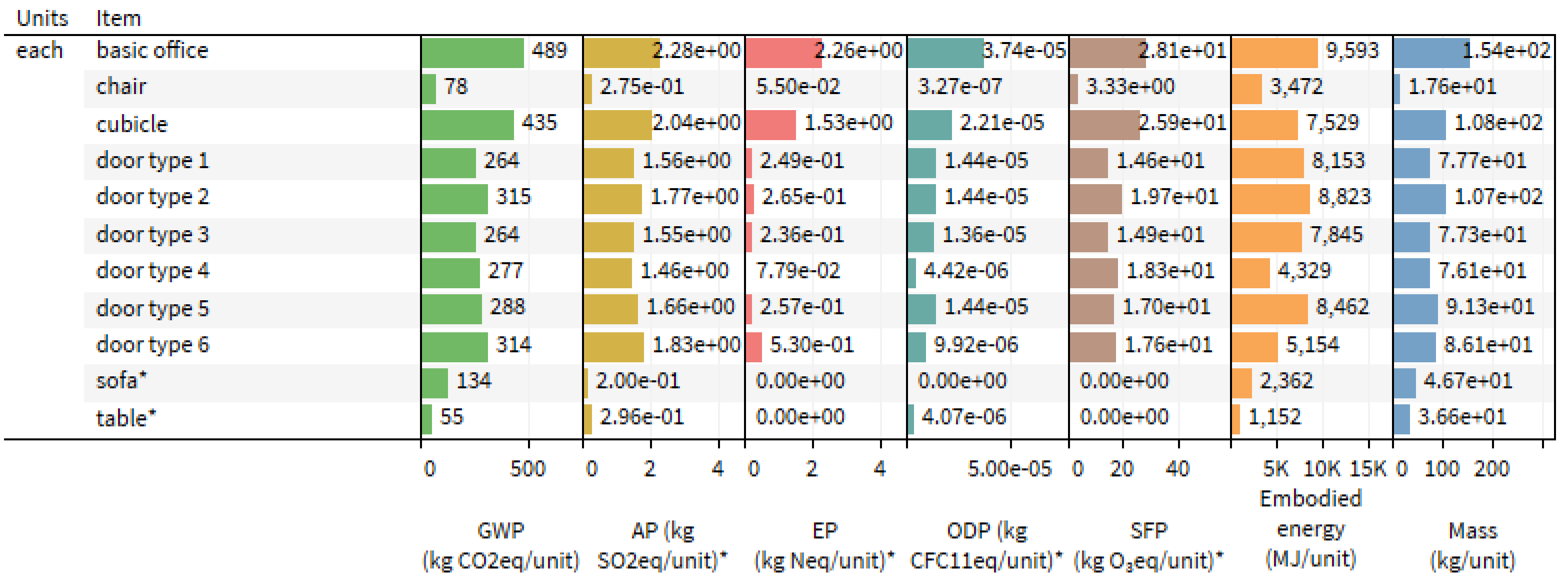

*Figure 7. Environmental impacts of items measured per each in the QTOs. * indicates items or measures that excluded data with inconsistent units.*

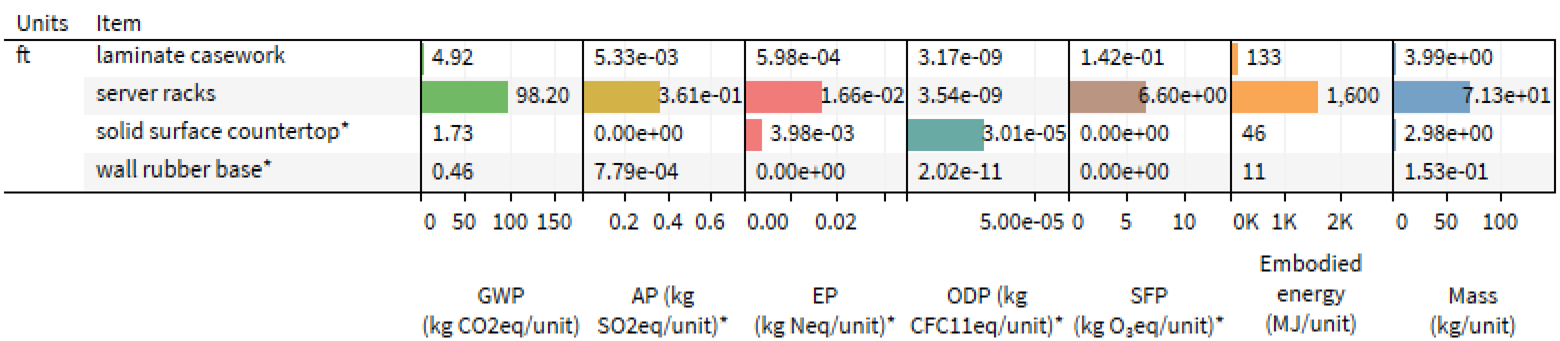

*Figure 8. Environmental impacts of items measured per linear foot (ft) in the QTOs. * indicates items or measures that excluded data with inconsistent units.*

Units	Subcategory	Item	GWP (kg CO2eq/unit)	AP (kg SO2eq/unit)*	EP (kg Neq/unit)*	ODP (kg CFC11eq/unit)*	SFP (kg O_3eq/unit)*	Embodied energy (MJ/unit)	Mass (kg/unit)
sf	Ceiling	acoustical panel	0.83	5.36e-03	9.22e-04	1.33e-08	4.13e-02	17.6	7.26e-01
		ceiling painting	0.03	1.51e-04	5.32e-06	3.38e-12	1.67e-03	0.6	1.49e-02
		ceiling panel suspension system	1.29	5.39e-03	2.74e-04	1.58e-08	7.74e-02	16.2	5.34e-01
		GWB ceiling	0.61	6.51e-03	4.00e-04	5.36e-10	1.39e-01	9.6	1.08e+00
		metal ceiling panel	18.69	9.35e-02	5.06e-03	1.05e-07	9.89e-01	285.7	1.22e+01
		wood slat ceiling	1.84	6.51e-02	9.60e-04	0.00e+00	1.47e-01	61.1	2.75e+00
	Flooring	carpet	1.63	4.11e-03	3.25e-04	1.92e-10	6.17e-02	29.6	1.86e-01
		concrete sealant	0.00	1.22e-05	7.26e-07	7.14e-13	2.02e-04	0.1	1.30e-02
		linoleum	0.26	4.45e-03	1.52e-03	1.02e-09	7.06e-02	15.3	2.70e-01
		sheet vinyl*	0.71	0.00e+00	0.00e+00	3.21e-09	0.00e+00	21.4	2.72e-01
		tile*	1.31	4.87e-03	0.00e+00	0.00e+00	0.00e+00	20.6	2.08e+00
		VCT*	0.58	0.00e+00	0.00e+00	9.42e-10	2.88e-02	12.9	6.36e-01
		wood flooring*	0.43	0.00e+00	0.00e+00	0.00e+00	0.00e+00	13.7	1.16e+00
	Wall	acoustical panel	0.83	5.36e-03	9.22e-04	1.33e-08	4.13e-02	17.6	7.26e-01
		interior glazing	3.01	1.25e-02	9.01e-04	9.39e-11	2.98e-01	39.3	1.72e+00
		operable partition*	8.69	5.91e-02	0.00e+00	9.56e-07	0.00e+00	210.0	1.18e+01
		partition wall	1.22	7.70e-03	8.44e-04	2.79e-08	9.25e-02	16.8	1.45e+00
		wall painting	0.03	1.51e-04	5.32e-06	3.38e-12	1.67e-03	0.6	1.49e-02
		Axis scale	0 10 20 30	0.00 0.10	0.000 0.010	0.00e+00	0.0 1.0 2.0	0 200 400	0 10 20

*Figure 9. Environmental impacts of items measured per square foot (sf) in the QTOs. * indicates items or measures that excluded data with inconsistent units.*

3.3 Overall impacts per project

Figure 10 presents the total impacts per square meter for each project in the study, and Figure 11 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. It can also be observed that overall environmental impacts are roughly correlated with mass, which is logical.

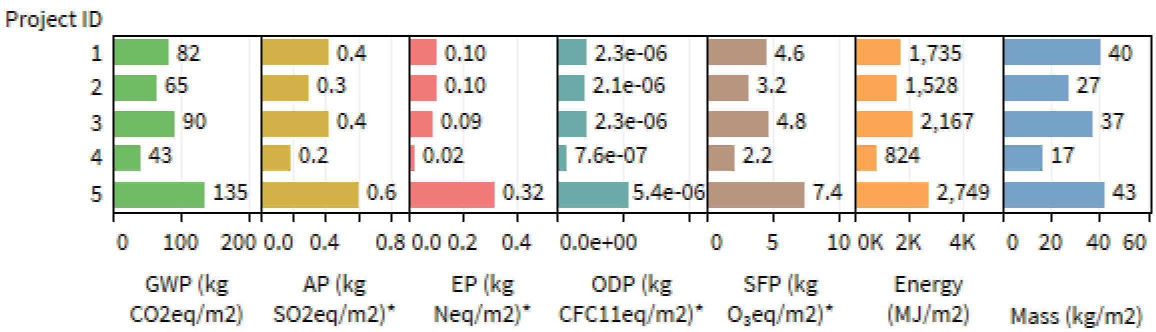

*Figure 10. Total impacts per square meter by project. * indicates items or measures that excluded data with inconsistent units.*

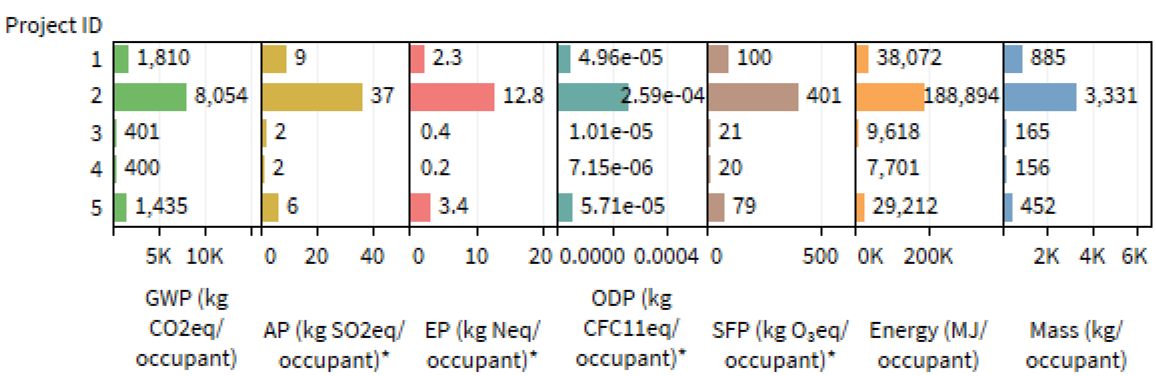

*Figure 11. Total impacts per occupant by project. * indicates items or measures that excluded data with inconsistent units.*

Figure 12 shows the variation in item impacts between projects. Due to space constraints, some items were consolidated into similar groups, and only three impacts categories are shown. From this figure, it can be observed that for different projects, different TI items are more or less significant as a result of their quantity and impact per item. However, some items are significant across projects and the three impact categories shown, such as: chairs, tables, cubicles, carpet ceiling panel suspension system, and acoustical panels. Note that Project 4 had zero impact from cubicles, since this was the medical office so there were no cubicles, while Project 5 was densely packed with working stations.

