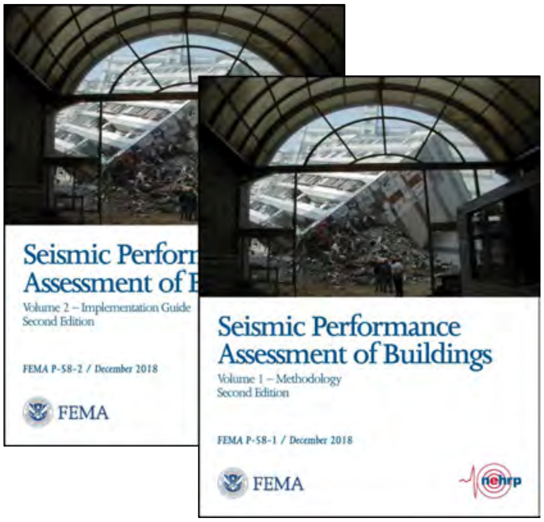

Background Document

FEMA P-58/BD-3.7.20

Methodology for Environmental Impact Assessment

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Background Documentation

FEMA P-58 Background Documents are a series of reports documenting the technical background and source information for key aspects of the FEMA P-58 methodology and its implementation. This report was developed over the course of the 5-year ATC-58-2 Project funded under FEMA Contract HSFE60-12-C-0243.

Background Documents were developed by consultants, serving at various levels within the project hierarchy, reporting the results of: (1) decisions on technical development protocols; (2) focused studies on the development of key aspects of the methodology; (3) documentation of recommended procedures; and (4) collection of available data for the development of structural and nonstructural fragilities. They were initially intended to serve as a record of the technical state-of-knowledge at the time they were produced, and as resources for the development of the eventual project reports. As such, they represent a snapshot in time, and may, or may not, match the technical content, recommended procedures, or data incorporated into the final methodology and its implementation.

This Background Document is intended for the purpose of providing supplemental knowledge to users of the FEMA P-58 methodology. Information contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Specifically in the case of certain nonstructural component fragilities, the NISTIR fragility classification numbering scheme was modified over the course of the project, and the fragility classification number assigned in this document might be different from numbers assigned in the final fragility database. Users of information in this document assume all liability arising from such use.

Notice

Cover photograph – Collapsed building viewed through the archway of an adjacent building, 1999 Chi-Chi, Taiwan earthquake (courtesy of Farzad Naeim, Farzad Naeim, Inc).

Background Documentation

FEMA P-58 Background Documents are a series of reports documenting the technical background and source information for key aspects of the FEMA P-58 methodology and its implementation. These reports were developed over the course of the 10-year ATC-58/ATC-58-1 Projects funded under FEMA Contracts EMW-2001-RP-0056 and HSFEHQ-06-D-1105.

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Notice

Table of Contents

1 Introduction

As part of the Federal Emergency Management Agency (FEMA) funded Applied Technology Council's Project 58 (ATC-58), *Seismic Performance Assessment of Buildings*, environmental impacts have been computed for seismic damage in the project's computational tools (FEMA 2012c) – namely the software *Performance Assessment Calculation Tool* (PACT) – using life cycle assessment techniques. The user can refer to *Volume 2 - Implementation Guide* (FEMA 2012b) for guidance on how to determine environmental impacts using PACT. The material presented in that volume is supplemented by this background document, which details the environmental impact calculation methodology. It is meant to provide the greatest amount of detail for the calculation of environmental impacts for ATC-58.

The contents of this report are as follows:

- Section 2: Framework for Analysis
- Section 3: Calculating Environmental Impacts for a Fragility
- Section 4: Results
- Section 5: Estimating Initial Construction and Building Replacement Impacts

Section 6 contains a summary, Section 7 contains the References, and Section 8 contains the Appendices.

Note that the data provided to ATC were normalized to the unit measurement of the fragility (e.g. square foot of wall, each brace), but for the purposes of analysis in this report, the environmental impact results were normalized to the dollar, regardless of fragility type.

The environmental impact research team included: Monica Huang, Peter Morris and Kathrina Simonen

2 Framework for Analysis

The environmental impacts were calculated using life cycle assessment (LCA) principles to assess the cradle-to-consumer impacts of manufacturing materials needed to repair seismic damage. The calculation process combined the LCA calculations with the PACT repair cost estimates to produce quantities of environmental impact per dollar spent in repair for a given fragility and damage state. More information about this methodology, including assumptions and limitations, is discussed in this section.

2.1 Selection of Analysis Method

The research team initially proposed two methods to integrate Life Cycle Assessment (LCA) based environmental impacts into the seismic performance assessment methodology of FEMA P-58-1 (FEMA 2012a): economic input-output (EIO LCA) and process-based LCA (PLCA). The team evaluated the two methods for their technical merit, implementation feasibility and relative value to support both the P-58 methodology and PACT refinement by working independently, discussing via telephone conference calls, and meeting for two daylong working meetings. Additionally, LCA experts and the developers of two different whole building LCA tools (and associated datasets) were contacted to gain added perspective on the relative strengths and weaknesses of the different methods and to estimate the costs of developing the needed LCA datasets.

The team recommend the EIO method because it aligns with the current state of P-58/PACT. The team also had greater confidence that the effort, precision and results will be comparable to the existing PACT consequence data of 'dollars, death and downtime.' Additionally, EIO LCA can enable high-level decision-making including a comprehensive assessment of the building structural and non-structural components.

2.2 PACT Cost Estimates

The research team was provided with the costs of repairing the various vulnerable building components (fragilities) in varying degrees of seismic damage (damage states) in a set of cost estimates previously developed for the PACT project. The cost estimates were contained in a Microsoft Excel spreadsheet.

2.3 About Economic Input-Output Life Cycle Analysis (EIO LCA)

As outlined in FEMAP-58-4, the EIO method translates dollars spent in a specific industrial sector (e.g. flat glass manufacturing) to environmental impacts. The Carnegie Mellon Green Design Institute's EIO LCA data (CMU GDI 2008) is publicly available via a web interface at www.eiolca.net. As noted on the CMU GDI website, the EIO LCA data from the online tool is available for non-commercial use to all.

PACT calculates damage costs for each component within the probabilistic analysis and outputs a summary of dollars spent per NISTR number, damage state, intensity, and so forth. From there, the environmental impact can be estimated by allocating the material costs related to repair into the appropriate industrial sectors from the EIO LCA data.

The key benefits of this method are summarized here:

- **Detail**: EIO LCA reflects the information likely available at the time of conducting a PACT analysis. In order to assess the full building (including items such as mechanical equipment) design teams can reasonably estimate the building component costs but would have difficulty accurately estimating the detailed material quantities needed to use PLCA.
- **Precision**: EIO LCA matches the precision of the current analysis model damage estimates. For example, the repair time and EIO LCA method both modify the repair cost estimates with fragility specific factors to generate expected impacts. This precision enables comparisons between options.
- **Conservative Estimates**: Using EIO LCA is less likely to underestimate the environmental impact of seismic damage. The absolute value of environmental impacts estimated using EIO tends to be larger than that attained using PLCA.
- **Cost and Effort**: The EIO LCA method requires significantly less effort and half the cost to implement. EIO data is free for non-profit applications while the effort to estimate process-based material quantities is substantial.

Some noted concerns with weaknesses of the EIO LCA method are: the data is perceived as too imprecise to be meaningful, the data is out of date, established whole building LCA tools use process-based methods instead of EIO, and the LCA data does not include known variability. The team discussed these issues internally and with external LCA practitioners and structural engineers, and concluded that these concerns, while reasonable, do not overcome the relative merit of the method at this time. A summary of our response to these concerns is as follows:

- **Perception**: Although most LCA practitioners and engineers who use LCA are more confident in process-based LCA, when the limitations of the data (most notably the current lack of detailed material quantities used in repair and the lack of material quantity data for MEP systems) were explained, the other LCA practitioners and engineers understood that the precision of EIO matches the precision of the method in its current state of development and therefore is appropriate to use.
- **Out-of-Date Data**: The update of the EIO LCA dataset to the most recently published government economic and environmental data is currently unfunded. However, independent experts expect that the funding will be attained and an EIO dataset will be updated in the relatively near future. Private EIO datasets are also available for a fee. Note that the fragility cost estimate data will require updating at a future date as well.

- **Whole-Building LCA Tools**: Although most whole building LCA tools use PLCA, components such as mechanical and electrical systems and elevators are not typically included. Users (with guidance) should be able to develop their baseline building analysis using freely available EIO datasets and relatively simple spreadsheet calculations to link cost estimates to environmental impact. This method has been used with success on the independent research project.
- **Variability**: The available EIO LCA datasets do not include variability (and neither do available process LCA data), however the methods to develop this variability have been developed and the research team at Carnegie Mellon is looking to fund this effort. Their lead researcher, Scott Matthews, estimates that the dataset can be updated to current financial and environmental impacts and include variability without significant additional cost. If funding is not available to support this data development, the variation in environmental impact can be extrapolated from the variation predicted in repair costs and quantities.

The LCA dataset developed in support of ATC 58-2/PACT should remain as an independent and updatable file. This will permit the tool to be updated when better data and/or user specific data is available. We propose that the LCA data be developed within the format of the existing fragility databases and could be integrated within an updated PACT or developed as a post processing method.

2.3.1 Note about EIO LCA Models

The data selected from www.eiolca.net was taken from the US 2002 Benchmark Purchaser Price Model, which differs from Producer Price Model in that it has the boundaries of "cradle to consumer", as opposed to the "cradle to gate" of the Producer Price Model. The Purchaser Price Model was selected because it reflects the costs from the perspective of the consumer, which is appropriate when evaluating repair costs of earthquake damage. The reference year of the source data is 2002, which is consistent with TRACI 1.0 (Bare et al, 2002) (Jolliet et al, 2003).

2.4 Selection of Metrics

The environmental analysis included all thirteen TRACI impact categories available from the EIO LCA dataset, which are:

- Global warming (also known as greenhouse gas emissions, climate change potential, carbon footprint)
- Acidification, air

- Human health criteria, air
- Eutrophication, air and water
- Ozone depletion
- Smog, air
- Ecotoxicity, low and high
- Human health cancer, low and high
- Human health non-cancer, low and high

This analysis also includes a metric for embodied energy, so 14 environmental metrics in total were evaluated.

For later analysis of the data, the BEES Environmental Impact Score (see Appendix D) was computed from the TRACI environmental impact categories. The BEES score combines multiple environmental metrics into a single value, and the selection of metrics was narrowed down to the five that had consistent units between the EIO LCA database (which was based on TRACI 1.0) and the updated normalization factors from Ryberg et al 2014 (which was based on TRACI 2.1). The comparison of the metrics and their units is shown in Table 1, and the five selected metrics for the BEES score calculation are highlighted in gray (the air and water modes of eutrophication were combined into one eutrophication category).

Table 1. Comparison of environmental impact categories and units between the EIO LCA database and the normalization units from Ryberg et al 2014. The five selected metrics for the BEES score calculation are highlighted in gray.

Environmental Impact Category Name and Unit Comparison	
EIO LCA Database (TRACI 1.0)	**Normalization Data from Ryberg et al 2014 (TRACI 2.1)**
Glob Warm (kg CO2e)	Global warming (kg CO2 eq)
Acidif Air (kg SO2e)	Acidification (kg SO2 eq)
HH Crit Air (kg PM10e)	Respiratory effects (kg PM2.5 eq)
Eutro Air (kg Ne)	Eutrophication (kg N eq)
Eutro Water (kg Ne)	Eutrophication (kg N eq)
OzoneDep (kg CFC-11e)	Ozone depletion (kg CFC-11 eq)
Smog Air (kg O3e)	Photochemical ozone formation (kg O3 eq)
EcoTox (low) (kg 2,4D)	Ecotoxicity-non-metals (CTUe)
HH Cancer (low) (kg benzene eq)	Carcinogens-non-metals (CTUcanc.)

HH NonCancer (low) (kg toluene eq)	Non-carcinogens-non-metals (CTUnon-canc.)
EcoTox (high) (kg 2,4D)	Ecotoxicity-metals (CTUe)
HH Cancer (high) (kg benzene eq)	Carcinogens-metals (CTUcanc.)
HH NonCancer (high) (kg toluene eq)	Non-carcinogens-metals (CTUcanc.)

Two environmental impacts were submitted to ATC to be incorporated into PACT. These were:

- **Greenhouse gas emissions / embodied carbon** – also referred to as "climate change potential" in PACT Volume 4. This impact category was selected because it is the most widely recognized environmental impact metric (FEMA 2012c). For the remainder of this document, "embodied carbon" will be used to refer to the measurement of greenhouse gas emissions / global warming potential / climate change potential.
- **Embodied energy** – Embodied energy is also another common metric of environmental impact, so it was included in the analysis.

The environmental impacts were limited to these two because they were identified by the leadership team to be the impact categories most relevant to the building industry today. Furthermore, embodied carbon was later evaluated to be a suitable proxy for other environmental impacts typically tracked in building industry LCA studies; see Appendix E for a summary of the statistical evaluation of this determination.

2.5 Scope of Analysis

The scope of this analysis is cradle-to-site (or cradle-to-consumer). Transportation is included within the Purchaser Model from the EIO LCA database, described as follows: "*A purchaser priced model has the boundaries of "cradle to consumer", that is, it estimates impacts from resource extraction all the way up to purchase of the product (including delivery, for example, at a store. The appropriate economic input into the model is with this context, as in the total price from the purchaser's perspective at a store*" (CMU GDI 2008).

Figure 1 illustrates the system boundaries of this analysis, showing the inputs and outputs captured by and excluded from the analysis. Exclusions are discussed more in the following section.

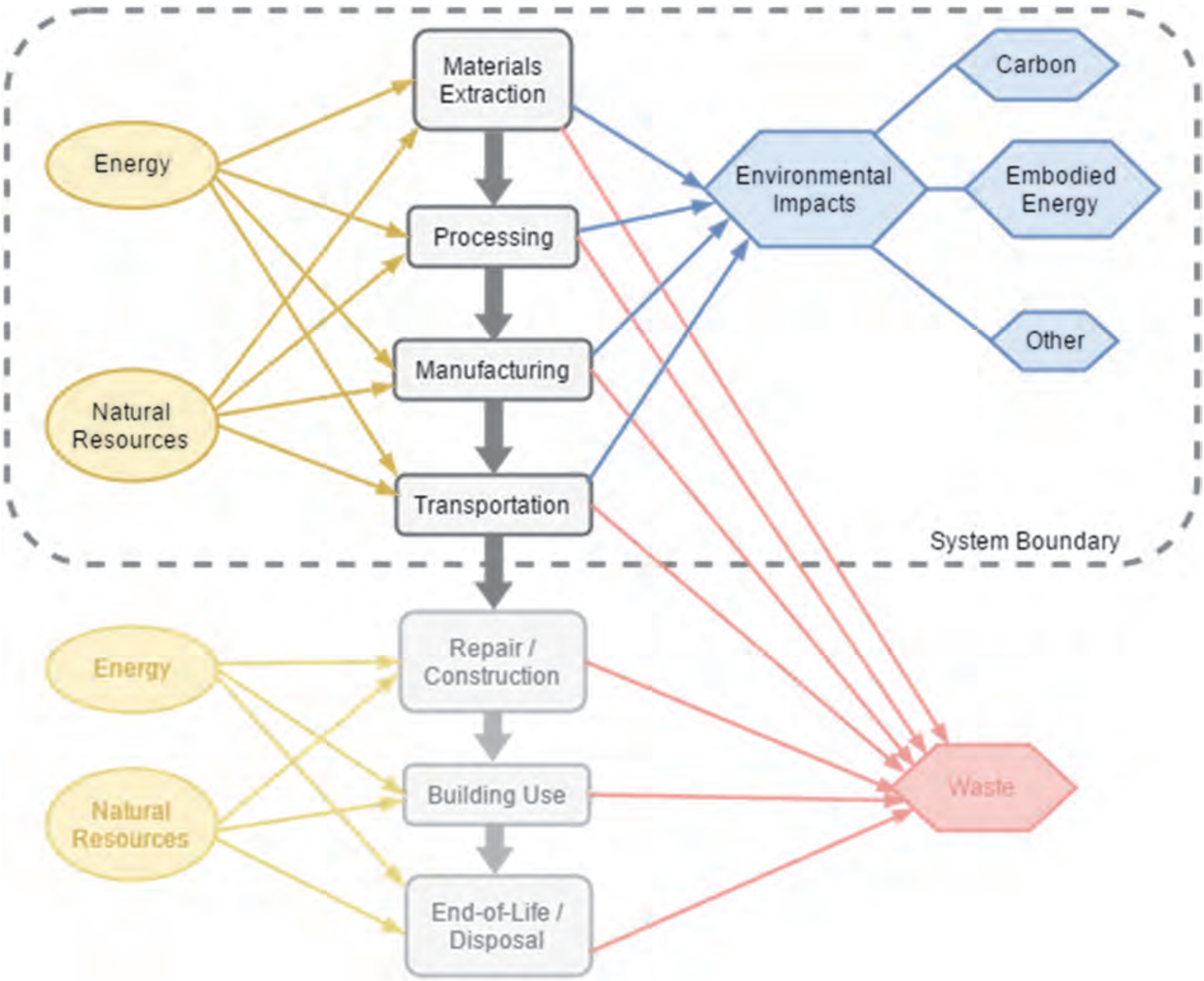


Figure 1. System boundary diagram. Objects within the dotted box are contained within the system boundary and thus included in the analysis, while objects outside of the dotted box in faded text are not included in the analysis.