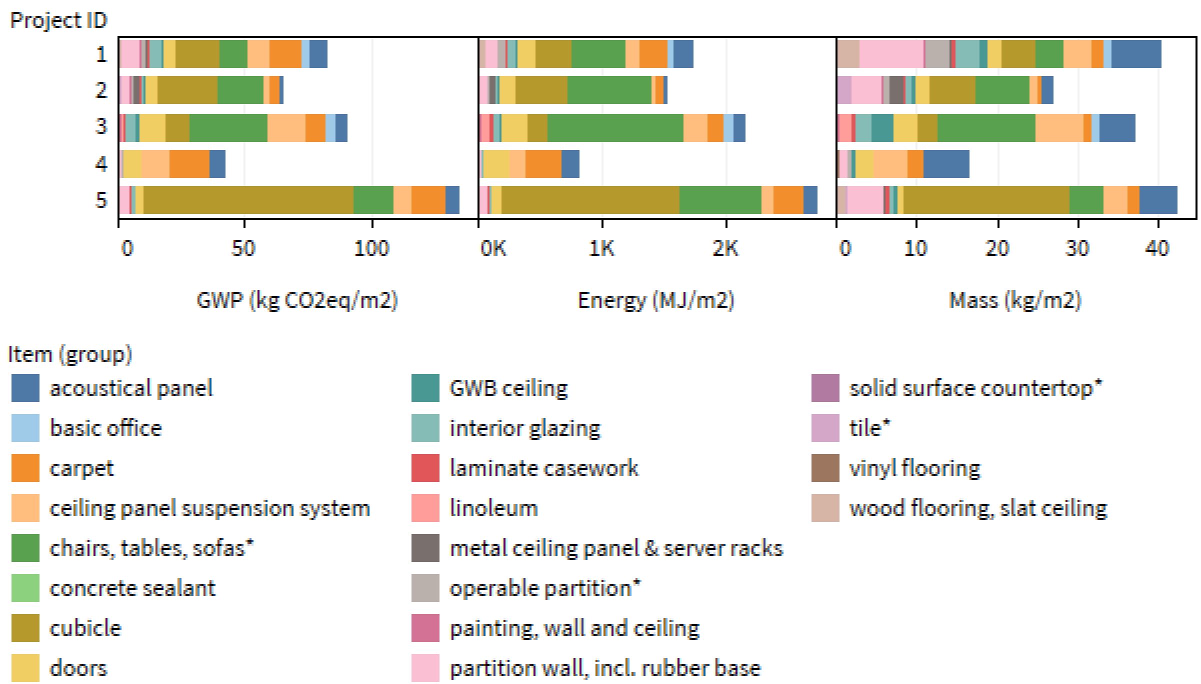

Figure 12. Variation in item contributions to overall GWP, energy, and mass between projects.

3.4 Average impact breakdown

Figure 13 presents the impacts per item per unit area, averaged across projects, and organized by the original QTO categorization scheme. Figure 14 presents the same but organized by Omniclass/Uniformat. These figures provide a sense of where the majority of TI environmental impacts reside in a building and how different environmental impact categories contribute differently to the overall picture. From this figure, it can be observed that the highest impacts can be attributed to office furniture or compartments (basic office, chairs, cubicles, tables), along with partitions, ceiling panel suspension systems, glass items (glass doors, interior glazing), carpet, acoustical panel, and metal ceiling panels. These items are not necessarily correlated with their corresponding masses, so Figure 15 explores the relationship between impacts and mass. From this figure, it can be observed that high impact-per-mass items according to various impact categories include: basic office, carpet, chair, cubicles, doors (which have a large part of their impact due to the metal frame), linoleum, sheet vinyl, solid surface countertops, and wood slat ceiling.

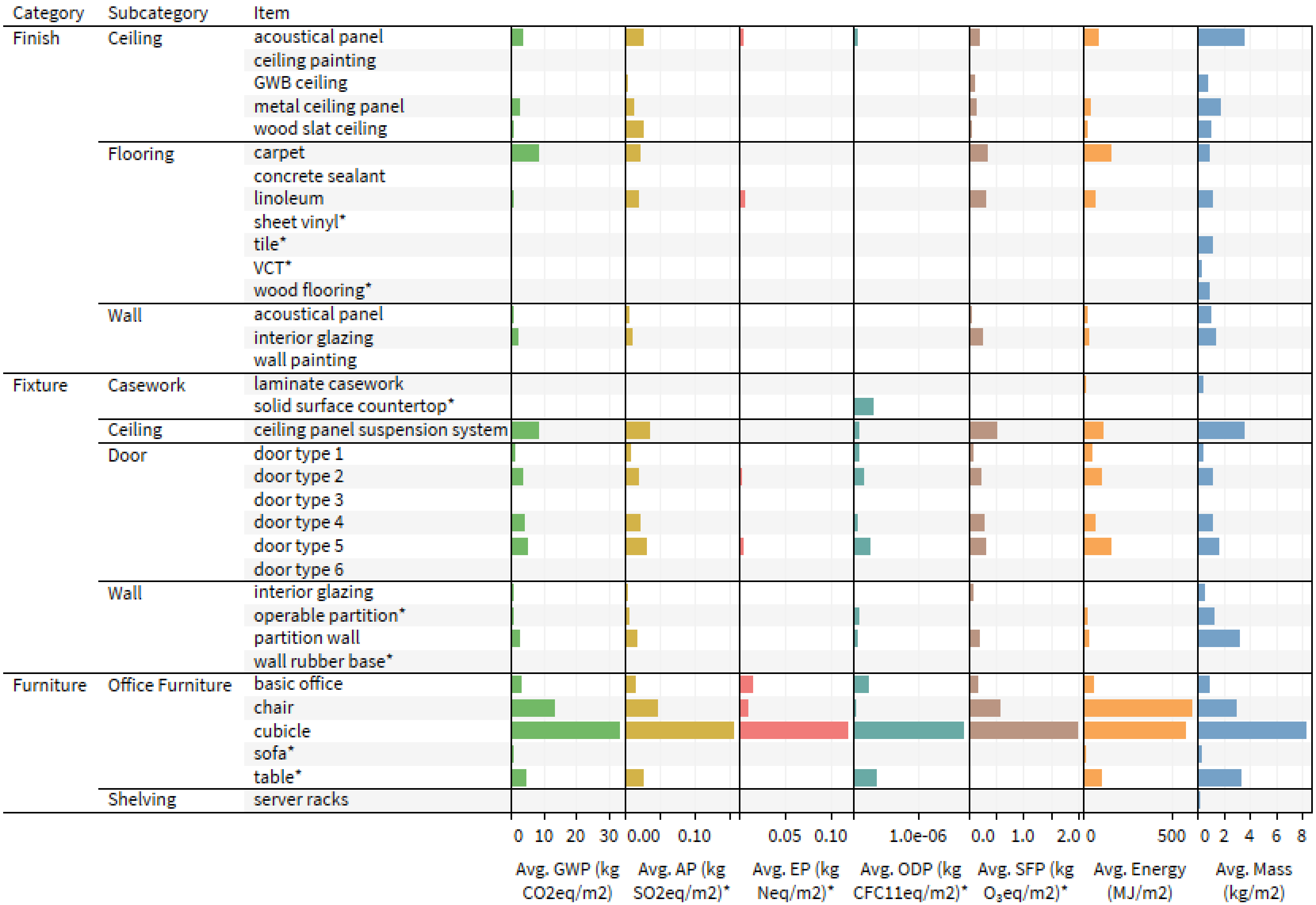

Figure 13. Breakdown of impacts by QTO categorization scheme, average of projects. (*) indicates that these items or measures excluded data that had inconsistent units.

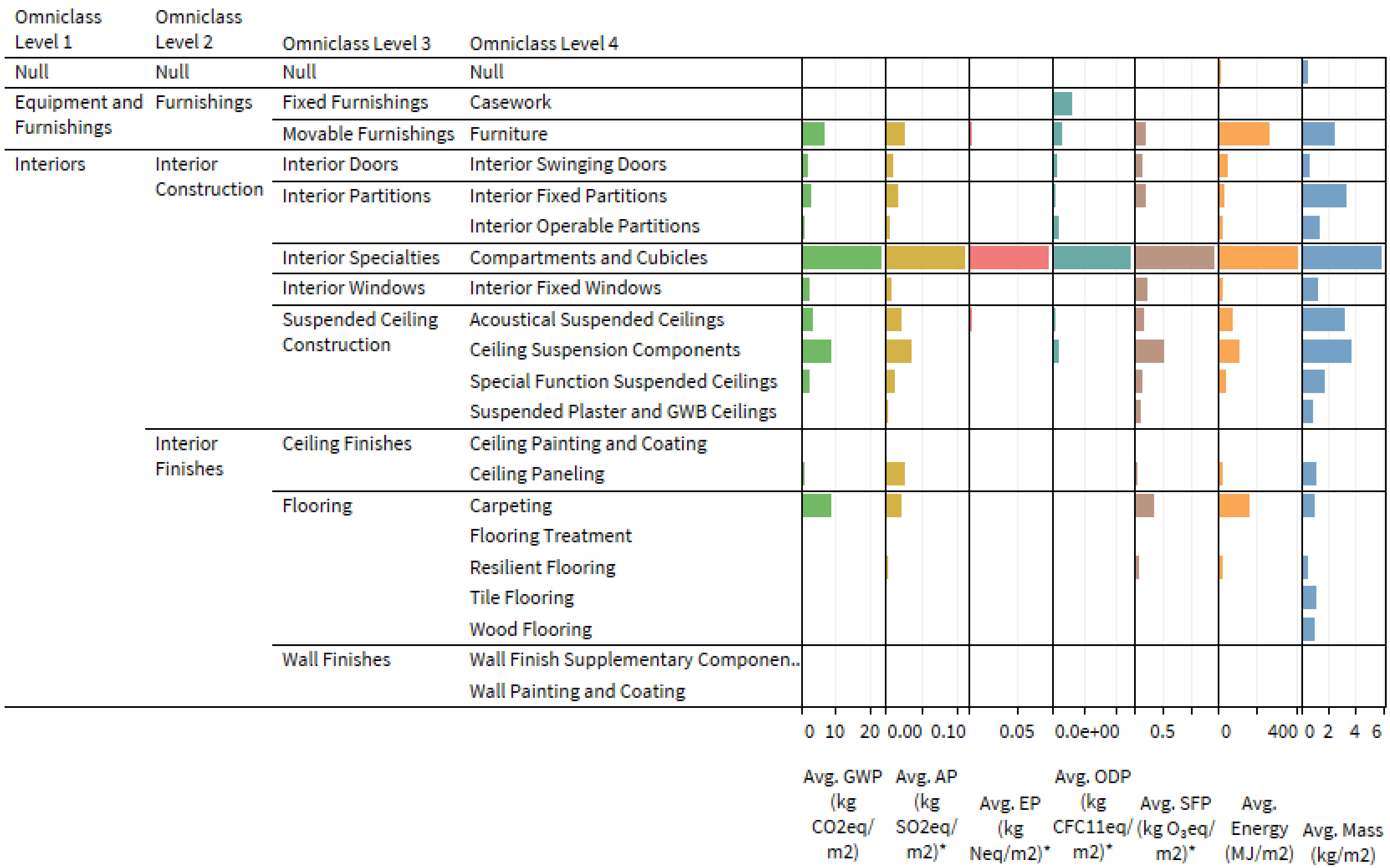

Figure 14. Breakdown of impacts by Omniclass classification, average of projects. (*) indicates that these items or measures excluded data that had inconsistent units.