2.6 Exclusions

The analysis initially aimed to include on-site energy consumption and waste generation, but these metrics were eventually omitted due to level of uncertainty of the available analysis methods for the scope of this project.

Factors that were explicitly excluded from this analysis are listed and discussed below:

- **Rental equipment** – excluded from the analysis because rental equipment are not produced exclusively for the repair activity nor are they consumed during the repair activity.
- **Worker (labor) impacts** – the impact of the workers (labor) were excluded from this analysis, as is typical for building LCA's (Simonen 2014).

- **Maintenance –** deemed outside the scope of the analysis.
- **On-site energy use / construction impacts** – energy use was originally intended to be included in the analysis, but due to high level of uncertainty and imprecision from the available data, the research team opted not to incorporate on-site environmental impacts in the final analysis. However, the research team did generate energy consumption and greenhouse gas emission estimates based on information from Sharrard et al (2007), and these calculations are presented in Appendix C for the reader who may wish to use these estimates.
    - Based on a study on the energy consumption of construction activities, "Environmental Implications of Construction Site Energy Use and Electricity Generation" by Sharrard et al (2007), the cost of on-site energy consumption was initially assumed to be 1% of overall repair costs. This estimate was based on 2002 U.S. Department of Commerce data, which estimated that overall spending on power/fuels represented approximately 1.2% of overall building construction costs. Even though this 1% should logically vary based on the energy intensity of the work activity, the specific percentages could not confidently be determined without conducting further studies that would be beyond the scope of this project. Additionally, the authors of the study observed that "current estimates of the construction industry's energy usage and air emissions are at only half of what the construction industry actually uses," so 1% is likely an underestimate. Appendix C includes more information about the option of including on-site energy consumption in the calculations.
- **Waste generation (end-of-life disposal)** – Waste impacts were originally intended to be included in this analysis, with a distinction between landfill waste and recyclable (metal) waste. However, without a bill of materials, estimating waste would have been too imprecise, and industry waste data was not available. At one point, the research team had proposed estimating a quantity (weight or volume) of waste based on the number of dollars spent in an industrial sector, much like EIO LCA, but this method was assessed to be too inaccurate without further study of empirical data, which was lacking. If future cost estimate data are created through the generation of bill of material quantities, estimating waste volumes would be fairly straightforward.

2.7 Uncertainties and Limitations

The environmental impact factors generated in this analysis are very broad, due to the nature of EIO LCA, since the impacts are generalized by industrial sectors. As listed on the EIO LCA website (CMU GDI 2008), some of the major uncertainties in their data are:

- Old data
- Uncertainties inherent in original data
- Incomplete original data
- Aggregated original data
- Aggregation of sectors

Beyond the uncertainties in the EIO LCA data, the uncertainties arising from the calculation methodology of this research work include:

- **Applicability of cost estimate data to modeled building** – the modeled building in PACT is likely to have different materials and quantities than those that were assumed for the cost estimates in this research work. Similarly, the transportation impacts from the EIO LCA data are unlikely to reflect the specific transportation impacts of the modeled building.
- **Selection of industrial sectors** – The selection of industrial sectors was limited to what was available in the EIO LCA database. The relevance of an industrial sector to a repair activity was not always clear-cut. For example, while casting concrete could easily be attributed to the sector named "ready-mix concrete", welding did not have its own industrial sector, so welding was attributed to the sector named "Iron, steel pipe and tube manufacturing from purchased steel" because it was assumed that iron and steel product manufacturing must involve welding. Also, some industrial sectors were broader than others (due to aggregation), so there is a variation in the specificity of the sectors to the individual repair activities.
- **Cost allocation to industrial sectors** – Cost allocation of a repair activity to the industrial sectors was estimated by the construction cost estimator on the research team, who allocated the costs to four major categories: 'Labor', 'Rental Equipment', 'Plant', and 'Temporary Materials.' It was not abundantly clear what 'Plant' or 'Temporary materials' meant in some cases, especially with regards to the demolition activities, so there is likely to be some uncertainty in attributing 'Plant' and 'Temporary Materials' to the correct sectors. Furthermore, the percentage allocations have a high degree of uncertainty of variability. More information about the assumptions made in cost allocations is found in Appendix A.
- **Date** – the EIO LCA data is from 2002, while the PACT cost estimates are from 2011. Inflation factors were used to bridge the gap between these two reference years, but the economy and environmental emissions today are likely different than in 2002.

The uncertainty in this analysis are based on the uncertainty in costs as defined by PACT. No uncertainties were calculated separately for the environmental impact analysis. Given that the environmental impacts are calculated from modified cost data, the use of cost uncertainty values is reasonable given the scope of this project. Note that there are no readily available data on the uncertainty of environmental impacts in each sector.

3 Calculating Environmental Impacts for a Fragility

Once the costs were allocated to the applicable industrial sectors, the EIO LCA environmental impact factors were applied to the costs to determine overall environmental impacts for the database of fragilities.

This section includes the overview of steps from Volume 2, but with specific commentary about how the calculations were performed to construct the database. The research team developed a spreadsheet that combined the original PACT cost estimate data with the EIO LCA data, and the development of this spreadsheet is documented in this section (specifically Section 3.2). However, the spreadsheet itself will not be made available to the public because its complexity may lead to user error, and its original purpose of populating a large database is unlikely to be the goal of the regular PACT user. Instead, the PACT user may follow the example calculation in Section 3.3 to independently develop original environmental impacts if needed.

Note about terminology: Although elsewhere in the report(s), “repair activity” is used to refer to the work done to repair seismic damage, “work item” is used here to describe individual line items in the cost estimate spreadsheet. This is partly because 1) the cost estimate line items were originally conceived as “work items”, and then later conceived as “repair activities” in the broader narrative discussions, and 2) many of the work items are not accurately described as an act of repair, i.e. “demolition.” Therefore, “repair activities” as “work items” and the terms are interchangeable. “Tab” and “worksheet” are also used interchangeably.

3.1 Overview of Calculation Procedures

The general steps for calculating the environmental impacts of a fragility are outlined as follows:

Step 1. Obtain the cost estimate.

The more detailed the cost estimate, the more detailed the LCA evaluation can be.

Step 2. Allocate the costs in the cost estimate to the relevant industrial sectors selected from the EIO LCA database (www.eiolca.net). Sum the costs in each applicable sector.

For the work items in the cost estimate, select the appropriate industrial sectors from the EIO LCA database (like the sectors listed in Appendix B), and allocate the costs to these sectors as well as 'Labor', 'Energy', and 'Rental Tools'. This will require some judgement on how the costs should be distributed.

Step 3. Obtain the environmental impact factors for the selected sectors from the EIO LCA database per $1 million. Then adjust the factors for inflation (considering the date of the EIO LCA data and the date of the cost estimate) and to reflect $1 instead of $1 million spent per sector.

Ensure that the 2002 Purchaser Price Model is selected when extracting the TRACI Impact Assessment and Energy factors.

To account for inflation between the year of the EIO LCA data (2002) and the cost estimate data (2011), the inflation factor was estimated to be 1.45 based on number of indices (Engineering News Record Building Construction Index, Marshal & Swift, Producer Price Index) consulted by the construction cost estimator. The environmental impacts / $\$_{2002}$ were divided by 1.45 to convert 2002 to values to 2011 values (because $\$1.00_{2002} = \$1.45_{2011}$). From there, the same process can be repeated to convert 2011 values to present values.

Step 4. Multiply the sector costs with the adjusted environmental impact factors to generate the total environmental impacts. If per dollar values are desired, divide the total environmental impact by the total cost of the fragility or project.

Multiplication by matrices is recommended for this step.

3.2 Detailed Calculation Procedures

This section contains a detailed account of how the calculations were performed to formulate the environmental impact database.

Step 1. Obtain the cost estimate.

In the spreadsheet developed previously by ATC construction cost estimator(s), the cost estimate calculations had been grouped by performance groups (i.e. 'Shear Tabs', 'Column Splices') with one performance group per tab. In some cases, multiple performance groups used the calculations from the same tab (probably for expediency). Each damage state then had its own cost estimate section, where the each work item was a line item with a unit, quantity, unit cost, and total cost. A screenshot of an example cost estimate for a fragility is shown Figure 2.

B1044.001 Concrete Wall Repair (Wall up to 8" thick)				
Standard Wall				
Estimate Basis - Wall 25' long x 15' high = 375 SF (8" thick)				
Damage State DS1				
Remove, protect and reinstall				
Office furniture and equipment	1	LS	1,000.00	1,000
Temporary				
Floor protection	300	SF	5.00	1,500
Scaffolding or work platforms - not required for this repair			Not Required	
Wall repairs				
Grout injection at wall cracks (300 LF of crack per 100 SF of wall)	1,125	LF	8.00	9,000
Mechanical and electrical modifications or relocations as required for repair work	1	LS	2,000.00	2,000
P50	**375**	**SF**	**36.00**	**13,500**

Figure 2. Screenshot of example cost estimate (for Concrete Wall Repair up to 8", DS1).

Step 2. Allocate the costs in the cost estimate to the relevant industrial sectors selected from the EIO LCA database (www.eiolca.net). Sum the costs in each applicable sector.

To maximize the efficiency of calculating environmental impacts for hundreds of fragilities spread across nearly 70 tabs in the spreadsheet, the research team employed the following sub-steps:

Step 2.1. Compile a list of work items from all fragilities being evaluated

All unique work items from all the cost estimates were gathered and placed into a single 'Work Items' sheet, resulting in a comprehensive list of approximately 300 work items total. There were some duplicates (the same activities occurring for different fragilities), but they were assumed have identical percentage cost allocations regardless of the fragility.

Note: Sometimes the name of the repair activity spanned multiple lines in the spreadsheet, which complicated the VLOOKUP() function needed in later steps. In these cases, a single-cell name was created instead, and the percentage allocations occurred only for that cell. For example, refer the following image:

Original	Revised
Remove portion of buckling #8 reinforcing steel	Remove portion of buckling #8 reinforcing steel
12" long, replace reinforcing steel with	12" long, replace reinforcing steel with
mechanical splices each end (10 locations	mechanical splices each end (10 locations
per 100 SF of wall)	10 locations remove rebar add mechanical splice

In the revised version, cells with the dark gray background indicate that they are not being used as a referenced work item, and cells with blue text indicate that that cell will be used in the VLOOKUP() function.

Step 2.2. Determine all applicable industrial sectors for the work items

The list of repair activities was then reviewed by the research team to determine the relevant industrial sectors to be selected from the EIO LCA database. In total, 25 industrial sectors were selected from the EIO LCA database. These sectors are listed in Appendix B with notes about assumptions and applicability.

Step 2.3. Allocate percentages of cost from the work items to the industrial sectors

A VLOOKUP reference table was set up to search the list of work items (with names revised if necessary) for their percentage allocations. The percentages were provided by the construction cost estimator, who assigned percentages to ‘Labor’, ‘Plant’, and ‘Rental Tools,’ while the remaining percentages were assigned to the industrial sectors by the UW research team using their best judgment. Typically, ‘Labor’ had the highest cost allocations (40 – 60%) and ‘Energy’ was defined by a constant (1%) that could be modified. These percentages were assumed to be consistent for all cost estimates where the work item appeared, regardless of the nature of the fragility. Most work items were specific to the fragility being repaired, but some others were more generic. For example, 'Dust protection' was assumed to have 94% Labor, 1% Energy, and 5% Plastic Film regardless of whether it was used to repair a concrete wall or replace a partition.

A screenshot of a portion of the 'Work Items' sheet used by the research team is shown in Figure 3. The list of work items appears on the left, followed by a check on total percentages in green, and the list of sectors with their assigned percentages extend to the right (not all sectors are shown).

			Energy %						
			1%						
Work Item	Total % Check	Labor	Energy	Rental Tools/ No impact	Adhesive	Aluminum	Clay product	Cleaning	Coating
N/A									
Expose, remove, replace, protect, etc									
Partitions obstructing works (2' high)	100%	99%	1%						
Concrete wall	100%	99%	1%						
Cut back roofing	100%	99%	1%						
Decommission/clean soot	100%	89%	1%	10%					
Demolition	100%	89%	1%	10%					
Floor finishes	100%	94%	1%					5%	
Gypsum wall board	100%	94%	1%					5%	
Partitions obstructing works (full height)	100%	94%	1%					5%	

Figure 3. Screenshot of portion of 'Work Items' sheet. The list of work items is shown in the medium-gray column on the left. Cost allocation categories (or sectors) are shown in the light gray header row. Percentages for each work item must add up to 100% (verified by green box). Energy was allocated as a constant 1% (yellow box) for all work items.

Appendix A contains a full list of guidelines and assumptions used by the research team in assigning cost percentages.

Step 2.4. Multiply the percentages with the total cost of each work activity, and sum the costs in the sectors

The LCA calculations were set up adjacent to the existing cost estimate calculations on each sheet. See Figure 4 for a screenshot of an example used by the research team. The figure shows the cost estimate with LCA calculations starting on Column X, with blue, red, and green boxes showing the various components of the LCA calculation table. Each work item (in gray background) was used to look up the percentage allocations from the 'Work Items' tab using VLOOKUP and the header row on the cost estimate sheet, which contained the sector names. The retrieved percentages were multiplied with the total cost of the work item. The sector costs were summed for each fragility, and the fragility was given a unique descriptive code (in pale red background) (i.e. "Standard Wall to 8" - DS1 - A") that could be referenced from a DS summary sheet (see below for more information). Sometimes, multiple fragilities referenced the same cost estimate results, as determined from the 'Master Summary' tab. In those cases, the row containing the sum of the fragility costs was duplicated (referencing the original row) and the unique code was modified. The fireproofed structural steel fragilities were treated similarly; fireproofing was typically appended as an extra several hundred dollars, so fireproofing was its own work item with disaggregated costs based on the particular fireproofing cost, and added on to the original fragility costs to produce the costs for the fireproofed fragility.

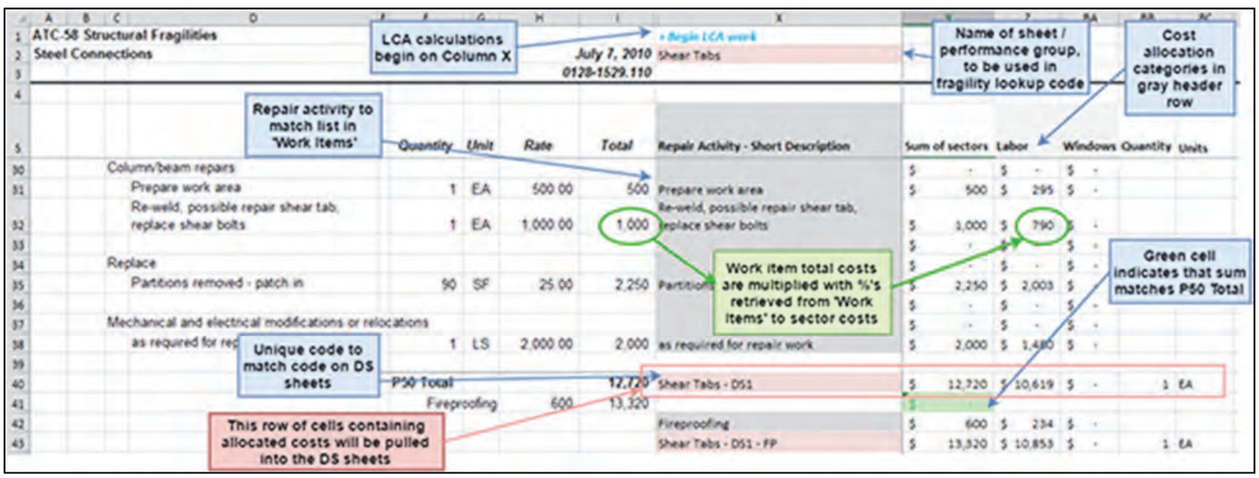


Figure 4. Cost estimate sheet and LCA calculation notes. Blue boxes/arrows indicate how the LCA calculation section is organized, the green boxes/circles/arrows indicate how the work item total cost is multiplied by the percentage retrieved from the 'Work Items' sheet to produce the sector cost for the work item, and the red box/arrow indicates the data selection that is being retrieved to the DS summary sheets.

Note about the descriptive codes used in the research team's spreadsheet:

> The code was usually specified as the sheet name (i.e. "Standard Wall to 8""), the damage state (i.e. "DS1"), and any descriptive characteristics for that fragility, which was designated as the 'Type' and sometimes a 'Sub-Type'. For example, the 'Walls' groups typically had various dimensions for the calculation assumptions, and were designed as 'A', 'B', and 'C' as follows:

A: 25'x15' = 375 SF
B: 25'x20' = 500 SF
C: 25'x35' = 875 SF

Thus an example code would be 'Standard Wall to 8" – DS1 – A'.

Or, for steel braces, the types and sub-types were typically:

Types	Sub-Types (w = lineal weight of brace)
Chevron	A: w < 40 PLF
Diagonal	B: 41 PLF < w < 99 PLF
X-brace	C: w > 100 PLF

In some performance groups, the distinction between the fragility descriptions was too lengthy or complex to differentiate, and easier to distinguish by referencing the unique NISTR number, which was obtained by examining the cell references in the 'Master Summary' sheet. The performance groups that used the NISTR number method of referencing were:

- Concrete MF
- RC Flat Slabs-Cols
- Glazing Systems
- Items in the HVAC category
- Items in the Electrical category

Notes about DS Summary Sheets used in the research team's spreadsheet:

After summing the costs in each sector for each fragility in a cost estimate tab, the costs could be collected on the respective DS summary sheets (DS1 – DS5). The DS summary sheets were created by partially copying the 'Master Summary' sheet. It includes the NISTR number, the fragility description, a field called "orig table" (not used except to determine which structural steel fragilities contained fireproofing, indicated by "sfp" instead of simply "s"), "Estimate UM" (unit measurement), and the DS-P50 values. The P50 values are the cost of repair that has a 50% probability of being achieved, and these were the costs that the LCA calculations were based on.

The DS summary sheets retrieved the disaggregated costs of the fragilities by using VLOOKUP to reference the specified sheet and range of columns that the LCA calculations were placed on in the cost estimate sheets (shown in the pale red outline in Figure 4). After the fragility sector costs were retrieved, the resulting total cost (which sometimes had to be divided by the unit measurement, which is why the units were also retrieved onto the DS sheets) was compared to the original P50 costs. If the difference between the total cost and the P50 cost, a.k.a. checksum, was zero, then the correct costs had been retrieved for that fragility. The checksum was performed for each DS summary sheet to ensure that the costs retrieved from all of the cost estimate sheets matched the official values in the 'Master Summary' sheet.

Step 3. Obtain the environmental impact factors, including energy impacts if applicable, for the selected sectors from the EIO LCA database per $1 million. Then adjust the factors for inflation (considering the date of the EIO LCA data and the date of the cost estimate) and to reflect $1 instead of $1 million spent per sector.

The EIO LCA database (www.eiolca.net) was accessed to gather the TRACI impact factors (per $1 million) and the Energy (TJ / $1 million). Detailed steps with screenshots for this step are shown in the example calculation in Section 0.

The factors were divided by 1 million to convert them into per dollar values, Energy was converted to MJ for better readability, and inflation was taken into account by dividing by a factor of 1.45 to convert from 2002 to 2011 values. The result was a matrix of environmental impact factors per dollar on the 'Env Impact Factors' tab. With 13 TRACI impact categories + 1 embodied energy category and 25 industrial sectors, the dimensions of the matrix were 25 x 14 (row x column). A screenshot of this matrix is shown in Figure 5.

Note that if the user is using this data for commercial purposes, please see the Usage & Copyright Page on the EIO LCA website about commercial usage:
http://www.eiolca.net/copyright/index.html

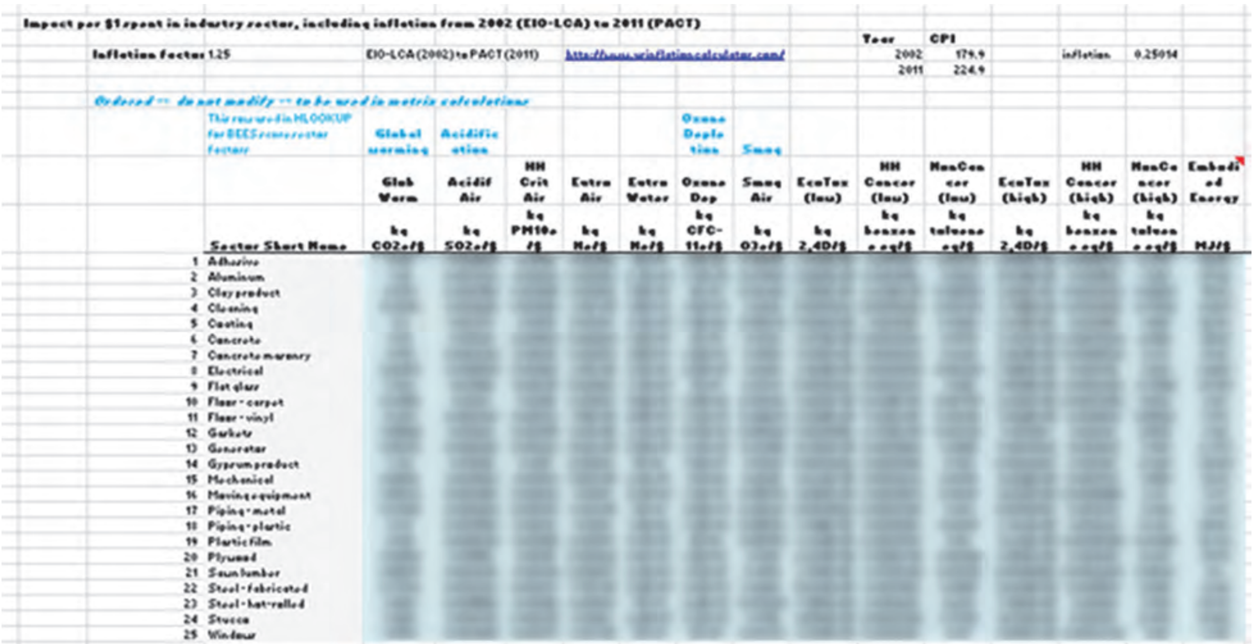


Figure 5. Screenshot of environmental impact factors matrix on 'Env Impact Factors' sheet. The values here are blurred to respect the intellectual property of the creators of EIO LCA.

Step 4. Multiply the sector costs with the adjusted environmental impact factors to generate the total environmental impacts. If per dollar values are desired, divide the total environmental impact by the total cost of the fragility or project.

After gathering the fragility costs, which have been subdivided by sector (Step 2), and compiling the adjusted EIO LCA factors into a matrix (Step 3), the EIO LCA calculations could then be performed. This can be done by matrix multiplication.

To execute Excel's matrix multiplication function (MMULT), the predetermined size of the matrix must first be selected (1 x 14), then the two matrices are entered as arguments into the formula. In the research team's spreadsheet, the two arguments for MMULT were:

1. The row vector (1 x 25) of sector costs for a single fragility, where the sector name in the first column matched the first sector in the EIO LCA matrix, and the last column matched the last sector.
2. The matrix (25 x 14) of environmental impact factors.

After the matrices were specified, the matrix multiplication could be executed by simultaneously holding down the keys CTRL+SHIFT+ENTER. Thus the set of environmental impacts for a fragility can be calculated from the sector costs. To repeat this calculation for the list of 800+ fragilities, the 1 x 14 group of cells can be dragged down for all the rows.

To convert into impacts per dollar, the whole MMULT() operation can be divided by the total cost of the fragility.

Not all damage states existed for all fragilities, so Step 4 only occurred where applicable. If a damage state did not exist for that fragility then the cells were left blank, since a value of '0' would suggest that zero environmental impacts exist for that fragility.

A summary of these steps and the workflow used by the research team in their calculation spreadsheet is shown in Figure 6.

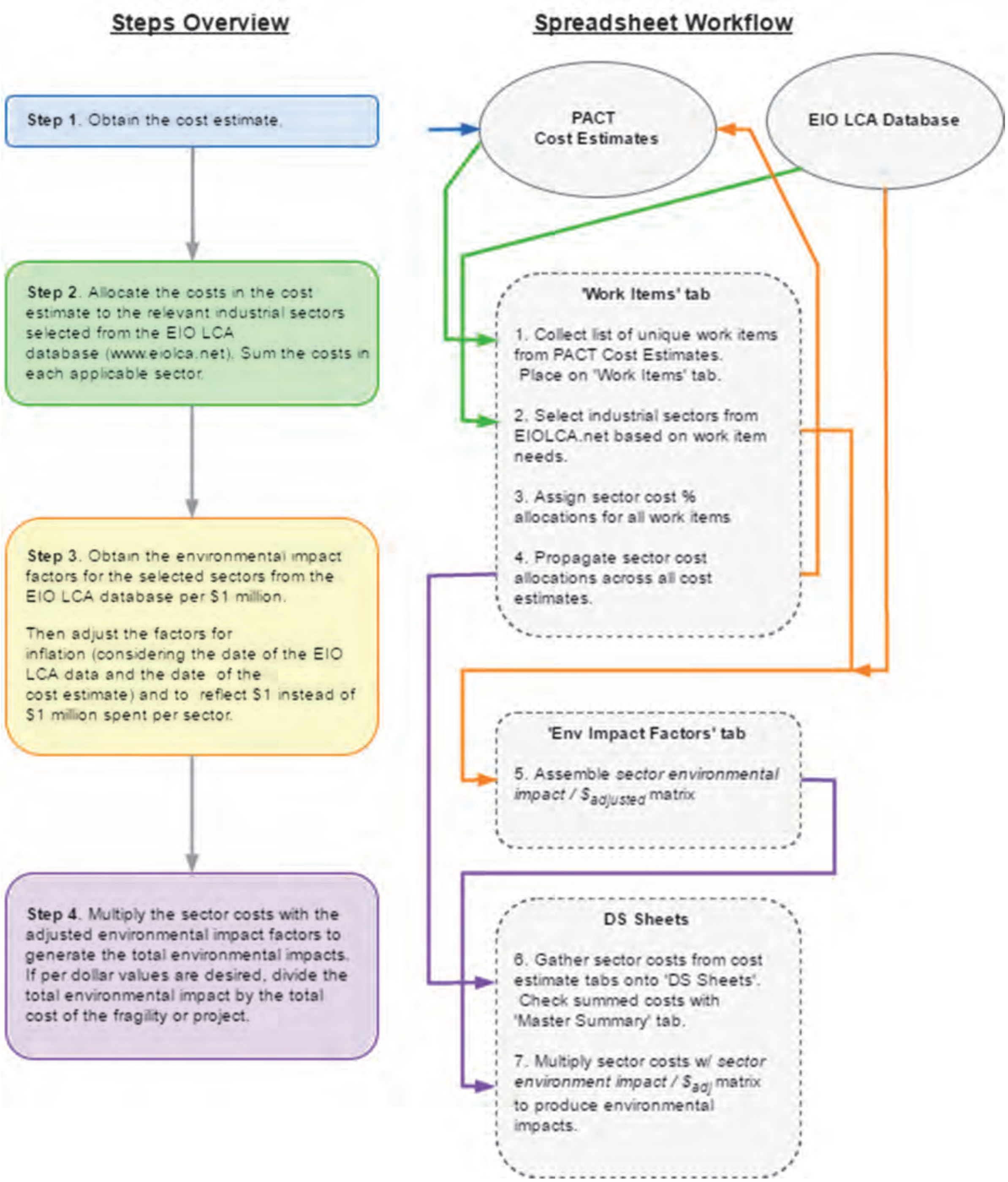


Figure 6. Calculation work flow diagram. Colors of arrows in the Spreadsheet Workflow column (right) correspond to the color of the steps in the Steps Overview column (left).

3.3 Example Calculation

Example Environmental Impact Determination Calculation for a Fragility
B1044.001 Concrete Wall Repair (Wall up to 8" thick)
Damage State DS2
Estimate Basis - Wall 25' long x 15' high = 375 SF

Step 1. Obtain the cost estimate.

Below is the cost estimate for an 8" thick concrete wall, 25' long x 15' high in Damage State 2 taken from the PACT cost estimate.

Work Activity	Quantity	Unit	Rate ($/unit)	Total ($)
Remove, store and reinstall				
Office furniture and equipment	1	LS	1,000.00	1,000
Temporary				
Floor protection	300	SF	5.00	1,500
Scaffolding or work platforms	750	SF	3.00	2,250
Wall repairs				
Grout injection at wall cracks (330 LF of crack per 100 SF of wall)	1,238	LF	8.00	9,904
Remove portion of concrete wall for access to reinforcing steel (15 SF per 100 SF of wall)	56	SF	75.00	4,200
Remove portion of buckled #8 reinforcing steel 12" long, replace reinforcing steel with mechanical splices each end (5 locations per 100 SF of wall)	19	EA	200.00	3,800
Install eight #4 ties at end of wall, re-bend sixteen horizontal reinforcing steel bars around new ties	2	EA	1,000.00	2,000
Cast 5000 PSI concrete at wall infill including formwork	56	SF	75.00	4,200
Mechanical and electrical modifications or relocations as required for repair work	1	LS	3,000.00	3,000
	375	SF	84.94	31,854

Step 2. Allocate the costs in the cost estimate to the relevant industrial sectors selected from the EIO LCA database (www.eiolca.net). Sum the costs in each applicable sector.

In this example, the industrial sectors were determined by assuming that Floor Protection required the sector 'Plastics packaging materials, film and sheet' (abbreviated as 'Plastic film'), grout injection required the sector 'Adhesive manufacturing' ('Adhesive'), and mechanical and electrical modifications required the sector 'Miscellaneous electrical equipment manufacturing' ('Electrical'), and so on.

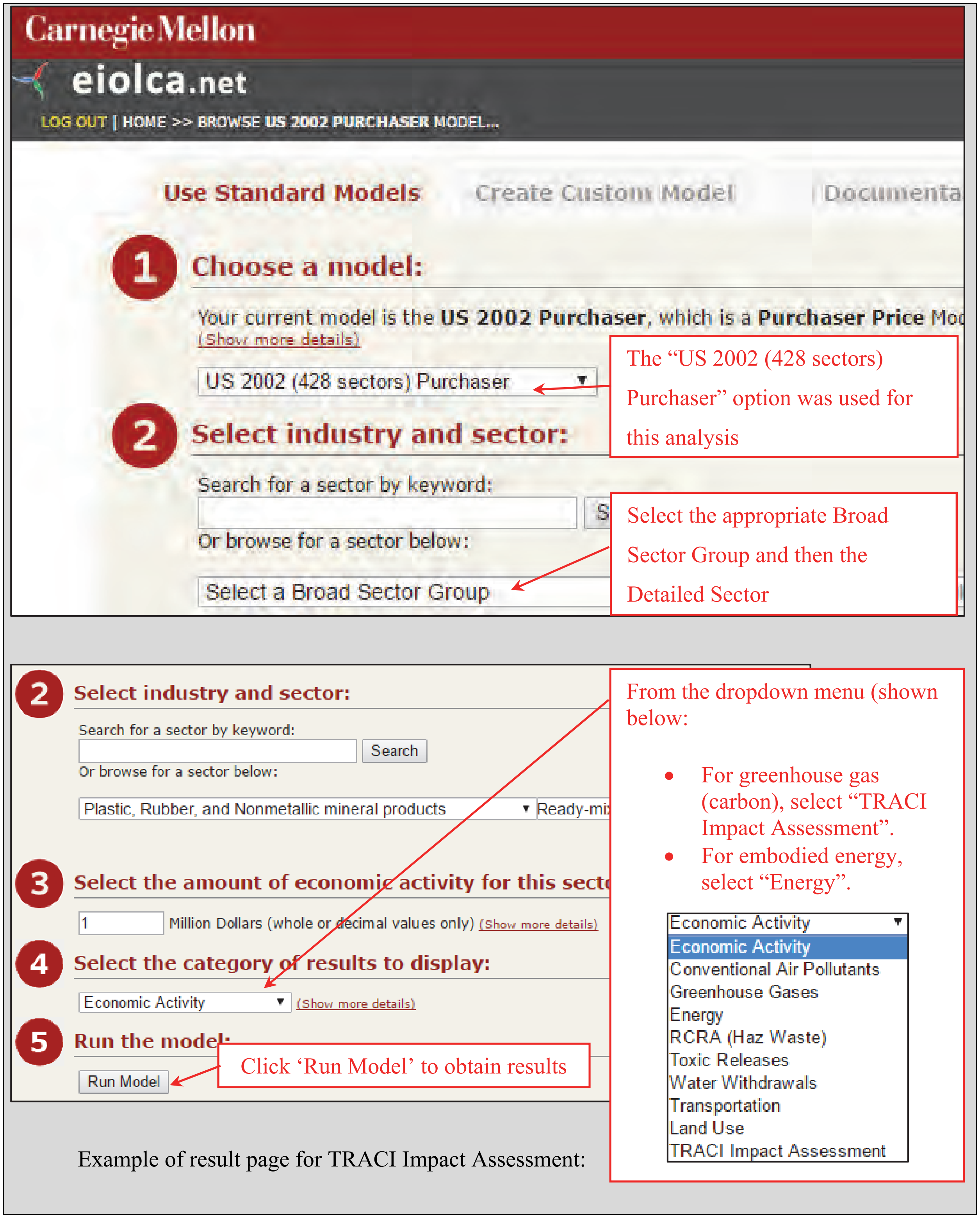
The percentage allocations to the various sectors and the calculated costs for the repair activities are shown in the following table.