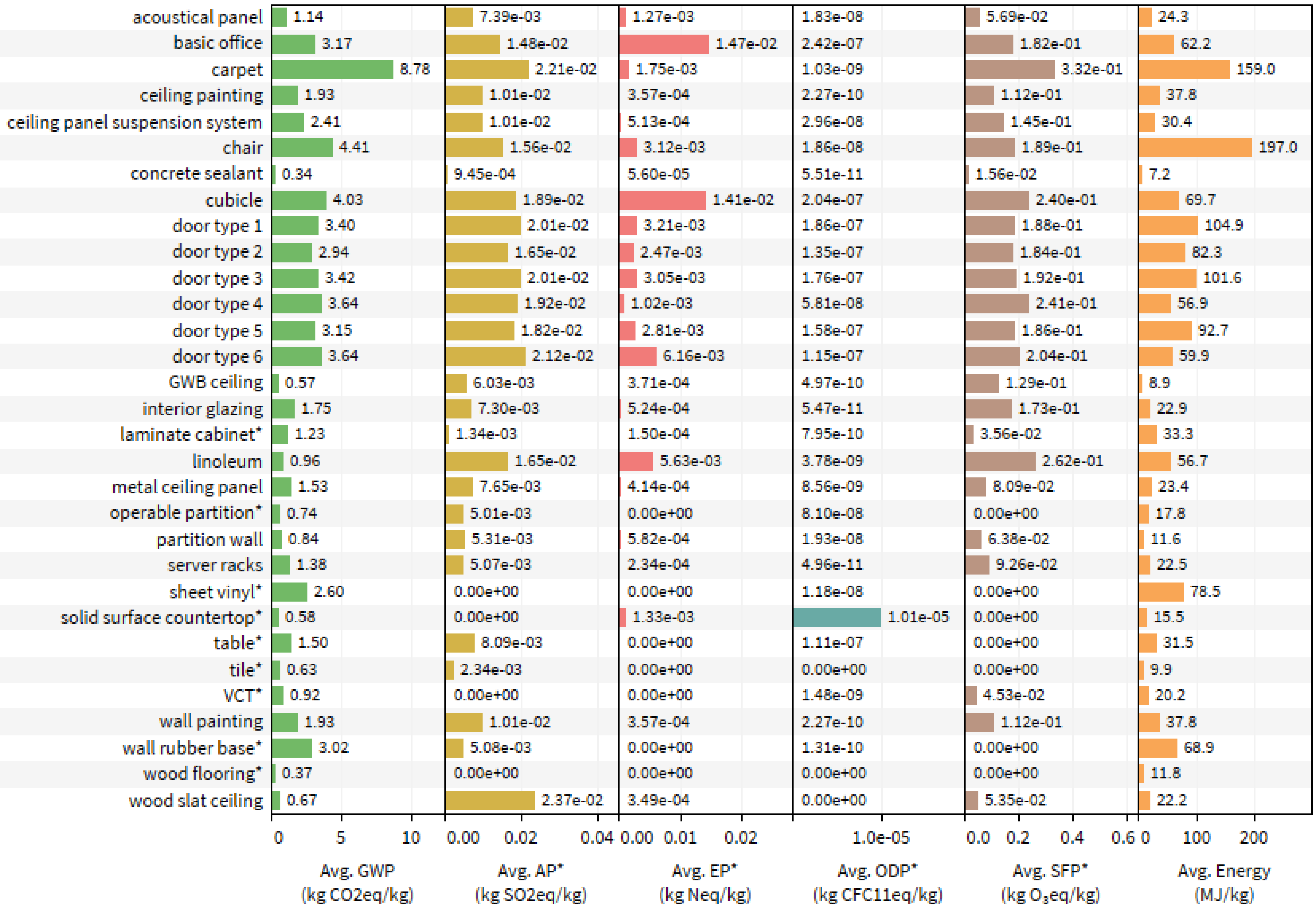

Figure 15. Impacts per kilogram mass.

Another way of visualizing the relationship (or lack of) between mass and the environmental impacts is shown in the scatterplots in Figure 16. The outlier point is from Project 5, resulting from the combination of the high quantity and high environmental impact per cubicle. For most of the impact categories, the points are not clustered tightly together, showing moderate correlation. The correlation coefficient R^2 ranged from 0.60 to 0.85 for the different impact categories.

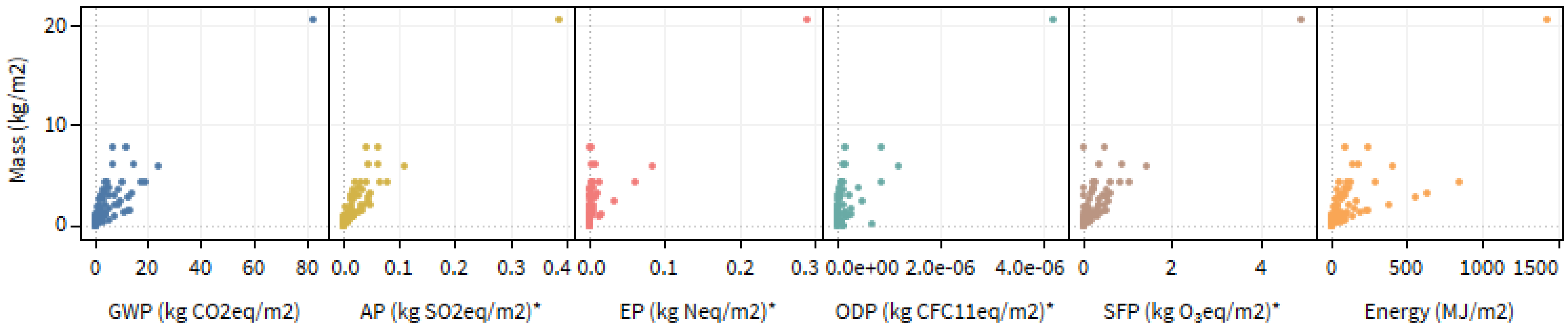

Figure 16. Scatterplot of mass vs environmental impact categories.

Alternatively, the correlation between GWP and the other impact categories can be observed in Figure 17. The correlation is not particularly strong, so it is debatable whether GWP would be a good proxy for other environmental impacts.

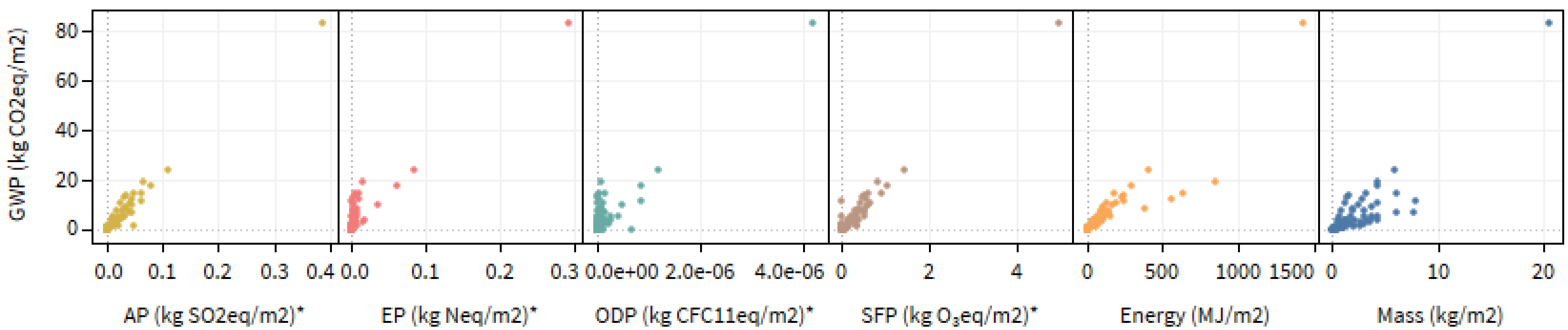

Figure 17. Scatterplot of GWP vs environmental impact categories.

3.5 Overall range of impacts

This section presents the results in boxplots to illustrate the range of impacts across projects.

Figure 18 presents the range in overall project impacts in each impact category. It can observed that the relative distances between the low, medium, and high points in the box plots differ by impact category, and this can be attributed to the unique variation in material types and quantities of each project.

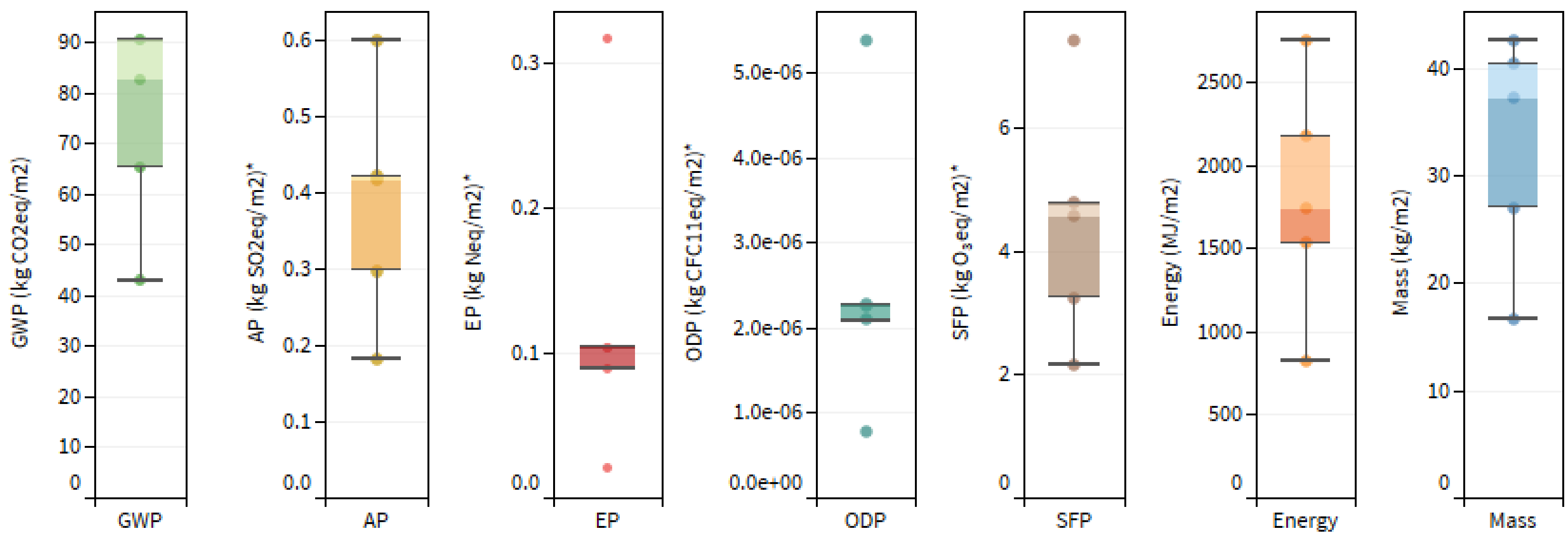

Figure 18. Boxplots of overall impacts per project.

Figure 19 presents the average impact per item across projects in each impact category. From this figure, it can be seen that the widest variations in impacts is attributed to cubicles/workstations, which had widely varying quantities by project, and the effect is amplified in the environmental impacts.

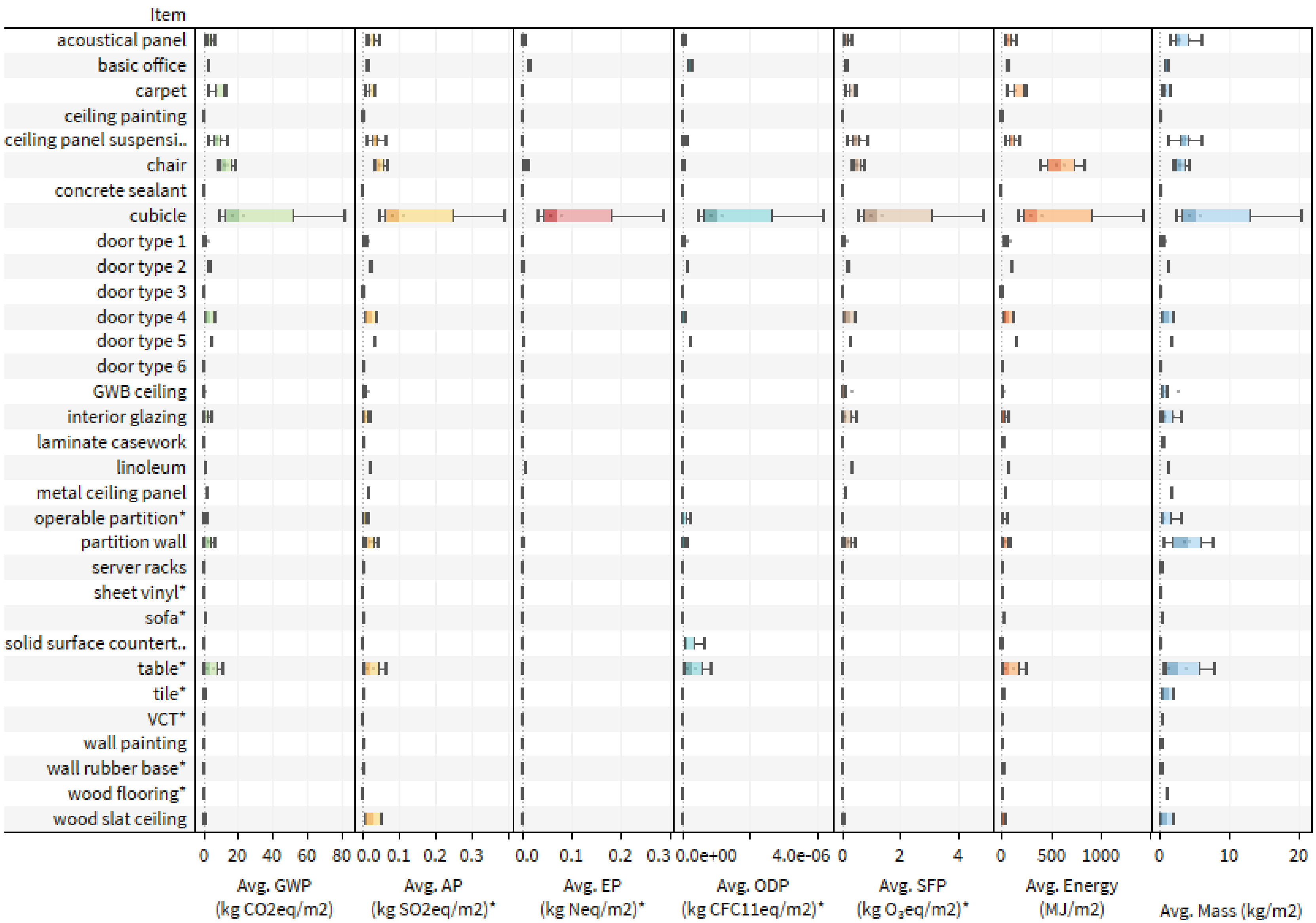

Figure 19. Boxplots of average impacts per item.

4 Discussion

4.1 Key observations

Key observations from the results of the study are as follows:

- Impacts normalized by total floor area presented a very different picture than impacts normalized by number of occupants when comparing projects.
- Overall impacts per unit of total floor area ranged approximately as follows:
    - GWP: 45 – 135 kg CO_2eq/m^2
    - AP: 0.2 – 0.6 kg SO_2eq/m^2
    - EP: 0.02 – 0.30 kg Neq/m2
    - ODP: $7.6x10^{-7}$ – $5.4x10^{-6}$ kg CFC11eq/m^2
    - SFP: 2.2 – 7.4 kg O_3/m^2
    - Energy: 820 – 2750 MJ/m^2, or approximately 73 – 242 kBTU/sf
    - Mass: 17 – 43 kg/m^2
- High-impact items, as observed across multiple impact categories in the context of building material quantities, were noted to be:
    - Cubicles (or workstations)
    - Other office furniture (tables, chairs, private offices)
    - Ceiling panel suspension system
    - Interior glazing
    - Carpet
    - Doors (including door frames)
    - Partition walls
    - Acoustical panels
- Impacts were typically correlated with mass in the context of an overall building, but necessarily on an individual item level.
- Some items that had high impacts in one impact category did not necessarily have high impacts in other impact categories, and vice versa.

4.2 Impact of recurrence

An important consideration for the environmental impacts of TI work is how frequently TI projects occur, or the recurrence rate. According to industry advisors, TI fit-out typically occurs every 10 – 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 – 810 kg CO_2e/m^2, using the GWP results estimated from this study. These estimates are within the range of the embodied carbon impacts of new construction in the Embodied Carbon Benchmark Study (between 50 - 1300 kg CO_2e/m^2) meaning that the impact of recurring TI is on the same order of magnitude as that of whole building new construction. This suggests that the environmental impacts of TI work are significant and should not be ignored in building LCAs.

End-of-life impacts were not included in this study, but it would have been an important aspect to consider, due to the recurring nature of TI.

4.3 Strategies for reducing TI impacts

Based on the results of this study, the following strategies for reducing TI impacts can be proposed:

- Reduce or re-use office furniture, including cubicles and private offices. These items were observed to have the highest impacts in the context of a building.
- Avoid using carpet, tile, and ceiling panels; expose floors and ceilings instead, or source low-impact products for these components.
- Limit use of interior glass.
- Limit use of doors.
- Limit use of metal items, such as metal ceiling panels and server racks.
- In general, reduce, re-use, or recycle carpet, ceiling panels, or any product as much as possible.

4.4 Limitations and uncertainty

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. Only three buildings were used in this study, and the buildings were not statistically representative of the building stock.

Additional sources of uncertainty in this study include:

- Occupancy: 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. Some project advisors did not provide a response to this query, so the research team estimated number of occupants based on cubicles and/or offices. Number of chairs could have been a substitute, but not all chairs are occupied at all times (e.g. in a conference room).
- Environmental data with differing units: Six of the 26 items considered in this study had one or two impact values that did not match units with other LCA data, which was standardized per TRACI 2.1. These items and impact categories, which were marked with an asterisk in figures and tables, have a higher level of uncertainty.
- Representativeness of data: The LCA data for TI 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 project, 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.

    - It should also be noted that EPDs tend to represent environmentally-conscious products or companies, and so the "true" typical environmental impacts for items represented by EPDs are likely to be higher than shown in this study.
    - Generalized conclusions should not be based on items based on product-specific EPDs. For example: It may be tempting to conclude that because a basic office (489 kg CO2e) has a higher impact than a cubicle (435 kg CO2e), offices should be minimized in favor of cubicles. However, these two products were based on EPD data and a limited sample of office plans, therefore the difference between their impacts is not that significant, so it is possible that a basic office is not necessarily lower impact than a cubicle, depending on the design. However, offices usually have doors, which are an additional impact compared to a cubicle.
    - Lastly, some items were based on European EPDs (Formica in the laminate cabinets, operable partition, tables, sofas) due to lack of North American EPDs for these products. Therefore, the results from these products are not considered geographically representative and thus have additional uncertainty.
- Limited number of sample projects: As stated earlier, having only four projects limits the strength and representativeness of the findings from this study. The projects were also not equally geographically representative of the two states -- one small project was located in Oregon, and three larger projects were located in Washington. The limited sample size also limited the selection of TI items analyzed in this study – a greater number of projects would probably have introduced additional TI items to analyze.
- Not all projects were from office buildings: The research team endeavored to collect projects from "commercial office spaces," intending them to be from commercial office buildings, but was provided projects from a variety of building types. Due to the difficulty in obtaining project plans, the research team opted to incorporate some projects that were not housed in commercial office buildings.
- End-of-life impacts: As stated earlier, end-of-life impacts would have been valuable to consider due to the recurring nature of TI work.

Due to these sources of uncertainty, the true impact of TI is likely to be somewhat higher than the results of this study.

5 Conclusion

This study characterized material quantities and environmental impacts of tenant improvement (TI) in office buildings in the Pacific Northwest. This was done by collecting material quantity data from four actual projects (three in Washington, one in Oregon). Environmental impact data were taken primarily from 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. These findings suggest that the environmental impacts of TI can be mitigated by re-using or recycling these high-impact and sometimes high-quantity components.

6 References

[1] R.D. Bergman, R.H. Falk, J. Salazar, H. Gu, T.R. Napier, J. Meil, Life-Cycle Energy and GHG Emissions for New and Recovered Softwood Framing Lumber and Hardwood Flooring Considering End-of-Life Scenarios, 2013. www.fpl.fs.fed.us. (accessed October 16, 2018).