					Industrial Sectors						
Work Activity	**Row total**	**Labor**	**Energy**	**Rental Tools/ No impact**	**Adhesive**	**Cleaning**	**Concrete**	**Electrical**	**Plastic film**	**Plywood**	**Steel – fabricated**
Percentage Allocation											
Remove, store and reinstall											
Office furniture and equipment	100%	94%	1%	0%	0%	5%	0%	0%	0%	0%	0%
Temporary											
Floor protection	100	94	1	0	0	0	0	0	5	0	0
Scaffolding or work platforms	100	74	1	25	0	0	0	0	0	0	0
Wall repairs											
Grout injection at wall cracks (330 LF of crack per 100 SF of wall)	100	59	1	0	40	0	0	0	0	0	0
Remove portion of concrete wall for access to reinforcing steel (15 SF per 100 SF of wall)	100	79	1	10	0	10	0	0	0	0	0
Remove portion of buckled #8 reinforcing steel 12" long, replace reinforcing steel with mechanical splices each end (5 locations per 100 SF of wall)	100	59	1	0	0	0	0	0	0	0	40
Install eight #4 ties at end of wall, re-bend sixteen horizontal reinforcing steel bars around new ties	100	59	1	0	5	0	0	0	0	0	35
Cast 5000 PSI concrete at wall infill including formwork	100	49	1	10	0	0	35	0	0	5	0
Mechanical and electrical modifications or as required for repair work	100	74	1	0	0	0	0	25	0	0	0

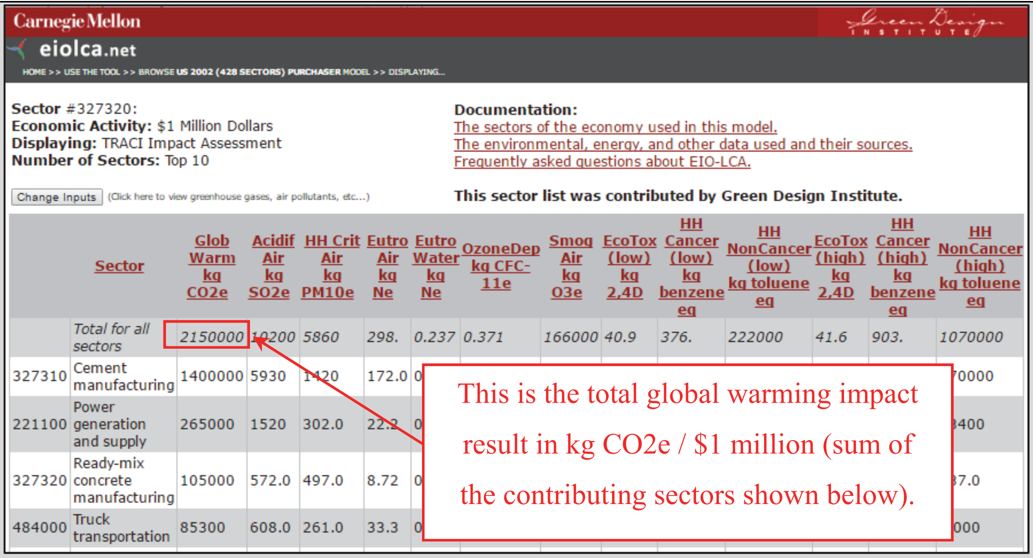
Resulting Costs											
Remove, store and reinstall											
Office furniture and equipment	$1000	$940	$10	$0	$0	$50	$0	$0	$0	$0	$0
Temporary											
Floor protection	1500	1410	15	0	0	0	0	0	75	0	0
Scaffolding or work platforms	2250	665	22.5	563	0	0	0	0	0	0	0
Wall repairs											
Grout injection at wall cracks (330 LF of crack per 100 SF of wall)	9904	5843	99	0	3962	0	0	0	0	0	0
Remove portion of concrete wall for access to reinforcing steel (15 SF Per 100 SF of wall)	4200	3318	42	420	0	420	0	0	0	0	0
Remove portion of buckled #8 reinforcing steel 12" long, replace reinforcing steel with mechanical splices each end (5 locations per 100 SF of wall)	3800	2242	38	0	0	0	0	0	0	0	1520
Install eight #4 ties at end of wall, re-bend sixteen horizontal reinforcing steel bars around new ties	2000	1180	20	0	100	0	0	0	0	0	700
Cast 5000 PSI concrete at wall infill including formwork	4200	2058	42	420	0	0	1470	0	0	210	0
Mechanical and electrical modifications or as required for repair work	3000	2220	30	0	0	0	0	750	0	0	0
Total Cost	31854	20876	319	1403	4062	470	1470	750	75	210	2220

Step 3. Obtain the environmental impact factors for the selected sectors from the EIO LCA database per $1 million. Then adjust the factors for inflation (considering the date of the EIO LCA data and the date of the cost estimate) and to reflect $1 instead of $1 million spent per sector.

Go to http://www.eiolca.net/cgi-bin/dft/use.pl to use the EIO LCA database tool. Remarks on how to use the EIO LCA database interface is shown in the following screenshots.



Example of result page for TRACI Impact Assessment:



	Sector	Glob Warm kg CO2e	Acidif Air kg SO2e	HH Crit Air kg PM10e	Eutro Air kg Ne	Eutro Water kg Ne	OzoneDep kg CFC-11e	Smog Air kg O3e	EcoTox (low) kg 2,4D	HH Cancer (low) kg benzene eq	HH NonCancer (low) kg toluene eq	EcoTox (high) kg 2,4D	HH Cancer (high) kg benzene eq	HH NonCancer (high) kg toluene eq
	Total for all sectors	*2150000*	*10200*	*5860*	*298.*	*0.237*	*0.371*	*166000*	*40.9*	*376.*	*222000*	*41.6*	*903.*	*1070000*
327310	Cement manufacturing	1400000	5930	1420	172.0	0								70000
221100	Power generation and supply	265000	1520	302.0	22.2	0								3400
327320	Ready-mix concrete manufacturing	105000	572.0	497.0	8.72	0								37.0
484000	Truck transportation	85300	608.0	261.0	33.3	0								000

The extracted environmental impact factors from the EIO LCA database are shown below.

Industrial Sector	Global Warming Potential (kg CO2e / $1M)	Embodied Energy (TJ / $1M)
Adhesive	1,200,000	17.6
Cleaning	492,000	6.21
Concrete	2,150,000	18.9
Electrical	372,000	5.61
Plastic film	1,270,000	20.8
Plywood	719,000	14.7
Steel - fabricated	967,000	12.3

The resulting values below account for inflation from 2002 to 2011 by dividing by a factor of 1.45. ‘Global warming potential’ was renamed to ‘embodied carbon’, and embodied energy was converted from TJ to MJ.

Industrial Sector	Embodied Carbon (kg CO2e/$)	Embodied Energy (MJ/$)
Adhesive	0.828	12.14
Cleaning	0.339	4.28
Concrete	1.483	13.03
Electrical	0.257	3.87
Plastic film	0.876	14.34
Plywood	0.496	10.14

Steel - fabricated	0.667	8.48

Step 6. Multiply the sector costs with the adjusted environmental impact factors to generate the total environmental impacts. If per dollar values are desired, divide the total environmental impact by the total cost of the fragility or project.

The calculations are shown below using matrix multiplication.

[Sector costs] x [environmental impact factors / $ in sector] = [overall environmental impacts]

$$= \begin{bmatrix} 20876 & 319 & 1403 & 4062 & 470 & 1470 & 750 & 75 & 210 & 2220 \end{bmatrix} \times \begin{bmatrix} 0.828 & 12.14 \\ 0.339 & 4.28 \\ 1.483 & 13.03 \\ 0.257 & 3.87 \\ 0.876 & 14.34 \\ 0.496 & 10.14 \\ 0.667 & 8.48 \end{bmatrix}$$

$$= \begin{bmatrix} 7543 & 95411 \end{bmatrix}$$

Thus, the total environmental impacts for this fragility, an 8" thick standard concrete wall with dimensions of 25' x 15' in DS2 is:

Embodied carbon = 7,543 kg CO2e
Embodied energy = 95,411 MJ.

To obtain the environmental impacts per dollar of repair, divide by the total cost of the fragility:

Embodied carbon = 7,543 kg CO2e / $31,854 = 0.24 kg CO2e/$
Embodied energy = 95,411 MJ / $31,854 = 3.00 MJ/$

3.4 Developing Custom Fragility Environmental Impacts

To develop environmental impact data for a custom fragility, the methodology described previously in this section can be employed, with the only difference being in Step 1 -- obtaining the appropriate cost estimate. The cost estimate can be based on an existing PACT cost estimate, or a new cost estimate could be developed from scratch. After the cost estimates have been developed for all damage states of the custom fragility, the environmental impacts can be calculated following the steps described at the beginning of this section. For Step 2, the cost allocation scheme developed for the current database can be used as a guide in allocating costs. For Step 3, it is recommended that the same industrial sectors, EIO environmental impact factors, and inflation factor be used for the existing database where possible to help ensure comparability. The calculation process for Step 4 is the same. Alternatively, one can modify the custom fragility to use the environmental impacts of a similar existing fragility.

After determining the environmental impacts for the custom fragility, the results should be incorporated into the final model using the PACT software using the Fragility Specification Manager. The environmental impact data is contained in the *Consequence Function* window of each fragility, in the *Other Consequences* tab, under *Environmental Losses*.

4 Results

This section analyzes the results of the database.

To view the results of this database in a meaningful way, the fragilities were grouped into comparable categories. The grouping scheme was based on the NISTR codes, which are based on the UNIFORMAT II classification system described in NISTIR 6389 (Applied Technology Council 2012a). The fragility groups are summarized in Table 2. To condense similar groups that contained relatively few elements, Cold-Formed Steel Structural Elements (B106) and Wood Light Frame Structural Elements (B107) were combined to form Light Frame Structural Elements, and Special Structures Including Storage Racks (F101) was added into Interior Finishes because there was only one fragility in the Storage Racks group.

Table 2. Fragility grouping scheme with typical component items.

Fragility Group Name	NISTIR Group Number	Number of Item Types in Group*	Typical Performance Group Items in Fragility Group
Structural Steel Elements	B103	562	Shear tabs, column base plates, column splices, WF SCBFs, HSS SCBFs, double L SCBFs, OCBFs, BRBFs, steel connections, steel link beams
Reinforced Concrete Elements	B104	414	Concrete moment frames, standard walls, walls with ret flange and boundary elements, slender walls, flat slabs-columns, concrete link beams
Masonry Vertical Elements	B105	50	Reinforced masonry walls
Light Frame Structural Elements	B106, B107	27	Light-frame steel walls (B106), light-frame wood walls (B107)

Exterior Enclosure	B20	63	Pre-cast concrete panels, light-frame exterior steel walls, light-frame exterior wood walls, glazing systems
Roof Elements	B30	22	Tile roofs, masonry chimneys, masonry parapets
Partitions	C101	20	Metal stud gypsum walls, wood stud gypsum walls
Stairs	C20	30	Prefabricated steel stair, precast concrete stair, cast-in-place stair, hybrid type stair
Interior Finishes	C30, F101	94	Finishes (wallpaper, ceramic, high finish), floor wetting, ceilings, pendant light fixture, elevators; includes ‘Special Structures Including Storage Racks’ (F101)
Plumbing	D20	127	Piping (potable, sanitary, chilled water, steam)
HVAC	D30	288	Chillers, cooling towers, compressors, fans, ductwork, diffusors, VAV boxes, air handlers
Fire Protection	D40	34	Piping, sprinkler drops
Electrical	D50	218	Transformers, motor control centers, switchgears, battery racks, battery chargers, generators

* Includes elements from all damage states

4.1 Cost Allocation

To summarize how the costs from the cost estimate data were allocated to the industrial sectors and the non-impact categories (‘Labor’, ‘Energy’, and ‘Rental Tools’), Figure 7 depicts the average percentage allocations by fragility group, where all applicable damage states were included in the average. Since the large number of sectors makes it difficult to differentiate between the sector colors, this figure is only meant to illustrate the distribution of costs between ‘Labor’ and some of the more prominent industrial sectors, such as ‘Steel’ (purple), ‘Gypsum product’ (red), ‘Mechanical’ (orange), and ‘Electrical’ (golden yellow). From this figure, it can be seen that ‘Labor’ forms the majority of the sector costs (40 – 70%) in most cases, except for ‘HVAC’ and ‘Electrical.’ ‘HVAC’ and ‘Electrical’ have low labor-to-material cost ratios because these items typically require replacement of complex, expensive equipment, thus reducing the relative impact of 'Labor', whereas the other fragility groups typically involve relatively more labor to assemble materials for the repair.

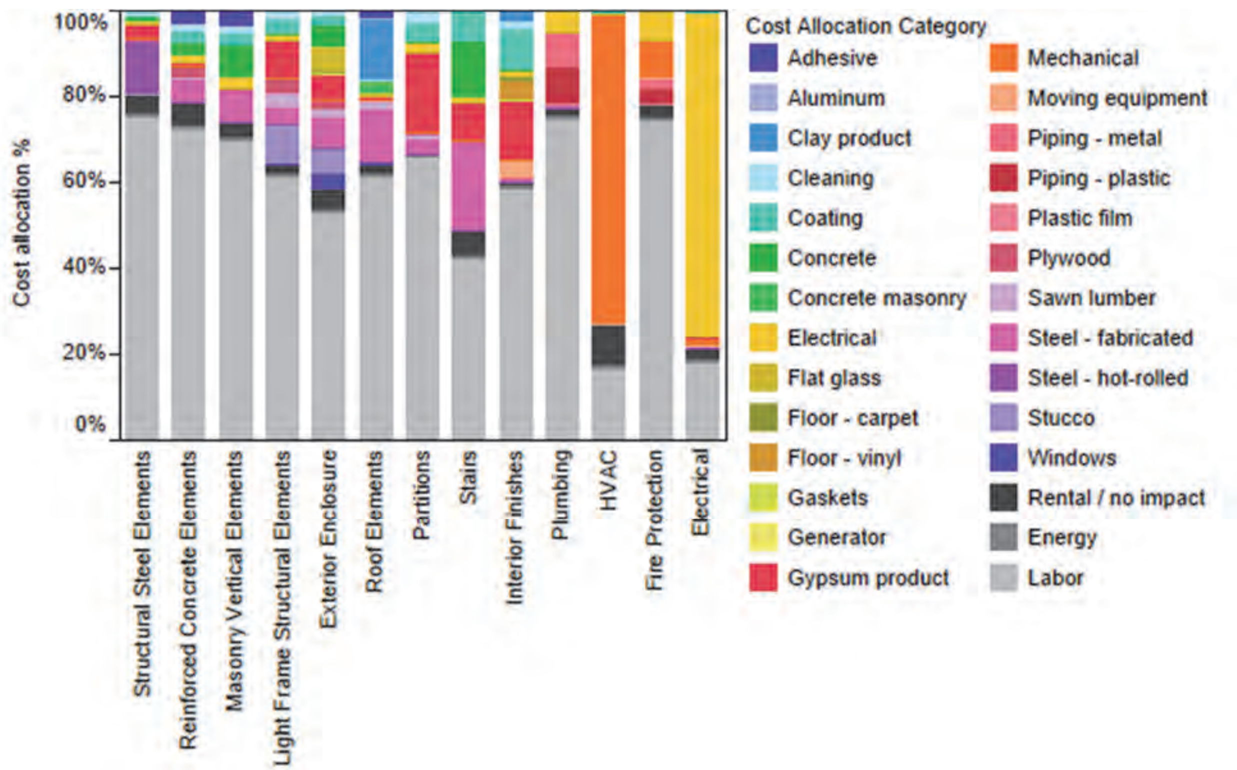


Figure 7. Percentage distribution of cost allocations for fragility groups, including non-impact sectors (shown in shades of gray), averaged across damage states within each fragility group.

4.2 Environmental Impacts of Industrial Sectors

The BEES Environmental Performance Score method of weighing environmental impacts (Lippiatt 2007) combines the different environmental impact categories in a meaningful way in order to assess which sectors had the greatest environmental impact per dollar. The five environmental impact categories considered were limited to 1) global warming (embodied carbon), 2) acidification, 3) eutrophication (air + water), 4) ozone depletion, and 5) smog; these were the only five categories that had consistent units between the EIO LCA data, which was based on TRACI 1.0, and latest normalization data, which was based on TRACI 2.1 (Ryberg et al 2014). More information about the calculation of the BEES score is provided in Appendix D. The results are shown in Figure 8 and the sectors are sorted from highest to lowest BEES score. Similarly, the embodied energy is shown in Figure 9. In both figures, 'Gypsum product' has the highest environmental impact per dollar, followed by 'Flat glass.' The four least impactful sectors in both metrics are: 'Generator', 'Mechanical', 'Cleaning', and 'Electrical.'