[2] K. Simonen, B.X. Rodriguez, E. McDade, L. Strain, Embodied Carbon Benchmark Study: LCA for Low Carbon Construction, (2017). http://hdl.handle.net/1773/38017.

[3] E. Hoxha, T. Jusselme, On the necessity of improving the environmental impacts of furniture and appliances in net-zero energy buildings, Sci. Total Environ. 596–597 (2017) 405–416. doi:10.1016/J.SCITOTENV.2017.03.107.

[4] U.S. Department of Energy, Building Performance Database, (n.d.). https://bpd.lbl.gov/#explore (accessed October 16, 2018).

7 Appendices

7.1 QTO Rhino modeling

7.1.1 Door

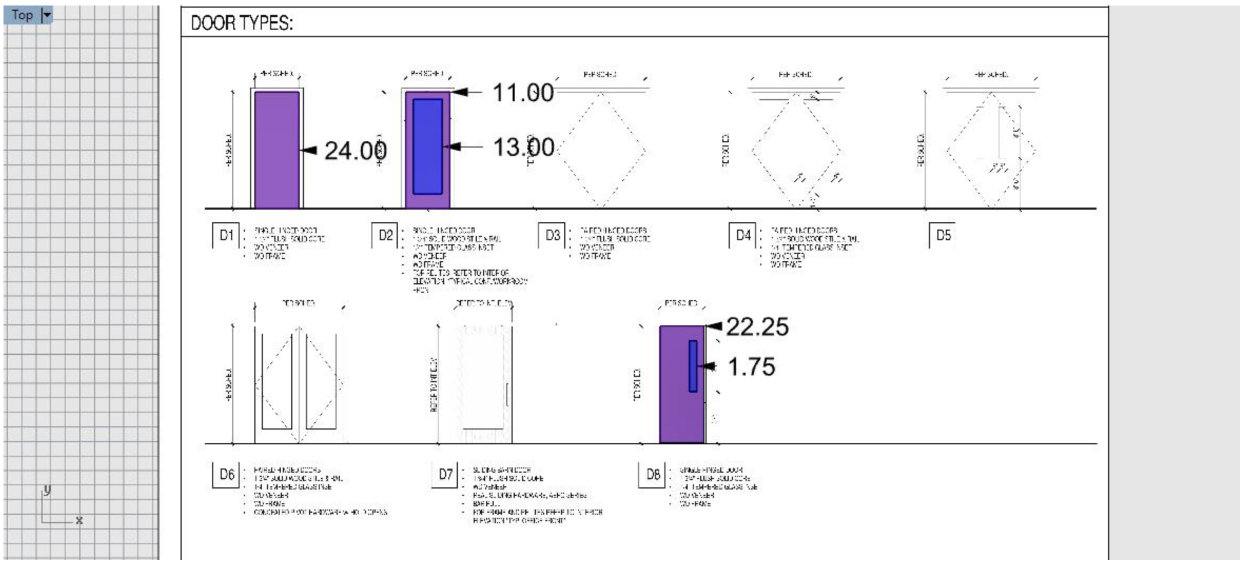

Figure 20. Modeled doors (door types 1, 2, and 3, which are colored in, from left to right). Doors were drawn using the images on the plans and then corrected to scale indicated on drawings. No volumetric data was required, hence the drawing and image being laid out in the "top" view. Areas were calculated by highlighted the object and typing "Area."

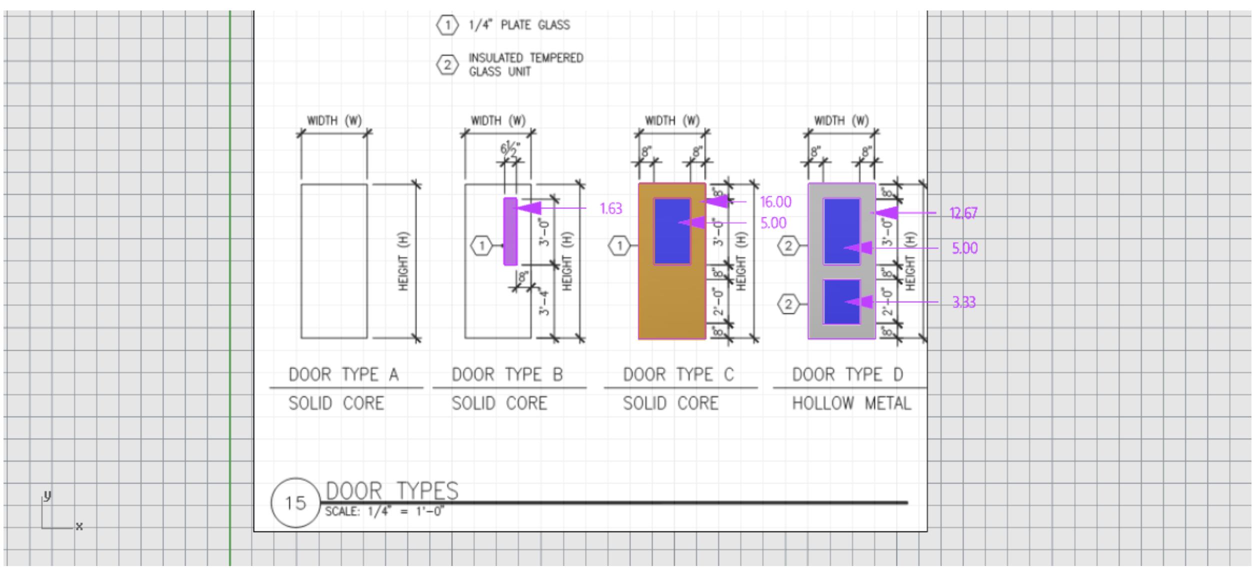

Figure 21. Modeled doors (door types 1, 3, 5, and 6 from left to right).

7.1.2 Interior glazing

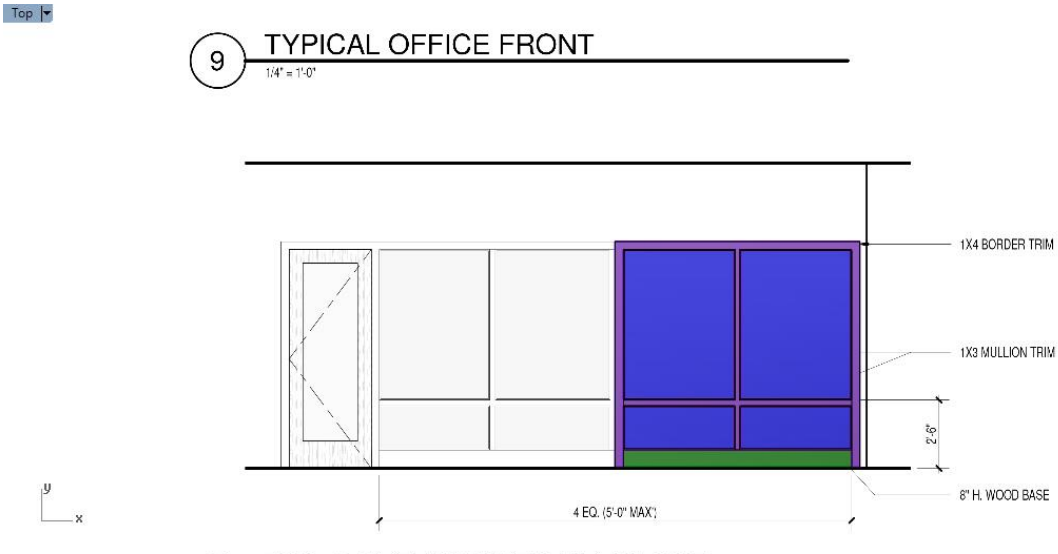

Figure 22. Top view of standard glazing panel modeled on top of TI plans. The model does not fit perfectly with the drawing due to lack of accuracy between described measurements and scale of drawings on plan.

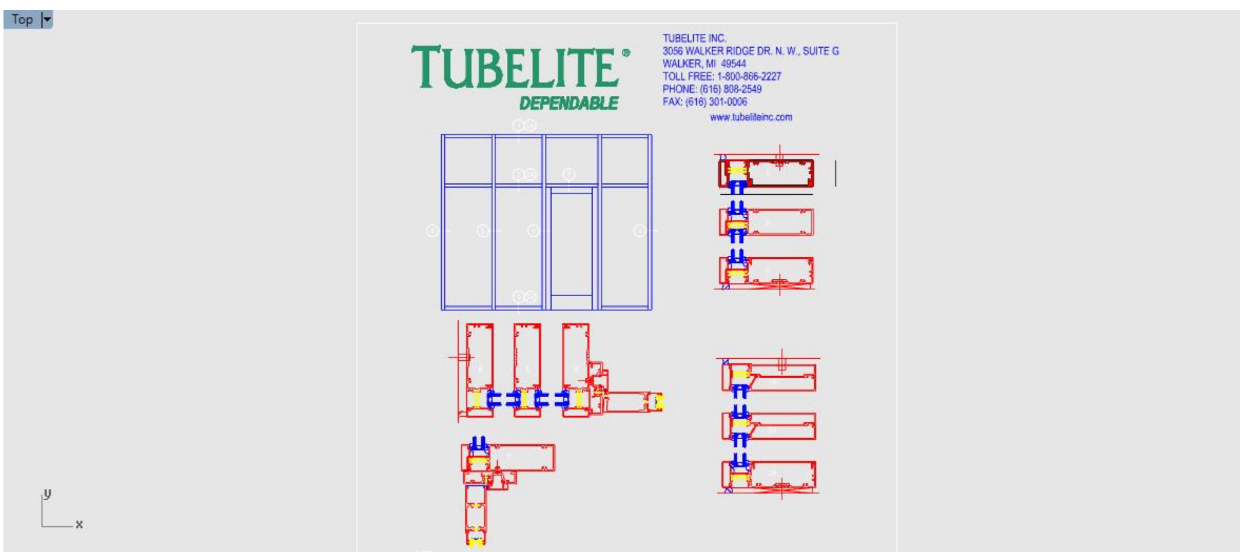

Figure 23. Mullion information was obtained through easily downloaded CAD files and directly imported into Rhino. An average piece was selected as representative of all mullion section cuts.