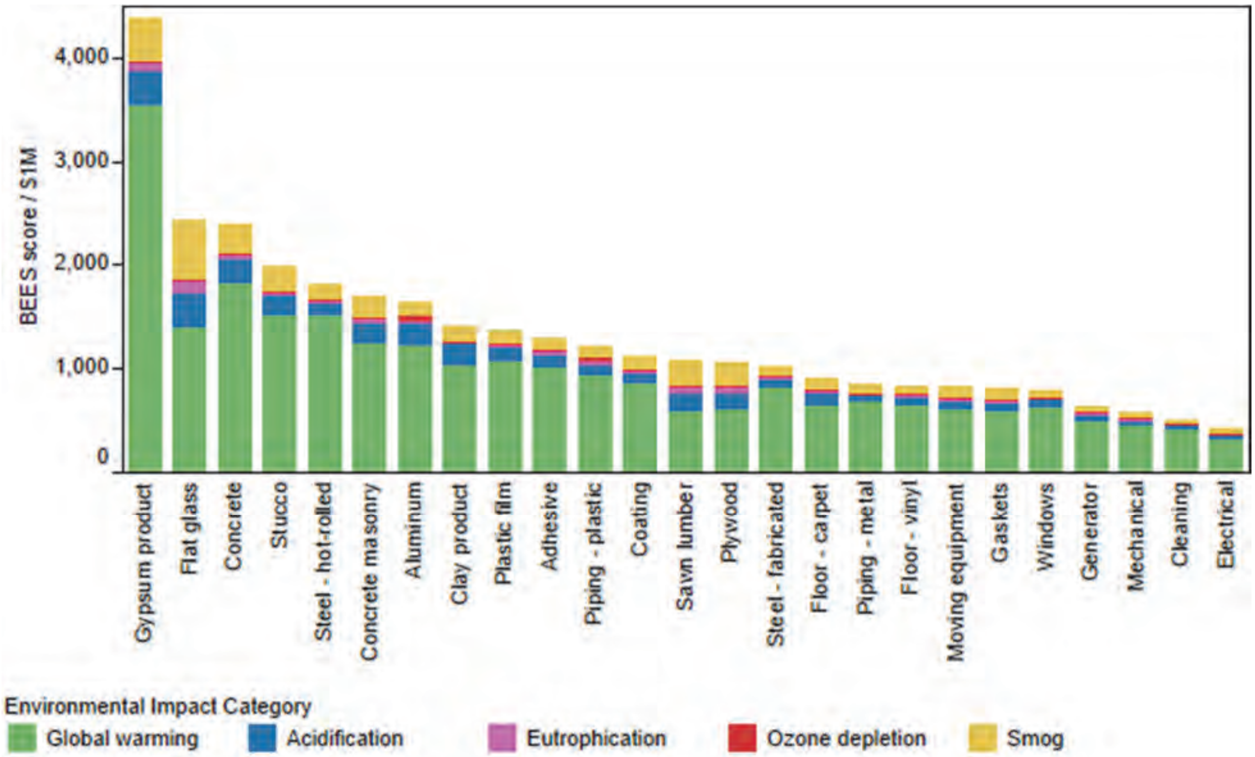


Figure 8. BEES environmental impact scores / $1 million for industrial sectors, sorted by highest to lowest overall BEES score.

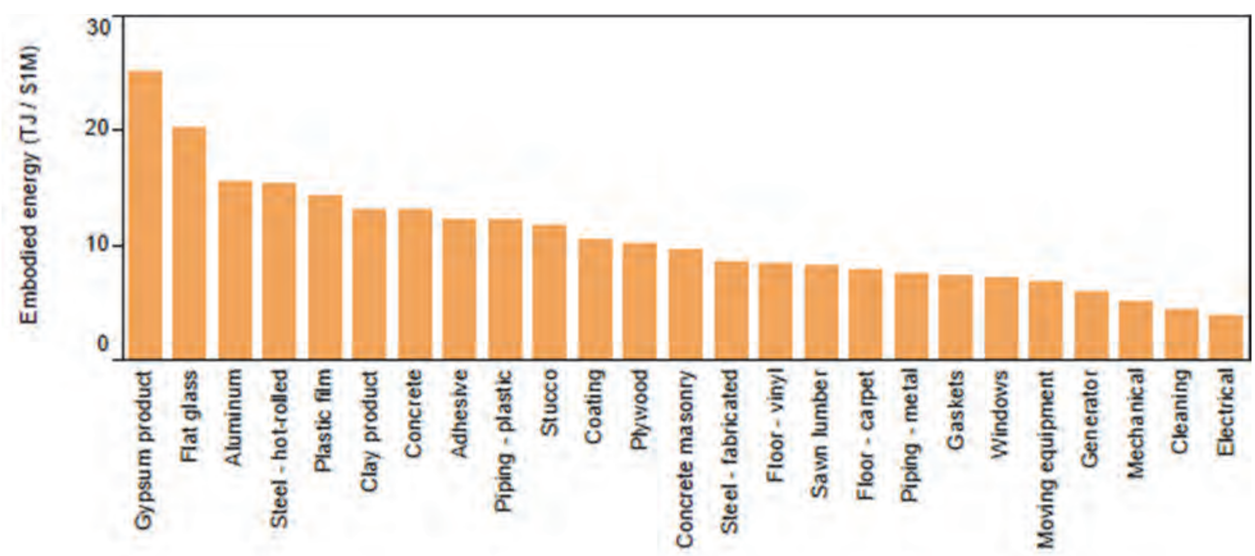


Figure 9. Embodied energy in TJ/$1M for industrial sectors, sorted from highest to lowest embodied energy.

4.3 Embodied Carbon Results

Given that carbon is one of – if not the most – common measure of environmental impact in the building industry, this section examines the database in greater detail using this metric. The figures presented in this section show the embodied carbon results of the LCA calculations as stacked bar charts. Each colored band represents the average embodied carbon within that sector, averaged across the fragilities within the performance groups.

The first of these figures, Figure 10, summarizes the embodied carbon results for the fragility groups (averaging the results across fragilities and damage states). Only the top 10 industrial sectors are shown to facilitate color differentiation; the remaining 15 sectors are grouped under the 'Other' category. By the sum of averages shown in this figure, it can be seen that Light Frame Structural Elements and Exterior Enclosures have the highest embodied carbon, followed by Interior Finishes, Partitions, and Stairs. It is interesting to note that damage to the heavy-duty structural elements such as the Structural Steel Elements and Reinforced Concrete Elements do not make much of an impact per dollar spent in repair. This suggests that investing more money in the structural components could potentially offset the environmental impacts of seismic damage in the more environmentally fragile architectural components of a building.

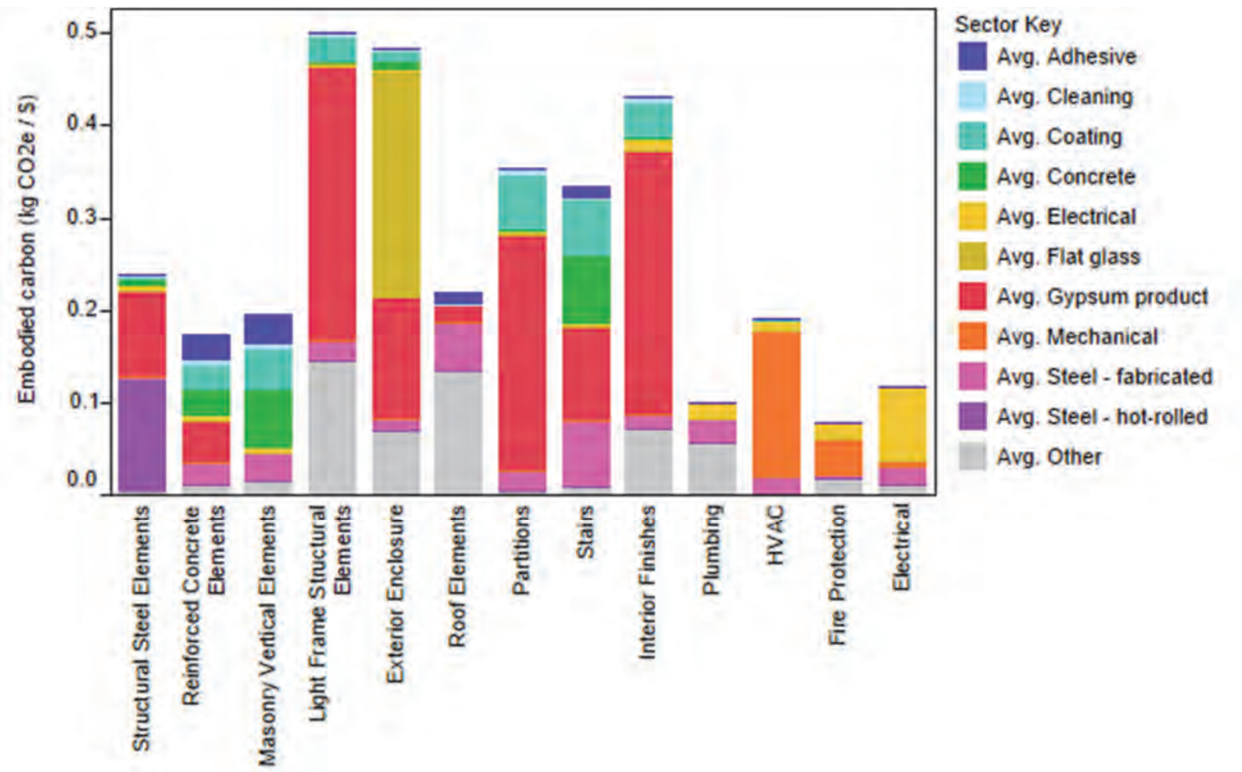


Figure 10. Embodied carbon summarized for all fragility groups.

The following figures break down the summary results from Figure 10 in more detail. Each figure has 10 plots on each row, ordered first by the NISTR number of the fragility group then by alphabetical order of performance group. The vertical scales are consistent for the two plots within a figure, but are not necessarily consistent across all figures. However, all of the tick marks are in units of 100. In the color legend, only the relevant sectors for the items shown in the figure are included for simplicity.

Figure 11 shows the items in Structural Steel Elements. Some notes and observations about these building components:

- ‘Hot-rolled steel’ and ‘Gypsum product’ are the most impactful sectors in this fragility group. It is expected that ‘Hot-rolled steel’ makes a significant contribution in this group, but ‘Gypsum product’ makes a signifcant contribution as well because partition walls often have to be torn down and rebuilt in order to access the steel frames behind the walls.
- BRBF frames only have one damage state because they have only one mode of failure (buckling).
- Because the cost estimate calculations for HSS SCBF Balanced Frames, HSS SCBF AISC Frames, OCBF w/ Compact Braces, and OCBF Ductile Braces were very similar (in some cases

sharing the same values) they were put into one group. The Braced Frames group was also based on similar calculations, but since it excludes some of the calculations for the higher damage states states, it was kept separate.

- 'Concrete' makes a significant contribution where concrete work is required, i.e. gouging out and replacing part of a concrete slab to repair a steel connection or column splice.
- For many of the braced frames (Double L SCBF, HSS SCBF + variants, OCBF + variants, WF SCBF), the embodied carbon for DS2 is greater than DS1, but DS3 is slightly lower than DS2. This is because DS2 repair activities typically require replacement of braces, while DS1 does not, which results in high material impacts from the steel in DS2. DS3 typically requires more heat-straightening, which increases the cost of labor (as well as energy, but those impacts are not included) but does not significantly increase material impacts, thus the material/cost ratio is slightly lower.

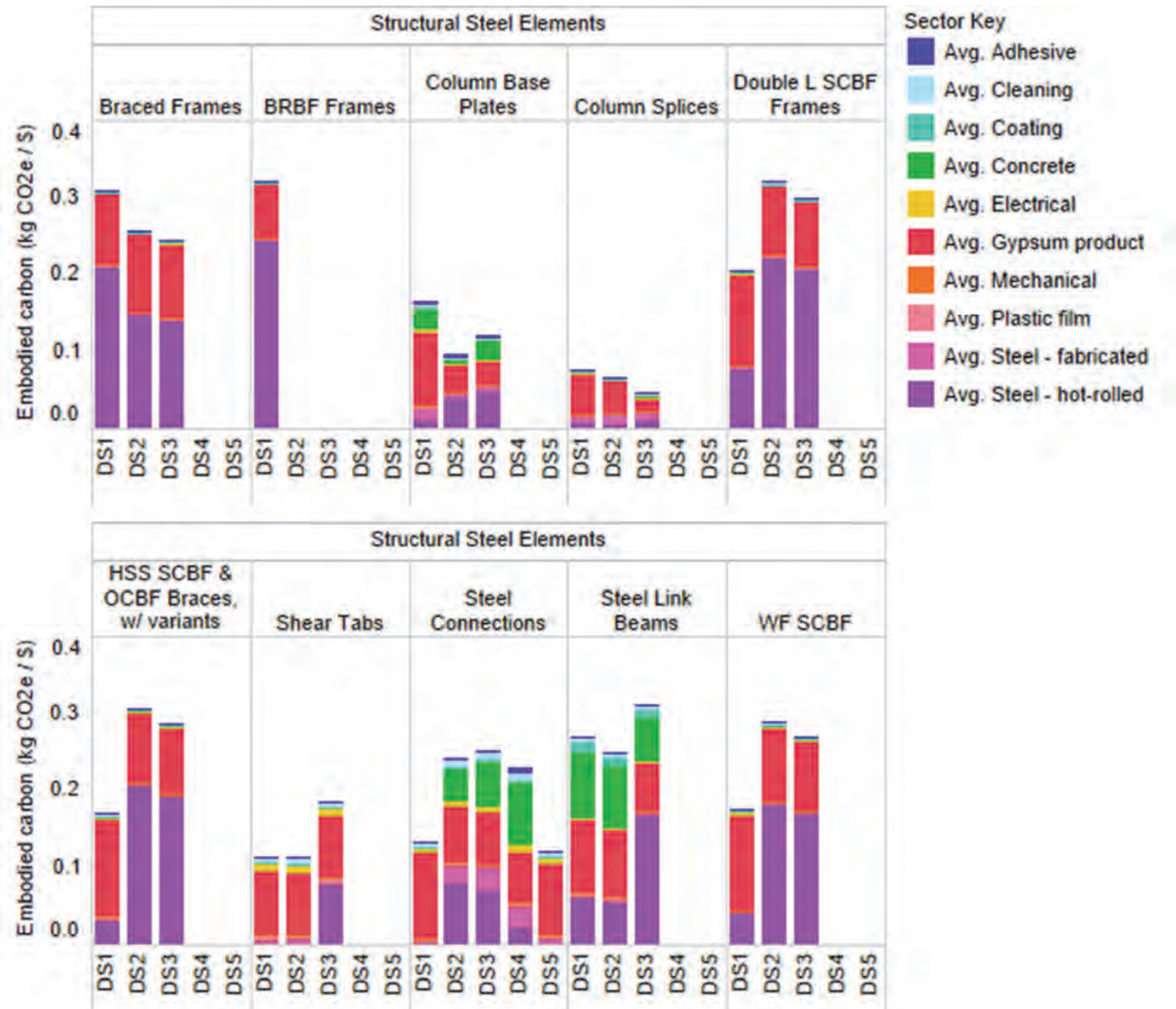


Figure 11. Embodied carbon for Structural Steel Elements.

Figure 12 shows the items in Reinforced Concrete Elements, Masonry Vertical Elements, and Light Frame Structural Elements. Note that the vertical scale is twice the range of the previous figure. Some notes and observations on these building components:

- The calculations for many of the Concrete MF elements were based on a baseline cost estimate, where the line items were broken down, and the remaining 40 or so elements were valued at +$2000 (or some other dollar quantity) of the baseline. In these cases, the sector impacts were calculated by scaling them up to match the final values.

- Light Frame Steel Structural Elements – some of the fragility variations were calculated in the 'Master Summary' sheet by multiplying the first fragility by a factor of 0.4 or 0.5.
- The environmental impact per dollar of the Reinforced Concrete Elements is comparable to the Structural Steel Elements; both fragility groups are in the 0.1 – 0.3 kg CO2e/$ range.
- The values for Light Frame Structural Elements are significantly higher than previous fragility groups (in the 0.4 – 0.7 kg CO2e/$ range). This can be attributed to the 'Gypsum product' sector (in orange), which has a very high environmental impact per dollar, as indicated previously in Figure 8.
- As observed with other fragility groups, the environmental impact per dollar tends to decrease with increasing damage state because the overall costs are higher in the higher damage states while the material impacts are not as significant, thus reducing the environmental impact dollar slightly. Additional possible factors to support this trend include:
    - In Wood Stud Gypsum Wall, DS3 requires 3 times as much floor protection, which has most of its cost in Labor (a non-impact category). Even so, there is a significant cost going into the replacement of gypsum wall board in DS3, as is the case with Metal Stud Gypsum Wall, but the overall Labor costs still exceed the 'Gypsum Product' costs.
    - Sometimes the highest damage states have demolition activities or require shoring. These activities have most of their costs in 'Labor', 'Cleaning' or 'Rental Tools', which have minimal material impacts. This increases the ratio of cost to material impacts, thus reducing the environmental impact per dollar.
    - In the Reinforced Concrete Wall items, grout injection is not used in DS3, so that is another activity that increases the materials impacts of the lower damage states.
- Link Beams and Masonry Walls are the exception to the pattern above; they have increased environmental impact per dollar with increasing damage states.
    - With Link Beams, the addition of steel (for splicing) is what sets DS3 apart from DS2, bumping up the overall environmental impact.
    - With Masonry Walls, the cell references overlap each other; the same cost estimate calculations are used for different fragilities in different damage states, so it is harder to distinguish the repair activities between damage states. The figure shows that only DS1 has coating activities, and DS2 and DS3 have increased concrete and steel work.

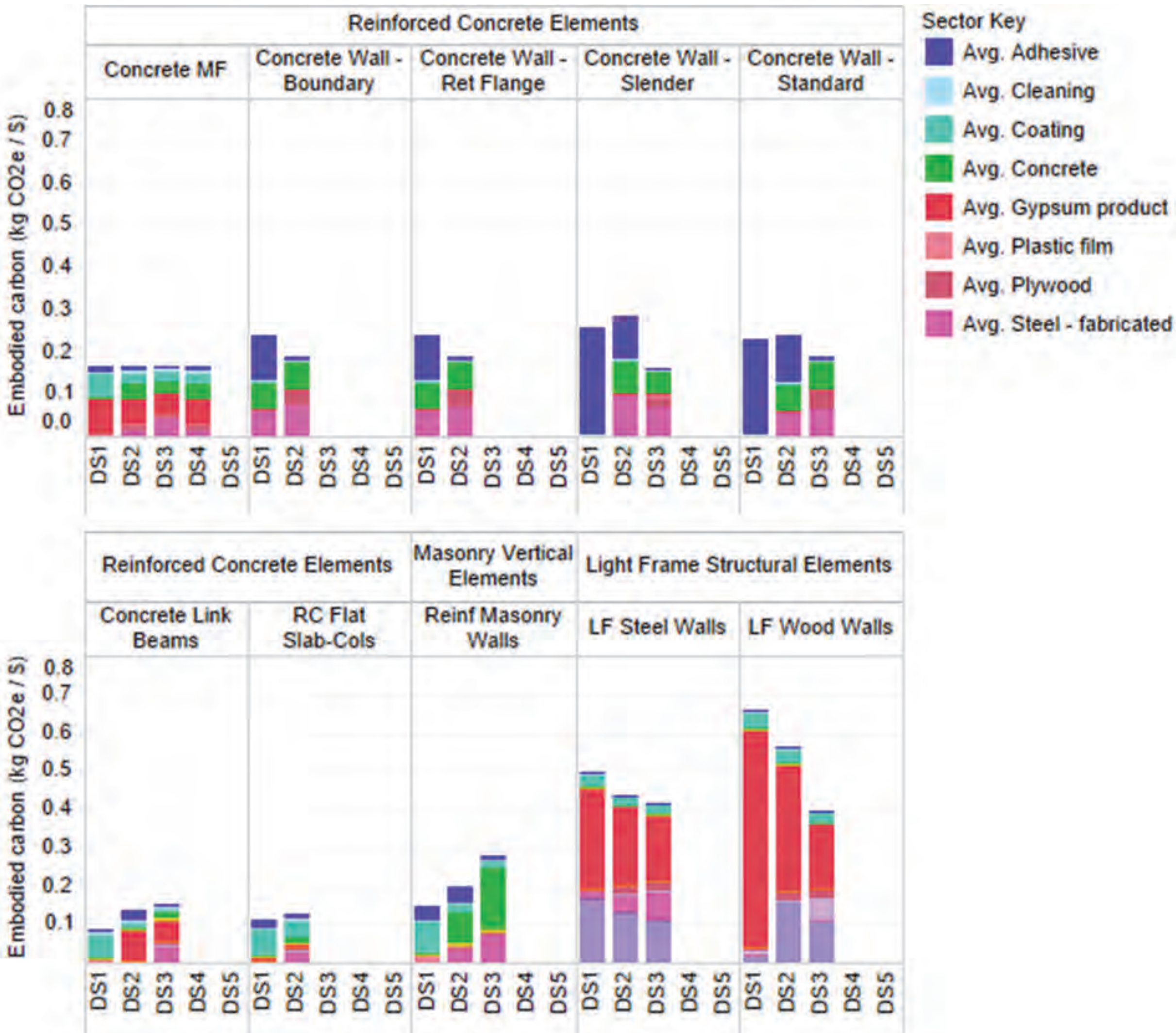


Figure 12. Embodied carbon for Reinforced Concrete Elements, Masonry Vertical Elements, and Light Frame Structural Elements.

Figure 13 shows the items in Exterior Enclosure, Roof Elements, Partitions, and one of the five Stair elements. The vertical scale goes up to 1.0 kg CO2e/$. Some notes and observations on these building components:

- The cost estimate calculations for External Walls are based on LF Steel Walls and LF Wood Walls (previous figure), thus the identical values between these categories.

- For Precast Concrete Panels, there were only two instances of cost estimates (in-plane and out-of-plane), both for DS1, where the total replacement of the cladding panels is required.
- In Masonry Chimney and Masonry Parapets, the DS1 and DS2 values are identical because the cost estimates were set up that way.
- The DS3 values of Partitions are one of the highest values in the data set. In DS3, the entire wall must be replaced with gypsum wall board, and gypsum products are very environmentally intensive, as seen previously in Figure 8.Figure 13

Comments about Stairs follow the next figure.

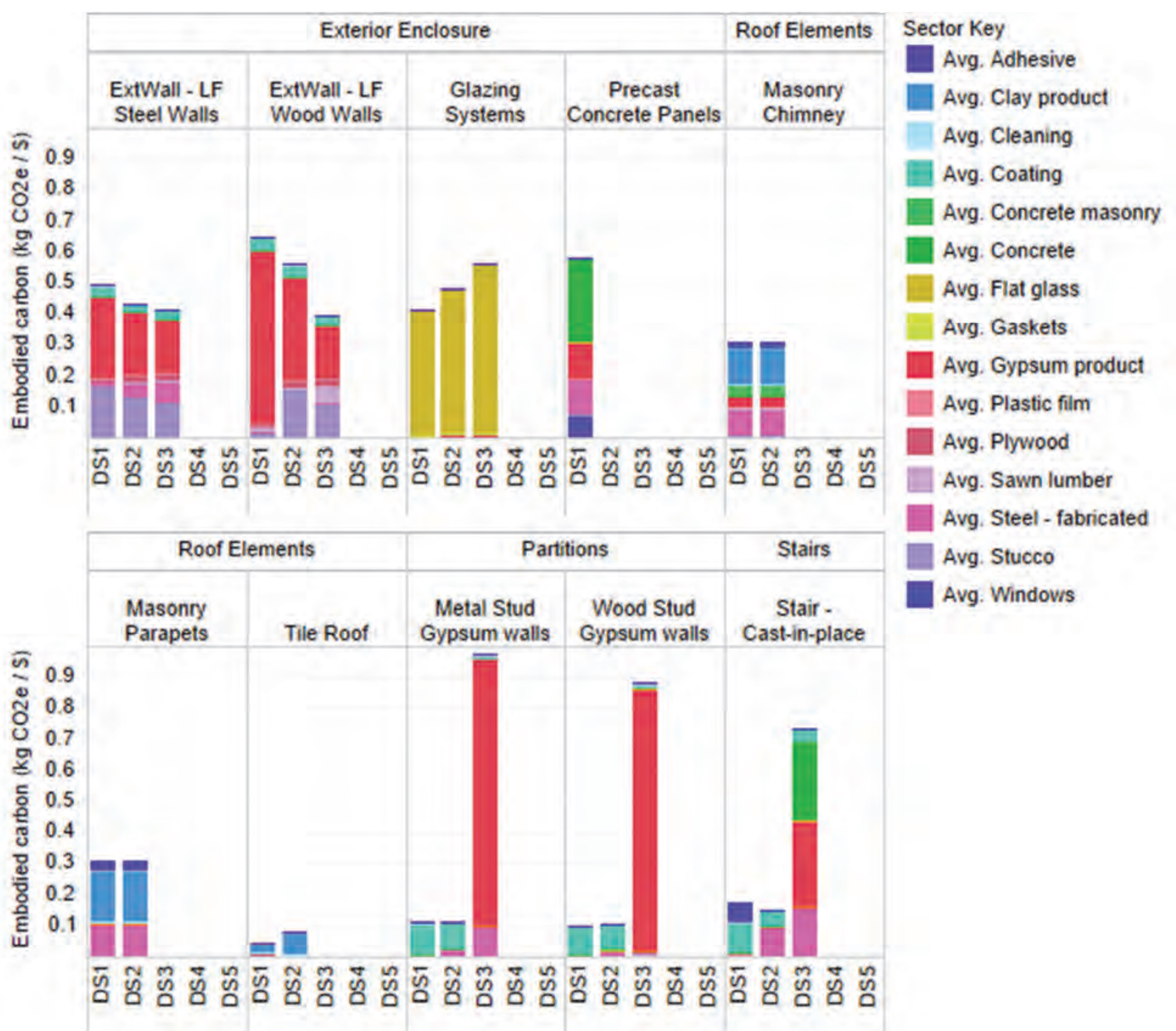


Figure 13. Embodied carbon for Exterior Enclosure, Roof Elements, Partitions, and 1 of 5 Stair elements.

Figure 14 shows the items in Stairs (4 of the 5 items, first item in previous figure), and Interior Finishes. The vertical scales also go up to 0.1 kg CO2e/$. Some notes and observations on these building components:

- The results for the Stair items are nearly identical to each other because the repair activities were very similar and so were the costs. In the repair activity named "New stair & landing – onsite assembly," no distinction was made between the different types of stair assemblies, so the percentage distribution is the same for all of them.
- The high impact of DS3 in Stairs can be attributed to the use of 'Gypsum product', which is used in replacement of ceilings/soffits, and concrete and steel, which are used to replace the entire stair assembly.
- Ceilings, especially DS3, is also another high-impact item, due to the prominent use of 'Gypsum product'.

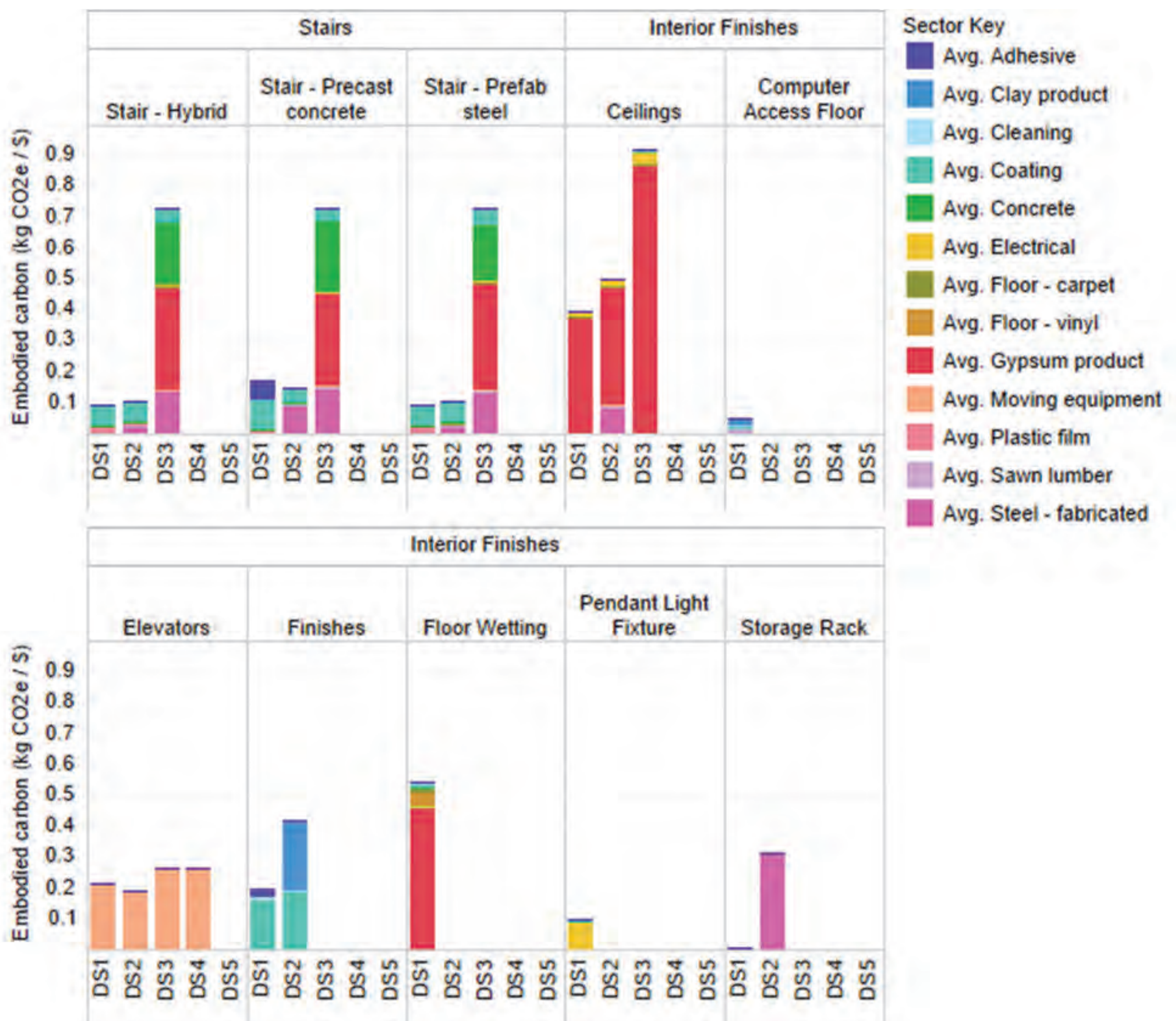


Figure 14. Embodied carbon for 4 of 5 Stair elements, and Interior Finishes, including Storage Rack.

Figure 15 shows in the items in Plumbing and HVAC (except for VAV Boxes, which is in the following figure). The vertical axis is scaled back down to a maximum value of 0.4 kg CO2e/$. Some notes and observations on these building components:

- Many of the HVAC cost estimates are set up where there are a range of equipment sizes (usually four) and categorized by “Equipment Only”, “Anchorage only”, and “Equipment + Anchorage”, and some fragilities were calculated to be a combination of other fragilities.
- In the HVAC items, the ‘Mechanical’ (and ‘Electrical’, where applicable) sectors clearly dominate.

- In Air Handlers, the cost estimate is set up so that DS2 and DS4 have equipment replacement, thus the high environmental impact in those damage states.
- DS1 typically derives a noticeable portion of its environmental impact from fabricated steel because it entails anchorage repair. The remaining damage states assume that anchorage is not an issue, so steel is not a part of the repair cost estimate.

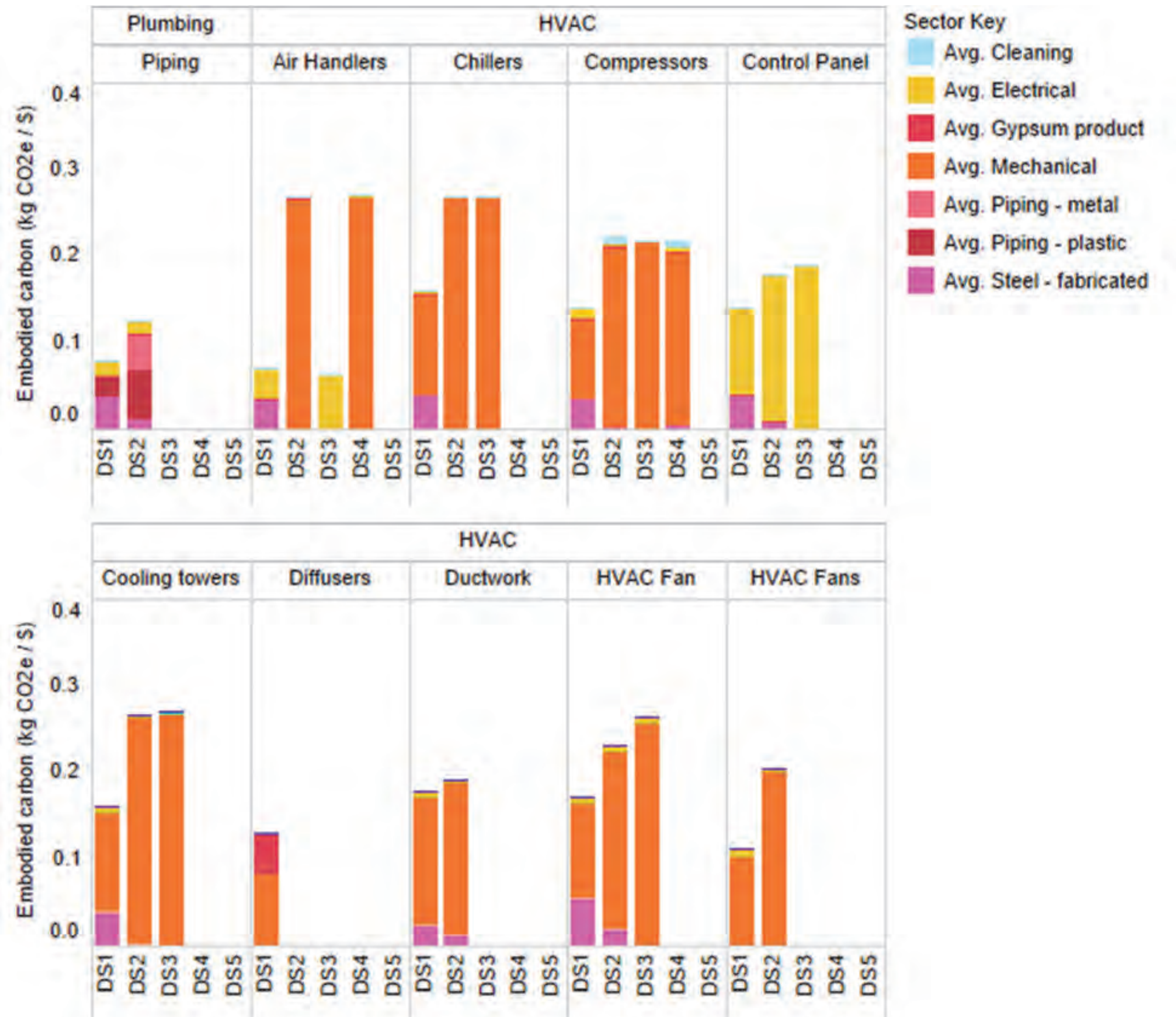


Figure 15. Embodied carbon for Plumbing, and all but one HVAC element.