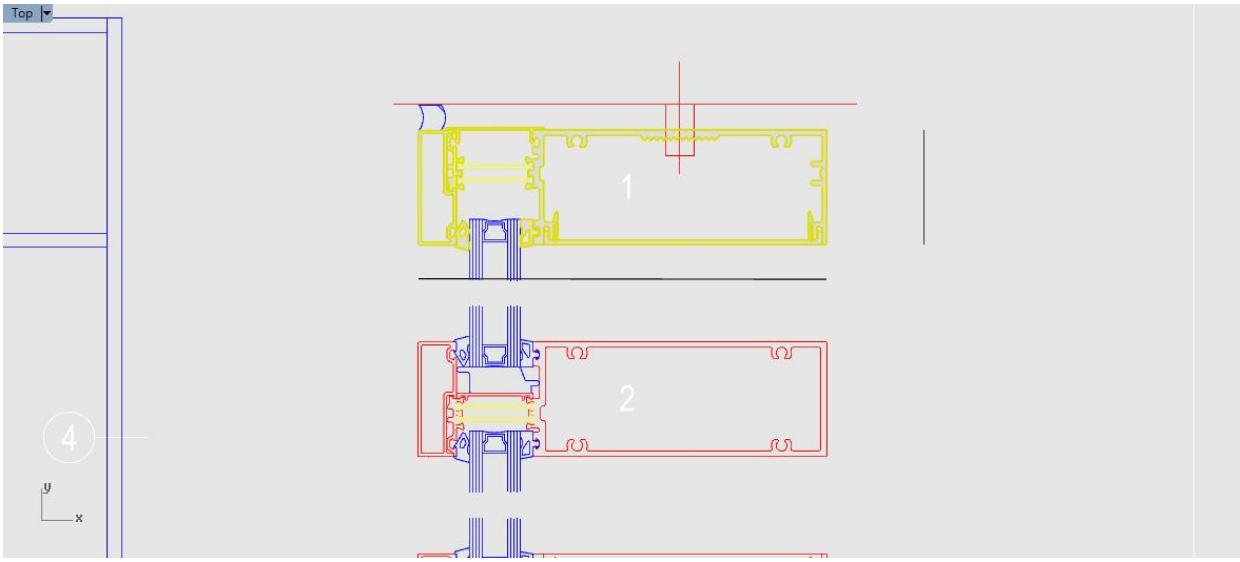

Figure 24. Linework was converted to planar surfaces, allowing easy extraction of surface area data.

7.1.3 *Laminate cabinet (casework)*

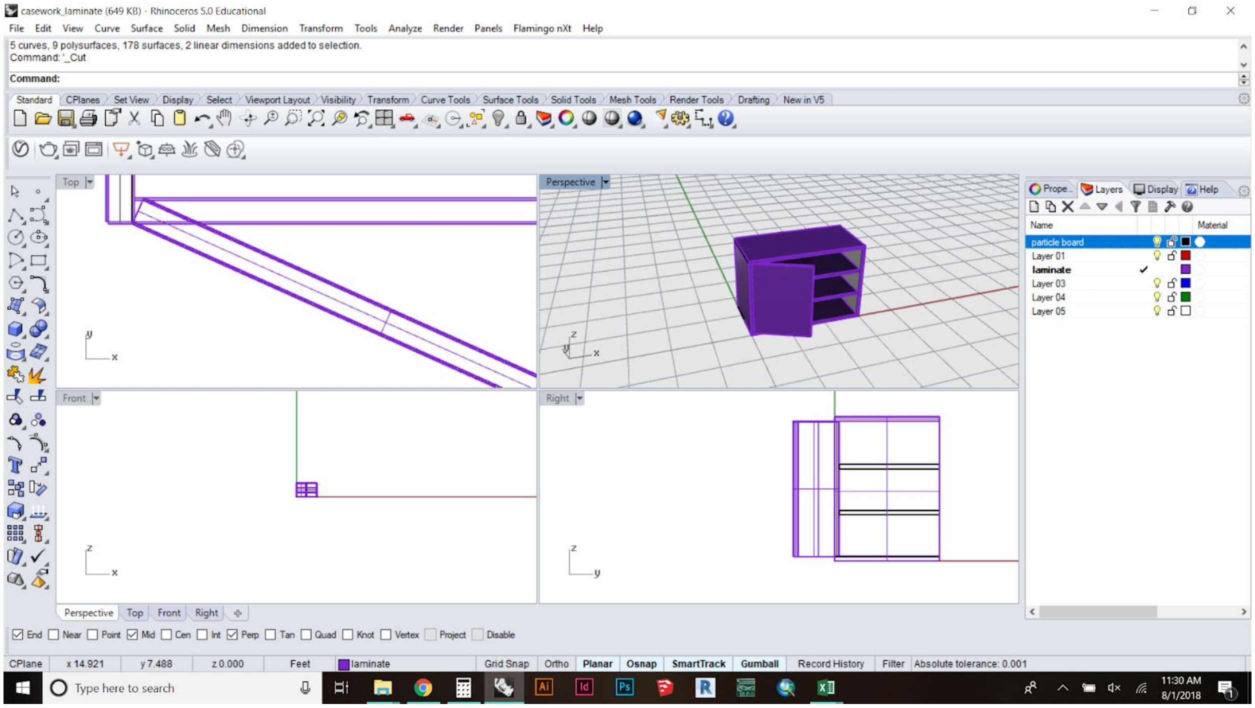

Figure 25. Screen capture of Rhino software with 3D laminate casework mockup used for estimating takeoffs.

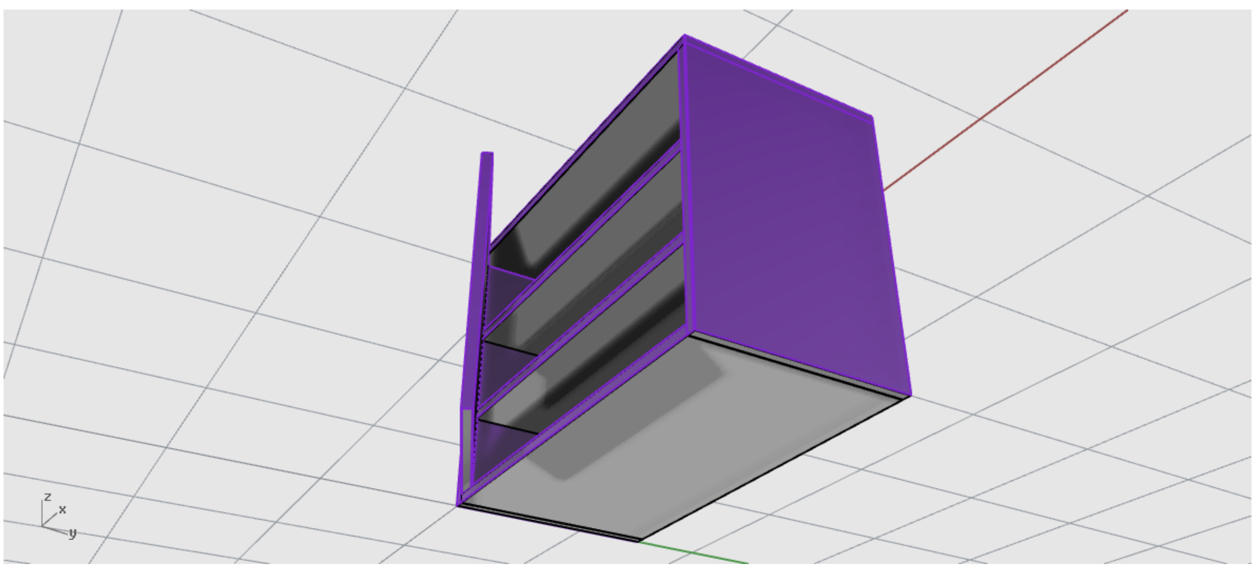

Figure 26. Laminate was applied only to those surfaces visible during normal use, as with most real world casework. Surface Area was then extracted for laminated surfaces.

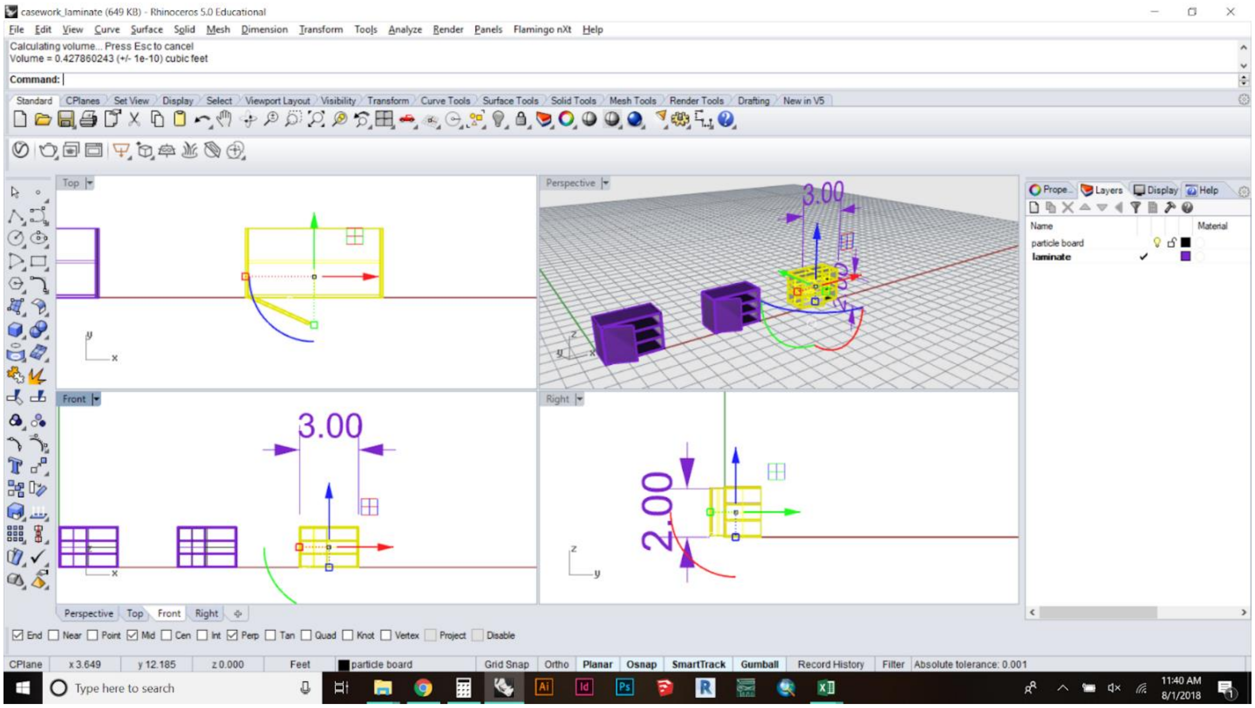

Figure 27. *The EPD used to establish impacts for particle board uses a functional unit of m³. Selecting the objects on the particle board layer allowed for easy extraction of the volume in ft³ which was then converted into m³.*

7.1.4 Partition wall

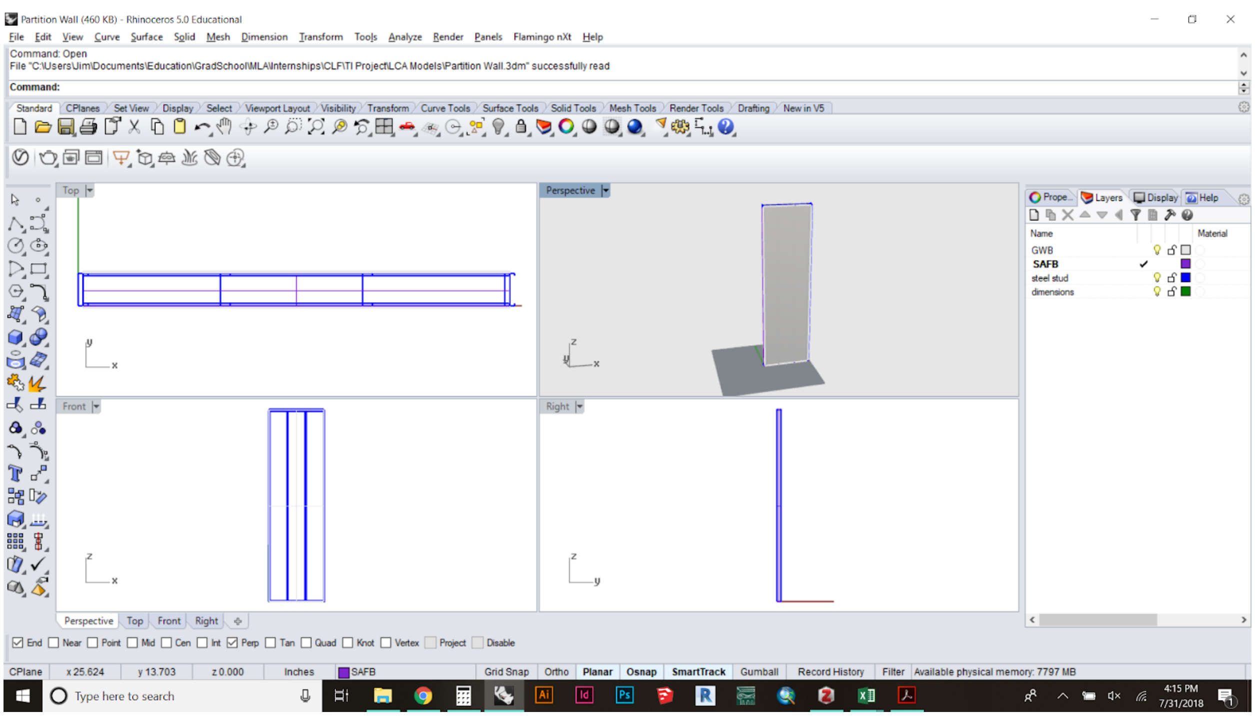

Figure 28. Screen capture of Rhino software with 3D Partition Wall mockup used for estimating takeoffs.

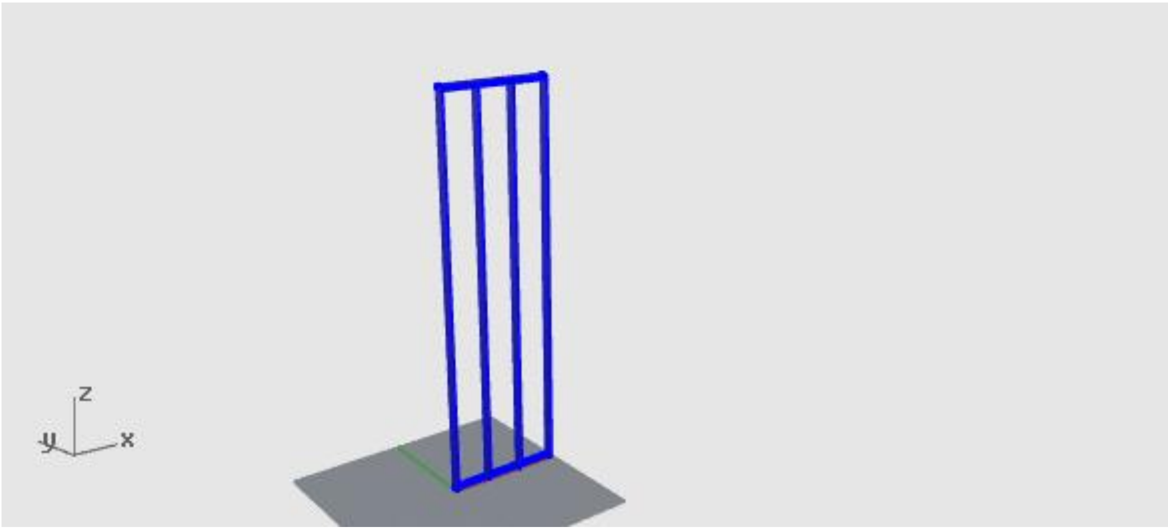

Figure 29. 3D view of Partition Wall mockup in Shaded mode, shown here with only the Steel Stud layer visible.

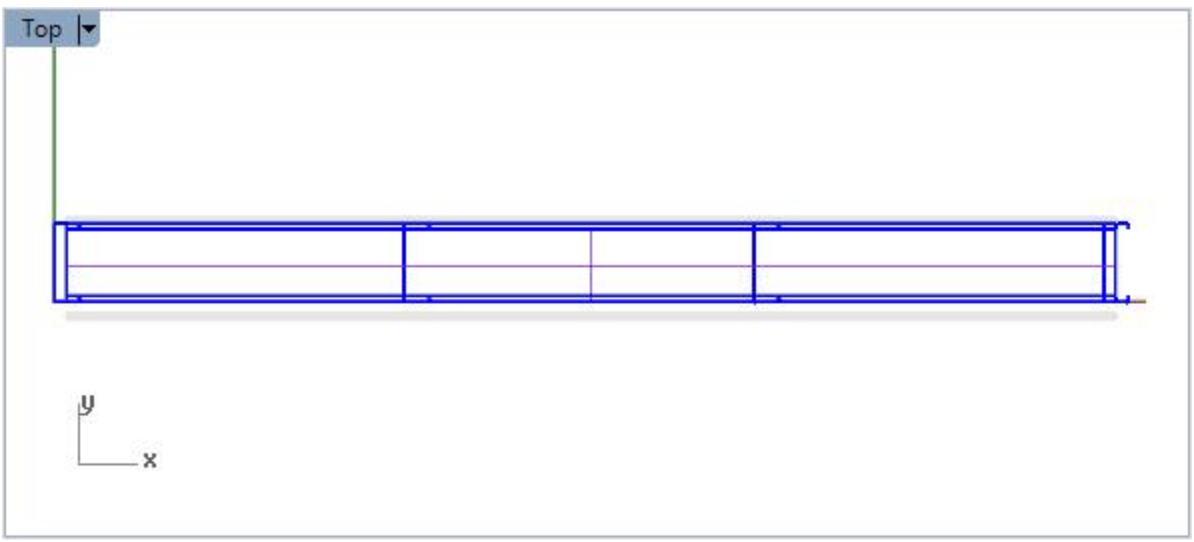

Figure 30. Top view of 3D Partition Wall viewed in Wireframe mode.

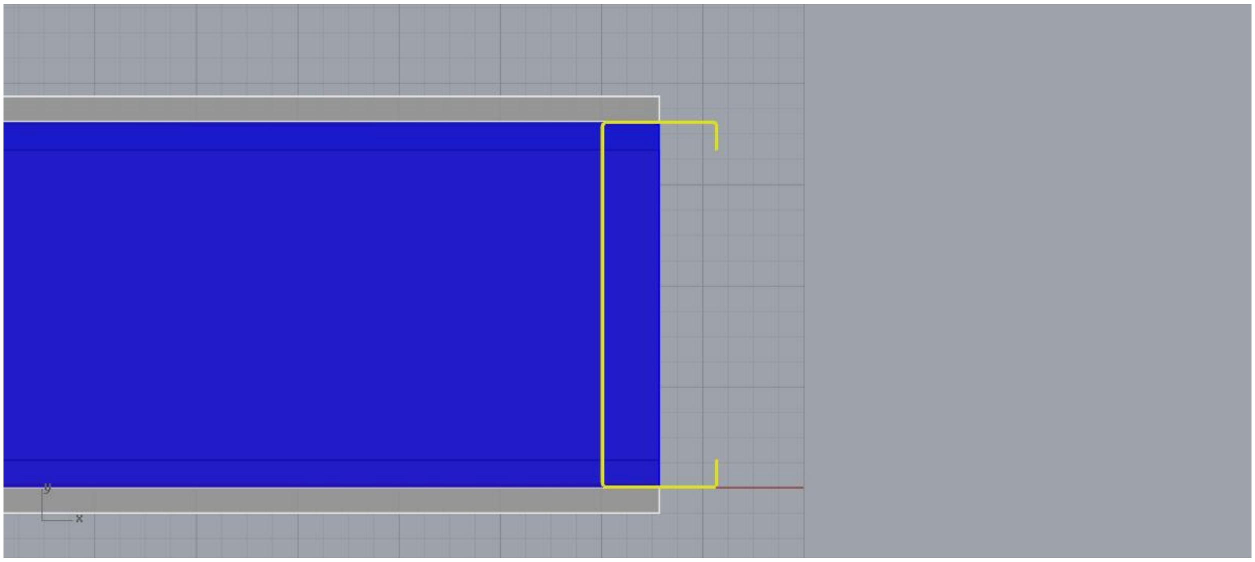

Figure 31. Top view of 3D Partition Wall viewed in Ghost mode with the surface area of the stud highlighted in yellow. Dimensions are to scale. (https://hw.menardc.com/main/items/media/CLARK024/Prod_Tech_Spec/ProSTUD_Physical-Structural.pdf)