Figure 16 shows elements from HVAC (the last of the set shown in the previous figure), Fire Protection, and Electrical.

- Predictably, the 'Electrical' sector dominates in the Electrical categories.
- 'Fabricated steel' is used in damage states where Anchorage repair is specified.
- 'Plastic film' is required in Battery Rack's DS2 for cleaning acid.

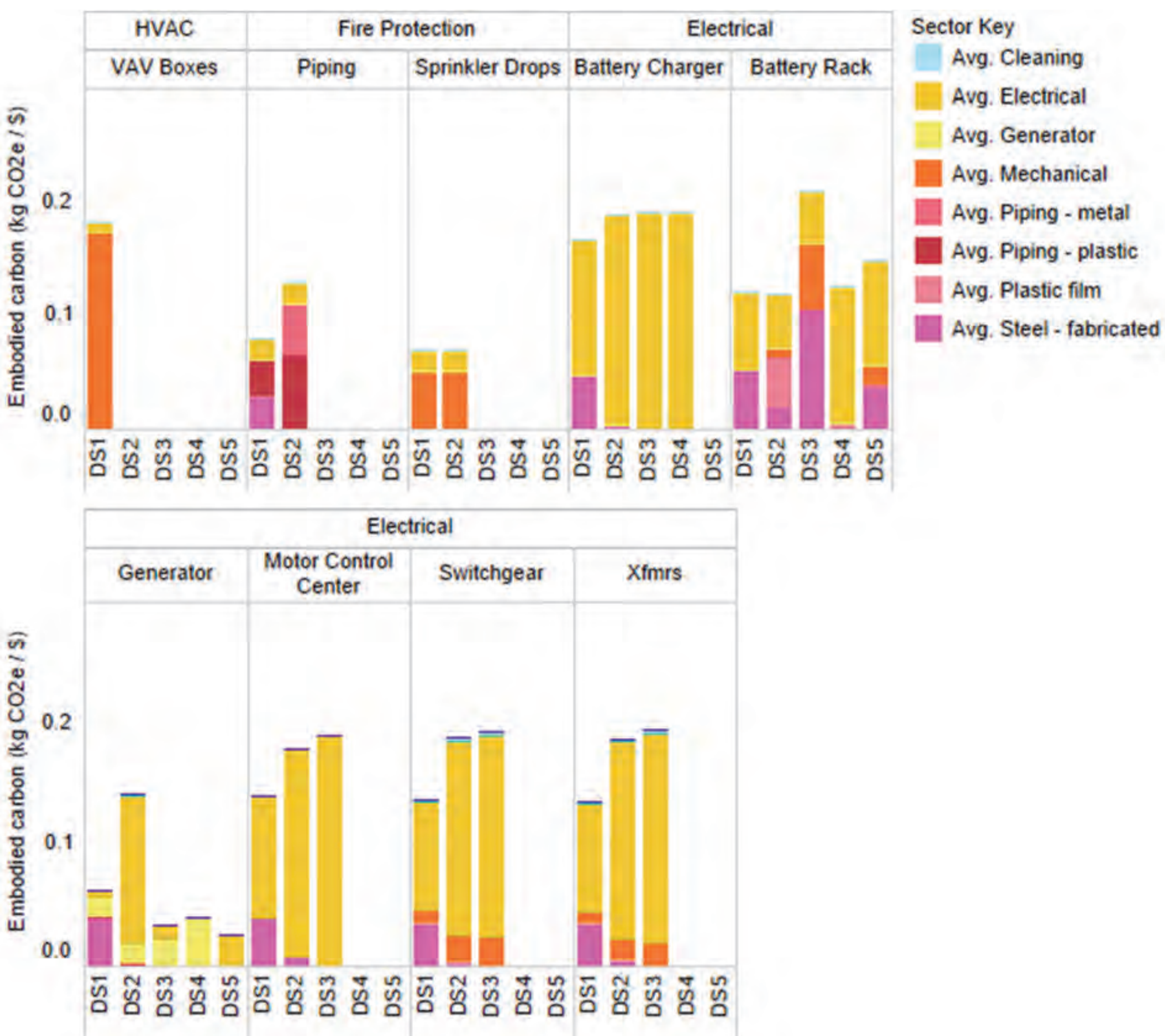


Figure 16. Embodied carbon for 1 of 10 HVAC elements (see previous figure for remaining HVAC elements), Fire Protection, and Electrical elements.

5 Estimating Initial Construction and Building Replacement Impacts

Estimating the environmental impact of initial construction and building repair can be conducted using EIO LCA at a broader level of detail, using the project lump sum costs instead of the detailed cost estimates. The EIO LCA database reports environmental impact in seven different segments of the construction sector, which can be applied to the lump sum construction cost. These factors have been extracted from the database (US 2002 Purchaser Price Model) and adjusted for inflation from 2002 to 2011 using the 1.45 factor mention previous, and is shown in Table 3. The initial cost estimates can be multiplied by these factors to obtain an estimate of environmental impact.

Table 3. Embodied carbon and embodied energy impacts for construction sectors, taken from the EIO LCA database (CMU GDI 2008), US 2002 Purchaser Price Model, adjusted for inflation from 2002 to 2011.

Sector Name		**NAICS Code**	**Embodied carbon (kg CO2e/$)**	**Embodied energy (MJ/$)**
Initial Construction	Nonresidential commercial and health care structures	230101	0.408	5.752
	Nonresidential manufacturing structures	230102	0.303	4.297
	Other nonresidential structures	230103	0.424	5.697
	Residential permanent site single- and multi-family structures	230201	0.457	6.145
	Other residential structures	230202	0.403	5.407

5.1 Overview of Calculation Procedures

The general steps for estimating the environmental impacts of a project (either initial or replacement phase) is outlined as follows with brief commentary below each step:

Step 1. Obtain the cost estimate.

This is simply the lump sum cost of the project for either initial or replacement costs. The cost should include labor and transportation but not tax.

Step 2. Allocate the costs in the cost estimate to the relevant industrial sectors selected from the EIO LCA database (www.eiolca.net). Sum the costs in each applicable sector.

Option 1: Simplified Method

This method is simpler, less precise and enables the analysis to be completed without detailed construction cost information. Select the sector that best describe the project from the 'Construction' category of the EIO LCA database, or see the list in Table 3. The costs do not need to be disaggregated, since one sector is assigned to each cost.

Option 2: Detailed Method

This method is possible when the construction cost estimate is broken down into detail. For each line item of the cost estimate, disaggregate the costs due to material, labor and construction energy (similar to the process described in Section 3.2 for the damage repair cost estimates) and identify the appropriate industrial sector for each item.

Step 3. Obtain the environmental impact factors for the selected sectors from the EIO LCA database per $1 million. Then adjust the factors for inflation (considering the date of the EIO LCA data and the date of the cost estimate) and to reflect $1 instead of $1 million spent per sector.

Ensure that the 2002 Purchaser Price Model is selected to extract the TRACI Impact Assessment and Energy factors for the construction sector selected in the previous step.

If the EIO LCA data is 2002 and the cost estimate data is 2011, the inflation factor was estimated to be 1.45, which was based on number of indices (Engineering News Record Building Construction Index, Marshal & Swift, Producer Price Index) consulted by the construction cost estimator. The environmental impacts / $\$_{2002}$ are divided by 1.45 to convert 2002 to values to 2011 values (because $\$1.00_{2002} = \$1.45_{2011}$). From there, the same process can be repeated to convert 2011 values to present values.

Step 4. Multiply the sector costs with the adjusted environmental impact factors to generate the total environmental impacts. If per dollar values are desired, divide the total environmental impact by the total cost of the fragility or project.

Multiply the project cost by the adjusted environmental impact factors to obtain the project environmental impacts.

5.2 Example Calculation

The following example demonstrates how to use the factors in Table 3 to estimate initial and replacement impacts of a sample building.

Example Environmental Impact Determination Calculation for Initial and Replacement Costs Case Study 42-Story Building

Step 1. Obtain the cost estimate.

The cost estimate for this example was derived for a theoretical 42-story residential building obtained The initial cost was estimated to be $176,000,000.

Step 2. Allocate the costs in the cost estimate to the relevant industrial sectors selected from the EIO LCA database (www.eiolca.net). Sum the costs in each applicable sector.

Since this is a residential, multi-family structure, the best applicable sector for the initial construction cost is 'Residential permanent site single- and multi-family structures'. Thus, $176,000,000 will be attributed to the sector 'Residential permanent site single- and multi-family structures.'

Step 3. Obtain the environmental impact factors, including energy impacts if applicable, for the selected sectors from the EIO LCA database per $1 million. Then adjust the factors for inflation (considering the date of the EIO LCA data and the date of the cost estimate) and to reflect $1 instead of $1 million spent per sector.

The extracted EIO LCA data for 'Glob Warm' (a.k.a. embodied carbon) and 'Energy' (embodied energy) is shown below, along with the adjusted factors in the far right two columns. The adjusted factors were obtained by dividing the original factors by an inflation factor of 1.45 to convert from 2002 to 2011 values, and also divided by 1 million to obtain per dollar values.

Constr-uction Phase	Sector Name	Original EIO LCA Data		Adjusted EIO LCA Data	
		Glob Warm (kg CO_2e/\$1M)	Energy (TJ/\$1M)	Embodied carbon (kg CO_2e/\$)	Embodied energy (MJ/\$)
Initial	Residential permanent site single- and multi-family structures	662,000	8.91	0.457	6.145

Step 4. Multiply the sector costs with the adjusted environmental impact factors to generate the total environmental impacts. If per dollar values are desired, divide the total environmental impact by the total cost of the fragility or project.

The environmental impacts are obtained by multiplying the project costs by the adjusted environmental impact factors. The calculations and results are shown below.

Initial cost:

Embodied carbon = (\$176,000,000)(0.457 kg CO_2e/\$) = 80,353,103 kg CO_2e

Embodied energy = (\$176,000,000)(6.145 MJ/\$) = 1,081,489,655 MJ

The results are summarized below, rounding for significant figures and converting MJ to a more readable TJ form (1 TJ = 10^6 MJ):

Construction Phase	Cost	Total embodied carbon (million kg CO_2e)	Total embodied energy (TJ)
Initial	\$176,000,000	80.4	1,080

6 Summary

EIO LCA data (Purchaser Price Model, US 2002) from Carnegie Mellon University Green Design Institute was applied to a set of cost estimate calculations previously formulated for the PACT project. 14 environmental impact categories were initially included in the analysis, and two were presented in the final deliverable to ATC. The results of the analysis found that gypsum product had the highest environmental impact as measured by carbon and embodied energy per dollar, and consequently any building product that contained significant quantities of gypsum, such as partition walls or light-frame walls, had some of the highest environmental impacts per dollar spent on repair.

Since gypsum-containing walls are particularly vulnerable to incurring environmental impacts as a result of seismic damage (especially considering the quantities that they are found in most buildings), it might be worth increasing the protection of these building components by investing more in less environmentally-intensive building components, such as the structural systems. The gypsum-containing walls ranged from 0.4 – 1.0 kg CO2e/$ spent in repair, depending on the damage state, while the steel and concrete structural systems ranged from 0.1 – 0.4 kg CO2e/$.

Other notable high-impact fragility groups include Glazing Systems, where most of the impact was due to glass, and Precast Concrete Panels, where total replacement of cladding panels would be required at the lowest damage state. Stair assemblies were also environmentally-intensive if they required replacement (at DS3), and ceilings, like partition and light-frame walls, had relatively high environmental impacts due to the gypsum product contribution.

7 References

FEMA (2012a). *Seismic Performance Assessment of Buildings Volume 1 – Methodology*. Prepared by the Applied Technology Council for Federal Emergency Management Agency, Washington, D.C. https://www.atcouncil.org/files/FEMAP-58-1_Volume%201_Methodology.pdf

FEMA (2012b). *Seismic Performance Assessment of Buildings, Volume 2 - Implementation Guide*. Prepared by the Applied Technology Council for Federal Emergency Management Agency, Washington, D.C. https://www.atcouncil.org/files/FEMAP-58-1_Volume%201_Methodology.pdf

FEMA (2012c). *Seismic Performance Assessment of Buildings, Volume 4 – Methodology for Assessing Environmental Impacts*. Prepared by the Applied Technology Council for Federal Emergency Management Agency, Washington, D.C. https://www.atcouncil.org/docman/fema/19-fema-p-58-4-volume-4/file

Bare, J., Thomas, G., & Norris, G. (2006). Development of the Method and U.S. Normalization Database for Life Cycle Impact Assessment and Sustainability Metrics. Environmental Science & Technology, 40(16), 5108-5115.

Carnegie Mellon University Green Design Institute (CMU GDI). (2008) Economic Input-Output Life Cycle Assessment (EIO-LCA), US 1997 Industry Benchmark model [Internet], Available from: <http://www.eiolca.net> Accessed 01 November, 2016.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., & Rosenbaum, R. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. The International Journal of Life Cycle Assessment, 8(6), 324-330.

Jolliffe, I. (2002). Principal component analysis (2nd ed., Springer series in statistics). New York: Springer.

Lippiatt, B.C. (2007). *BEES 4.0 Technical Manual and User Guide* (NISTIR 7423). Gaithersburg, Maryland: National Institute of Standards and Technology.

Lu, He, & Dong. (2011). Performance assessment of air quality monitoring networks using principal component analysis and cluster analysis. Building and Environment, 46(3), 577-583.

Morris, P. and Simonen, K (2014). *ATC58-2: Incorporating Environmental Impact into PACT*.

Ryberg, M., Vieira, M., Zgola, D., Bare, M., & Rosenbaum, M. (2014). Updated US and Canadian normalization factors for TRACI 2.1. Clean Technologies and Environmental Policy, 16(2), 329-339.

Sharrard, A., Matthews, H., and Roth, M. (2007). "Environmental Implications of Construction Site Energy Use and Electricity Generation." J. Constr. Eng. Manage., 10.1061/(ASCE)0733-9364(2007)133:11(846), 846-854.

Simonen, K. (2014). Life cycle assessment (First ed., PocketArchitecture, technical design series). London ; New York: Routledge.

Simonen, K., Merrifield, S., Almufti, I., Strobel, K., and Tipler, J. (2015) Integrating Environmental Impacts as Another Measure of Earthquake Performance for Tall Buildings in High Seismic Zones. Structures Congress 2015: pp. 933-944.

Statheropoulos, Vassiliadis, & Pappa. (1998). Principal component and canonical correlation analysis for examining air pollution and meteorological data. Atmospheric Environment, 32(6), 1087-1095.

U.S. Energy Information Administration (US EIA). (2016) Carbon Dioxide Emissions Coefficients [Internet], Available from: <https://www.eia.gov/environment/emissions/co2_vol_mass.cfm> Accessed 19 August, 2016.

8 Appendices

8.1 Appendix A: Assumptions in assigning cost percentages

The following is a list of guidelines formulated by the UW research team in assigning cost percentage allocations to the industrial sectors, since some of the estimates provided by the construction cost estimator did not add up to 100%:

- Used the percentage values provided by the construction cost estimator as much as possible. Labor, Plant, Rental equipment, and Temporary Materials were the given categories.
- Allocated Energy as a constant 1% for all work items by subtracting 1% from Labor.
- For the ‘Plant’ percentage allocation in demolition activities, this percentage was assigned to the ‘Cleaning’ sector.
- Assumed that costs for concrete were split 50/50 between concrete and steel, then 5% was taken from the steel cost to be placed in ‘Adhesive’ for epoxy.
- The cost allocation for steel braces and gusset plates was assigned to the sector named “Iron, steel pipe and tube manufacturing from purchased steel” (hot-rolled steel), and all other materials, including rebar, joists, welding (if it was explicitly described as a repair activity) was assigned to “Plate work and fabricated structural product manufacturing” (fabricated steel). The distinction between the two sectors was unclear, probably because the reference to structural shapes or structural metal products could be found in multiple sector categories. A third possible sector for steel products could have been “Iron and steel mills”, which is upstream of the previous two sectors, because it is reasonable to assume that structural metal products are produced directly in the steel mills. The environmental impact per dollar spent decreases in magnitude with more processing, so one can obtain more conservative results by using “Iron and steel mills” for all steel products.