7.1.5 Ceiling panel suspension system

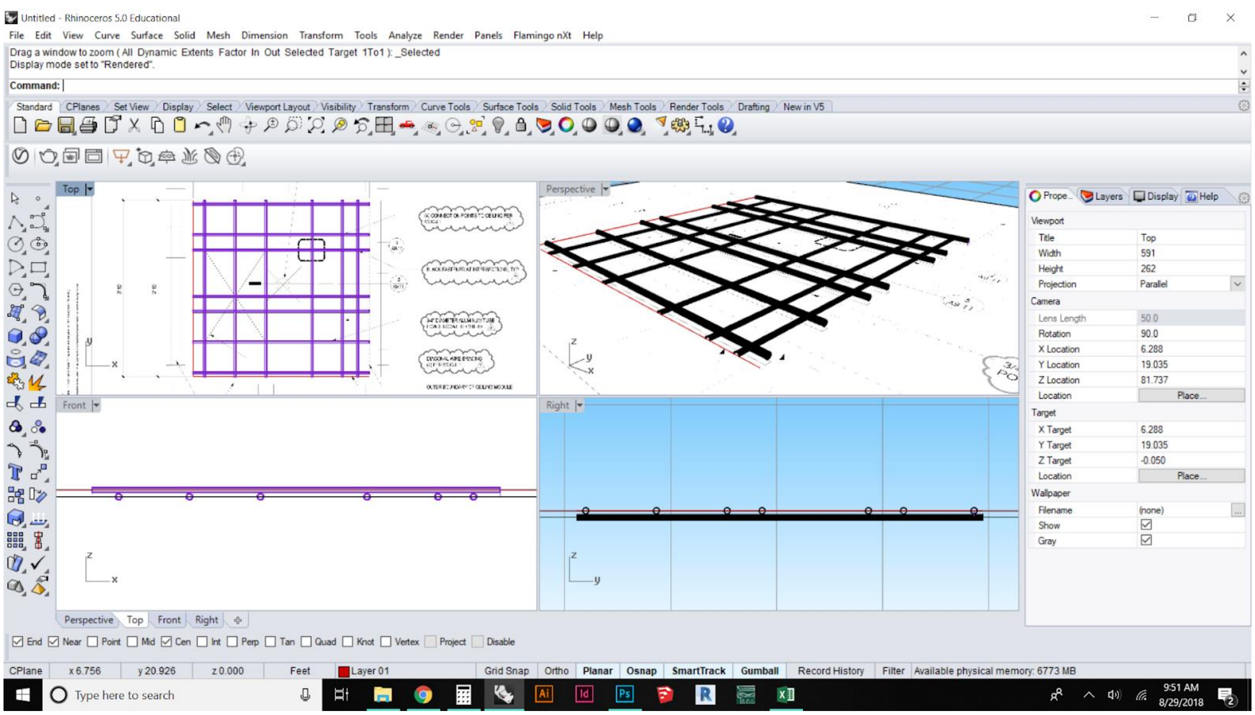

Figure 32. Screen capture of Rhino software with "modified metal suspension system" mockup used for estimating takeoffs. Aluminum tubes are specified in the plans, with unlabeled dimensions (diameter, wall thickness) being taken from the following source: http://www.speedymetals.com/pc-4564-8371-34-od-x-0049-wall-tube-6061-t6-aluminum.aspx

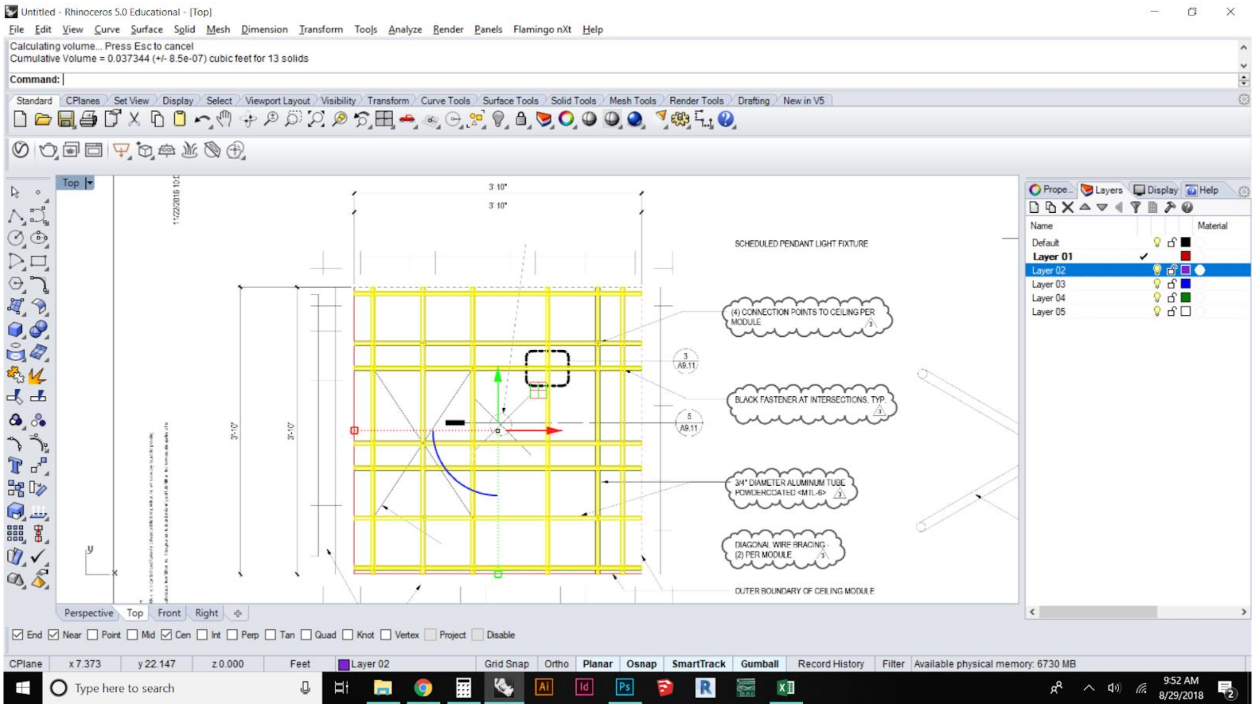

Figure 33. The EPD used to establish impacts for aluminum uses a functional unit of 1 kg. Rhino allowed for easy calculation of the volume of material for the aluminum tubing, which was then multiplied by the density of aluminum to determine the overall weight of the aluminum structure in kilograms.

7.2 Comparison to other datasets

7.2.1 Embodied Carbon Benchmark Study

The Carbon Leadership Forum's Embodied Carbon Benchmark Study contains embodied carbon data for approximately 1,000 buildings. The embodied carbon of the office buildings subset is reproduced in Figure 34.

For the purposes of comparing the TI results with the Embodied Carbon Benchmark study, Figure 34 was modified to include US buildings only. The result is shown in Figure 35, along with the range of the TI results (135 kg CO2e/m2) shown by the red band. From this figure, it can be observed that the embodied carbon estimates for TI are significantly lower than most (98%) of the buildings in the ECB study. This means that in initial construction, TI is likely to be an insignificant portion of the overall environmental impact of a building.

The summary document contains additional analysis on the impact of recurrence

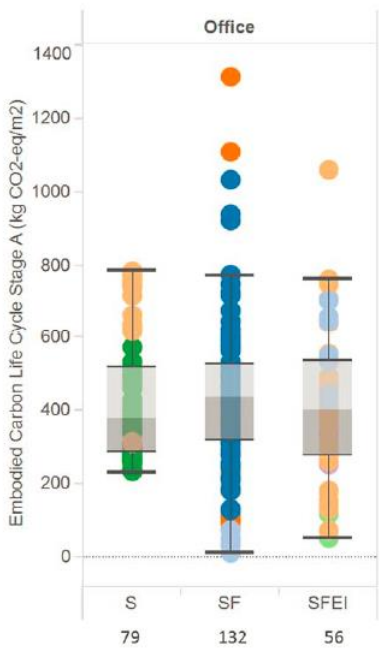

Figure 34. Embodied carbon per square meter, office buildings, from the Embodied Carbon Benchmark Study. Building scope abbreviations: S = structure only; SF = structure and foundation; SFE = structure, foundation, enclosure; SFEI = structure, foundation, enclosure, interiors. Color-coding indicates different data sources.

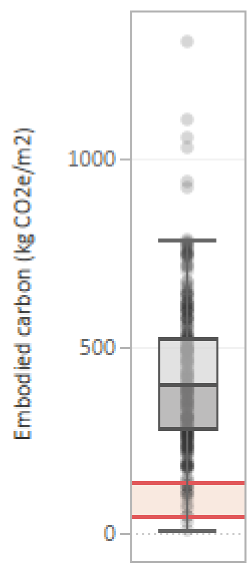

Figure 35. Embodied carbon values of US office buildings from the Embodied Carbon Benchmark study, all building scope categories combined. Quartile values are labeled by 25% increments. The upper limit of GWP results from the MEP and TI study is indicated in red

7.2.2 Building Performance Database

The U.S. Department of Energy's Building Performance Database [4] contains energy use intensity (EUI) data on approximately 98,000 buildings of various types and sizes. EUI is expressed in thousands of British Thermal Units (kBTUs). Filtering for office buildings produced 1270 buildings. The histogram of the office building subset is shown in Figure 36. The X-axis represents EUI in kBTU/sf/year, and the Y-axis represents the percentage of buildings in the subset that fall within the EUI bin. The circled "157" is the median value, and the dashed vertical lines represent 25th and 75th percentiles, corresponding to values of 121 and 198 kBTU/sf/year, respectively.
To compare, the embodied energy of TI from the projects collected in this study ranged from 73 – 243 kBTU/sf, which is on the same order of magnitude of impacts shown in Figure 36. This suggests that TI fit-out consumes approximately the same amount of energy that an office building would consume in a year.

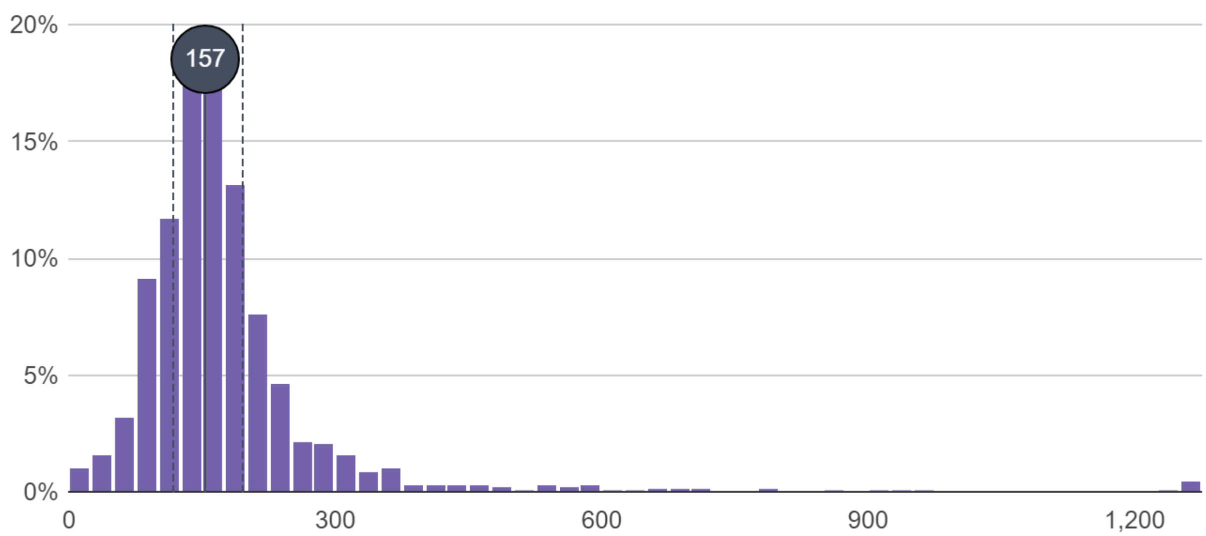

Figure 36. Histogram of buildings from the Building Performance Database Tool from the U.S. Department of Energy. The X-axis represents Source EUI in (kBTU/sf/year), and the Y-axis represents the percentage of buildings in the data subset that fall within that EUI bin. The circled "157" is the median value, and the dashed vertical lines represent 25th and 75th percentiles respectively.

Although completing a literature review was beyond the scope of this study, the research team came across one study that found that the impacts of furniture were responsible for approximately 10% of the overall environmental impacts of a building [3].