The following is a list of “final” questions to the assumptions made by the UW research team to resolve them:

Question/Issue	**Final Action**
For reinforced concrete, the money was split 50/50 to concrete and steel based on a simple cost study.	No action – leave as is.

Work item named 'cut out existing beam' in attached file has 15% not assigned. What should be for? Similar for the two lines after this.	Assumed the 15% goes into cleaning
For 'construct new wall partially grouted' this is assumed to be reinforced CMU wall. What percentages should be used for concrete block, grout and steel?	Assumed 40% concrete, 40% steel, 5% adhesive (epoxy)
In the curtain wall sections there is no replacement of aluminum specified. Is the assumption that in all cases the aluminum frame can be re-used?	No action – leave as is. In review of curtain wall sections all damage remains in glass repair. No mention of aluminum repair/replacement.
For glass replacement, should a portion of the money be assigned to 'rubber' to account for the gaskets?	For 'Add glass cost', added 5% for gaskets. Although there is still 0% for labor for this unique cost estimate line item. Assume this is because labor is included elsewhere.
For 'remove store and reinstall' chillers, did not know how to break out the %'s	Set Labor and Rental %'s equal to 'Replace Chiller'; attributed 10% to cleaning and 65% to mechanical
For all replacement of large equipment, assigned 15% labor and 85% to mechanical equipment. Is this acceptable?	No action – leave as is.
For tabs that had fragilities costs defined by +$ instead of their own cost breakdown, the updated % allocation scheme differs from the proportions derived from the cost estimate. Applies to: Concrete MF (DS2, DS3), RC Flat Slabs-Cols, Link Beams (both)	Decided not to use most recent % allocations. Instead, scaled up the values derived from the cost estimate to match the final costs. Except for RC Flat Slabs-Cols, where the additional environmental impacts were based on epoxy impacts.
For Double L SCBF, the DS1 values don't fit the usual cell referencing pattern of the steel braces in DS1. Typically, all these DS1 values are the same for the different weight classes within a brace type. Is this correct?	Adhered to Master Summary cell references -- not sure if there was a reason for these inconsistent cell references.

LF Wood Walls (and Ext) -- the description in the fragility names do not match the descriptions in the cost estimate worksheet.	Changed the cell references in Master Summary to match descriptions in cost estimate.
There are some negative values in the cost estimate (negative quantities), which results in negative environmental impacts. How to deal with these?	Adjusted the percentages (in 'Battery Rack') to ensure that there would be no negative environmental impacts.
What to use for fire protection?	Gypsum product
Labor for 'Boundary elements', 'Boundary posts', 'New cladding panel' seems suspiciously low (10%)	Leave as is
What sectors to use for 'Retape' and 'Tie in with existing construction/finish'?	Assumed Coatings.
What sector to use for 'Heat Protection' and 'Roof and Floor Protection'?	Assumed Gypsum product or plywood

8.2 Appendix B: List of industrial sectors

Sector Short Name	Sector Full Name	NAICS Code	Comments
Adhesive	Adhesive manufacturing	325520	• Applies to glue, epoxy, grout
Aluminum	Aluminum product manufacturing from purchased aluminum	33131B	• Applies to aluminum window walls/curtain walls
Clay product	Brick, tile, and other structural clay product manufacturing	32712A	• Applies to brick, ceramic tile
Cleaning	Services to buildings and dwellings	561700	• Applies to material removal and disposal. • An alternative sector selection could have been Waste Remediation Services, since this sector is mostly applied to demolition activities.
Coating	Paint and coating manufacturing	325510	• Applies to paint, finishes
Concrete	Ready-mix concrete manufacturing	327320	• Applies to poured concrete
Concrete masonry	Concrete pipe, brick and block manufacturing	327330	• Applies to concrete masonry units

Electrical	Miscellaneous electrical equipment manufacturing	335999	• Applies to "Mechanical and electrical modifications or relocations as required for repair work" and most electrical items
Flat glass	Flat glass manufacturing	327211	• Applies to flat glass (windows)
Floor - carpet	Carpet and rug mills	314110	• Applies to carpet flooring
Floor - vinyl	Other plastics product manufacturing	32619A	• Applies to vinyl flooring
Gaskets	Gasket, packing, and sealing device manufacturing	339991	• For window gaskets • An alternative sector selection could have been a rubber manufacturing sector, but since the rubber in the cost estimate was specifically being used for windows, the 'gasket manufacturing' sector was chosen.
Generator	Motor and generator manufacturing	335312	• For generator items
Gypsum product	Lime and gypsum product manufacturing	3274A0/ 327420	• Includes heat protection, fireproofing (sheetrock), ceiling tile (maybe paper?), soffit, GWB tape.
Mechanical	Air conditioning, refrigeration, and warm air heating equipment manufacturing	333415	• Applies to HVAC equipment • HVAC equipment could have also been assigned to the following sectors: o "Air purification and ventilation equipment manufacturing" o "Heating equipment manufacturing"
Moving equipment	Material handling equipment manufacturing	333920	• Applies to elevators, since there were some elevator-specific repairs (hydraulics)
Piping - metal	Fabricated pipe and pipe fitting manufacturing	332996	• Applies to metal pipes
Piping - plastic	Plastics Pipe and Pipe Fitting Manufacturing	326122	• Applies to plastic pipe
Plastic film	Plastics packaging materials, film and sheet	326110	• Applies to protection of floor or office equipment or cleaning battery acid
Plywood	Veneer and plywood manufacturing	32121A	• Applies to concrete formwork, and floor protection in some cases
Sawn lumber	Sawmills and wood preservation	321100	• Applies to wooden joists

Steel - fabricated	Plate work and fabricated structural product manufacturing	332310	• For rebar, joists, and welding (manufacturing of structural steel products beyond rolling) • Could also have been "Iron and steel mills"
Steel - hot-rolled	Iron, steel pipe and tube manufacturing from purchased steel	331200	• For hot-rolled steel, plates. • Could also have been "Iron and steel mills"
Stucco	Miscellaneous nonmetallic mineral products	327999	• Applies to wood frame chimney with stucco, wall finishes with stucco
Windows	Ornamental and architectural metail products manufacturing	332320	• Includes Metal Window and Door Manufacturing

8.3 Appendix C: Calculating on-site energy consumption

During the process of generating environmental impact data, the impact of construction energy consumption was evaluated. Although the sensitivity studies noted that the environmental impacts from on-site energy construction are too uncertain to be included in the database, the background assumptions are presented here to enable future development of on-site energy consumption data.

Sharrard et al (2007) found that "that gasoline and diesel fuel represent the majority of energy consumption in the industry with 62–75% of all use. The share of natural gas in construction is fairly constant at 13–15% of energy required, and electricity varies between 10 and 25% of total energy." Using the average of these percentages, it was assumed for the purposes of this study that gasoline and diesel comprised 68.5% of the overall construction energy mix, natural gas was 14%, and electricity was 17.5%. The overall energy per dollar of energy source consumed on the construction site was determined by combining these energy mix percentages with the costs (provided by the authors) and thermal energy of the energy sources, the. The calculated values are summarized below:

Energy source	Units	Btu/unit	$/unit	Btu/$	% of energy mix	Btu/$ contribution to energy mix
Natural gas	CF	1,020	4.02E-03	253,731	14%	35,522
Electricity	kWh	3,412	4.91E-02	69,491	18%	12,161
Gasoline + diesel	gallons	132,000	1.03E+00	128,155	69%	87,786

Total	135,470

The overall energy per dollar contribution to the energy mix was converted from 135,470 Btu/$ to 142.9 MJ/$.

To obtain the greenhouse gas emissions from this mix of energy sources, data from the U.S. Energy Information Agency was used to convert BTU's to kilograms of carbon equivalent, the accepted measure for greenhouse gas emissions. The values were provided in kg CO2 / million BTU and converted to kg CO2e / BTU by multiplying by a factor of 12/44, as was recommended by the data source, and divided by a factor of a million. The retrieved and calculated values are presented below:

Fuel Type	**kg CO2 / million BTU**	**kg CO2e / BTU**
Natural gas	53.1	1.45E-05
Gasoline	71.3	1.94E-05
Diesel	73	2.00E-05

The greenhouse gas emission values for gasoline + diesel mix was calculated to be 1.97 x 10^{-5} kg CO2e / BTU, based on the ratio of gasoline to diesel provided by Sharrard et al, which was 1.325, resulting in 57% gasoline and 43% diesel.

Applying the greenhouse gas emission coefficients to the fuel mix in the previous calculations resulted in an overall value of 4.746 kg CO2e / $ energy cost on a construction site. The calculated values are summarized below.

Fuel Type	**Btu/$ contribution to energy mix**	**kg CO2e / BTU**	**kg CO2e / $ contribution to energy mix**
Natural gas	35,522	1.45E-05	0.514
Gasoline	12,161	2.06E-04	2.506
Diesel	87,786	1.97E-05	1.726
Total			4.746

8.4 Appendix D: BEES Environmental Impact Score

The research team explored different environmental impact metrics to use. One such metric is the BEES Environmental Impact Score (Lippiatt 2007) which combines different environmental impacts into a single ‘score.’ This score is weighted both based on the perceived ‘importance’ of the impact as well as the relative quantity of the emissions. Although the BEES score is not included in the final database presented, the information is shared here to enable readers to interpret the statistical analysis appropriately and to support future research.

Presented below are 1) the formula for the calculation of the BEES environmental performance score (Figure 17), and the BEES stakeholder panel weights (Figure 18). The normalization values were taken from Ryberg et al (2014). The final weights and normalization values used in this analysis are shown in Table 4.

Appendix A. BEES Computational Algorithms

A.1 Environmental Performance

BEES environmental performance scores are derived as follows.

$$\mathrm{EnvScore}_j = \sum_{k=1}^{p} \mathrm{IAScore}_{jk}\text{, where}$$

$\mathrm{EnvScore}_j$ = environmental performance score for building product alternative j;
p = number of environmental impact categories;
$\mathrm{IAScore}_{jk}$ = characterized, normalized and weighted score for alternative j with respect to environmental impact k:

$$\mathrm{IAScore}_{jk} = \frac{\mathrm{IA}_{jk} * \mathrm{IVwt}_k}{\mathrm{Norm}_k} * 100\text{, where}$$

IVwt_k = impact category importance weight for impact k;
Norm_k = normalization value for impact k (see section 2.1.3.3);
IA_{jk} = characterized score for alternative j with respect to impact k:

$$\mathrm{IA}_{jk} = \sum_{i=1}^{n} \mathrm{I}_{ij} * \mathrm{IAfactor}_i\text{, where}$$

n = number of inventory flows in impact category k;
I_{ij} = inventory flow quantity for alternative j with respect to inventory flow i, from BEES environmental performance data file (See section 4.4.);
$\mathrm{IAfactor}_i$ = impact assessment characterization factor for inventory flow i

Figure 17. Reproduction from the section of Appendix A of Lippiatt (2007) that describes the formulae for the BEES environmental performance score calculation.

Table 2.13 Relative Importance Weights based on Science Advisory Board Study

Impact Category	*Relative Importance Weight (%)*
Global Warming	16
Acidification	5
Eutrophication	5
Fossil Fuel Depletion	5
Indoor Air Quality	11
Habitat Alteration	16
Water Intake	3
Criteria Air Pollutants	6
Smog	6
Ecological Toxicity	11
Ozone Depletion	5
Human Health	11

Figure 18. Reproduction of the BEES stakeholder panel weights from Lippiatt (2007).

Table 4. BEES Stakeholder Panel weights and normalization values used in the analysis

Impact Category	**BEES Stakeholder Panel Weight**	**Normalization Value**	**Normalization units**
Global warming potential (embodied carbon)	29.3	24000	kg CO2e / year / capita
Acidification	3.0	91	kg SO2e / year / capita
Eutrophication	6.2	22	kg Ne / year / capita
Ozone depletion	2.1	0.16	kg CFC-11e / year / capita
Smog	3.5	1400	kg O3e / year / capita

8.5 Appendix E: Statistical Evaluation (Using Embodied Carbon as a Proxy for Other Environmental Impacts)

The (linear) relationship between two variables can be measured by their correlation, but a correlation does not capture the joint relationship between a collection of three or more variables. One popular technique to measure the (linear) relationship between three or more variables is Principal Component Analysis (PCA).

PCA is a mathematical technique that decomposes the variance of a set of variables (Joliffe 2002). Specifically, PCA transforms the original set of variables into "principal components," a new set of variables that are orthogonal linear combinations of the original variables. The principal components are determined such that the first component maximizes the variance of the data. Each subsequent component maximizes the residual variance after the previous components are removed.

The two main outputs of PCA are the principal component representation of each data point and a 'loading table' that maps the original variables to the principal components.

When a majority variance (>90%) is explained by the first few principal components, the data is considered to have a low 'effective dimension': the majority of variability in the data is along the first few principal components. In this case, the first few principal components can serve as a proxy for the full data and is why PCA is used for dimension reduction (Lu et al 2011, Statheropoulos et al 1998).

The following figure (A.1) presents the results of the Principal Component Analysis, plotting the environmental impact factors in the first and second principal components. Note how all of the vectors representing the environmental impact categories, except for ozone depletion, are closely aligned with Principal Component 1 (PC1, the horizontal axis), and ozone depletion is more aligned with PC2. This shows how embodied carbon is closely correlated with the other environmental impact categories (except for ozone depletion), and can thus serve as an appropriate proxy for these other environmental impacts.

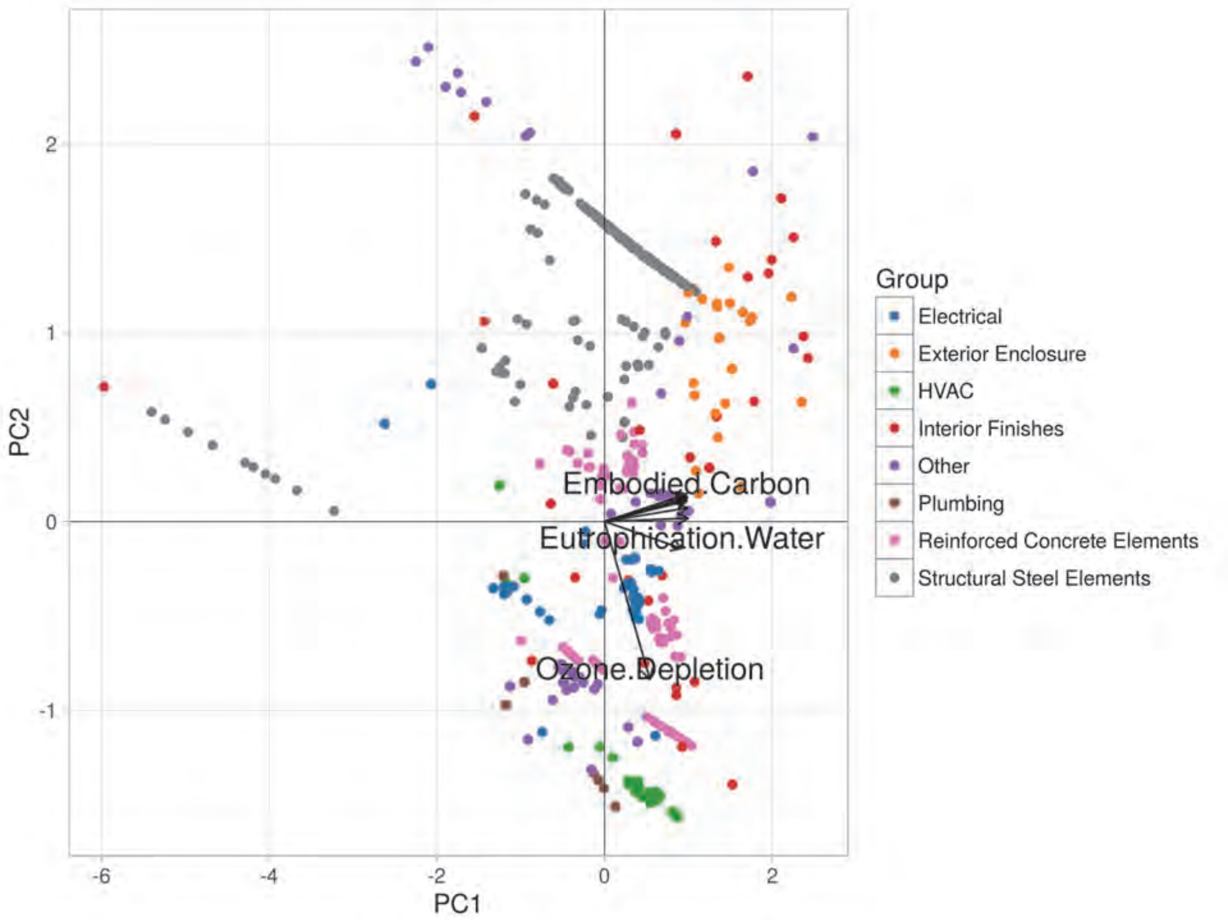


Figure A.1. Biplot of PC1 vs PC2 for Principle Component Analysis of environmental impact factors.