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Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts

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ABSTRACT

Decisions made during a building's early design stages critically determine its environmental impact. However, designers are faced with many decisions during these stages and typically lack intuition on which decisions are most significant to a building's impact. As a result, designers often defer decisions to later stages of the design process. Life-cycle assessment (LCA) can be used to enable better early stage decision-making by providing feedback on the environmental impacts of building information modeling (BIM) design choices. This paper presents a method for applying LCA to early stage decision-making in order to inform designers of the relative environmental impact importance of building component material and dimensioning choices. Sensitivity analysis is used to generalize the method across a range of building shapes and design parameters. An impact allocation scheme is developed that shows the distribution of embodied impacts among building elements, and an impact reduction scheme shows which material and thickness decisions achieve the greatest embodied impact reductions. A multi-building residential development is used as a case study for introducing the proposed method to industry practice. Results show that the method can assist in the building design process by highlighting those early stage decisions that frequently achieve the most significant reductions in embodied carbon footprint.

1. Introduction

Buildings consume significant amounts of energy and materials. They account for 41% of the total energy consumption in the U.S [1] and 38% of the nation's greenhouse gas emissions [2]. Buildings' embodied energy, which includes feedstock and process energy for production of building materials as well as the total fuel cycle energy for all processes required to construct a building, may be particularly significant [3,4]. In cases where buildings have been designed for low- or net-zero energy, embodied environmental impacts can approach the magnitude of impacts due to operational energy use [5–7].

A significant portion of a building's life-cycle impacts are determined by decisions made in the early design stages [8–10]. Choosing materials with low embodied impacts at this stage therefore has potential to significantly reduce a building's life-cycle impact [11]. However, evaluation of the environmental performance of these decisions and strategies for generating alternatives that improve upon the performance of designs are typically not performed until the design development stage [12]. Life-Cycle Assessment (LC), when applied to buildings, is a method for predicting how a facility will perform over its lifetime, which includes raw material extraction, manufacturing, construction, operation, maintenance, repair, replacement, and demolition [13]. LCA considers environmental and social impacts and is often coupled with life-cycle cost assessment methods that consider economic impacts [14]. Commonly applied environmental indicators include global warming potential, carcinogenicity, and resource consumption.

LCA is commonly used in such industries as automotive design, equipment manufacturing, and consumer product design [15–17]. Compared to products produced in these industries, buildings are unique, their lifetime is decades long, they have multiple functions, and they are locally assembled. Adoption of LCA methods to architecture, engineering and construction (AEC) projects has been

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limited due to these features. In addition, LCA methods typically require significant time and effort for implementation. The difficulties in applying LCA to the AEC industry have been noted by others, including obtaining complete environmental impact data for building components, tracking material flows, and clearly defining system boundaries [18–20]. In addition, building information modeling (BIM), which is increasingly used by AEC designers to digitally represent a facility during the early design stages, currently lacks interoperability with LCA software [4]. An additional challenge of performing LCA during the early stages of a building project is the complexity and large number of decisions that a designer faces. For example, the building design process requires material and dimensioning specifications for hundreds of components. Yet the design process is highly fragmented, with professionals working in an uncoordinated fashion on such solutions as safety, health, serviceability, and aesthetics. Applying LCA to early building design is therefore not straightforward, and material and dimensioning specifications are typically deferred to engineering and construction teams in the design development stage [21]. Postponing or making changes to such decisions during this stage has been shown to lead to significant increases in building impact [12].

In order for LCA to be an effective early stage decision-making tool for the AEC industry, designers must therefore be better enabled to understand which material and dimensioning decisions most significantly determine a building's environmental impact and which decisions are less important. This knowledge can be part of an integrated, BIM-enabled environmental impact feedback process, with designers focusing on decisions with large impact during the early design stages and deferring decisions with marginal impact to later design stages. This paper introduces a framework for providing designers with intuition on how buildings' embodied impacts are distributed throughout building elements. The framework is intended for application specifically during the early design stages, when the design problem is typically not well defined, the number of design alternatives is large, and the potential to reduce environmental impacts is greatest. The framework utilizes a computational method that integrates BIM software with LCA and energy analysis software, in order to quickly evaluate the embodied impacts of thousands of building designs. Sensitivity analysis is then performed on these results in order for designers to understand which building components' embodied impacts consistently contribute the largest to a building's environmental impact across the designs. Material choice and component dimensions, in the case of this paper a surface component's thickness, are selected as the two bases for demonstrating how designers can reduce a building's environmental impact. The framework is applied to a case study to show how impacts are distributed throughout a building in the early design stages as well as which building component decisions are the most important in terms of environmental impact. The framework requires a minimal number of inputs and accommodates a range of values for massing parameters and other design inputs. The inherent flexibility of the method and minimal required inputs therefore make it useful for the early design stages.

2. Literature review

Researchers and practitioners have recognized the importance of early design stages when reducing buildings' life-cycle environmental impact. Numerous researchers have shown that the earlier decisions are made in the design process and the fewer the changes to these decisions at later stages, the greater is the potential for reducing the building's environmental impact. For example, by selecting an environmentally preferred building shape and orientation during the early design stages, Cofaigh et al. [8] were able to reduce a baseline design's environmental impact by 40%. Massing changes made during late design stages were shown by Ellis et al. [9] to have considerable environmental and economic cost ramifications. Providing designers with early stage environmental impact performance feedback was demonstrated by Schlueter and Thesseling [12] to have strong effects on design choices, resulting in less energy intensive buildings and increasing awareness of ways to reduce energy consumption.

Building on this early stage design work, others have integrated BIM software with LCA methodology and optimization techniques in order to minimize buildings' environmental impacts during early stage design. Wang et al. [22] computationally integrated BIM, LCA, energy analysis, and optimization software in order to evaluate the environmental impact consequences of various early stage building design parameters. A multi-objective genetic algorithm was used to identify Pareto optimal solutions for minimized cost and environmental impact performance, resulting in a significant reduction in global warming potential. Similarly, Hauglustaine and Azar [23] developed a computational integration method for providing BIM energy performance feedback prior to the sketch design phase. A limited number of design variables were included, such as those relating to a building's geometry and thermal performance. A genetic algorithm was used to optimize cost and energy performance, and sensitivity analysis was performed to show the relationship between performance characteristics and changes to the design variables. Coley and Schukat [24] integrated BIM and thermal analysis software in developing a method for optimizing early stage building designs for energy performance. The method gives designers the flexibility to choose from a set of high-quality designs based on non-optimized criteria.

LCA has also been used to estimate impacts of buildings at the early design stages. Pushkar et al. [25] used LCA methodology to group design variables into four clusters then show each variable's environmental impact bounds for each phase in a building's life cycle. Common building material and dimensioning alternatives were considered. Sensitivity analysis was conducted using different fuel sources and production methods, in order to show the range of material quantity impacts for each life-cycle stage. Bribian et al. [26] also applied LCA to early stage building design using common building component materials and sizes, in order to provide material selection guidelines based on minimized embodied impacts.

A number of software tools have also been developed for using LCA to assess buildings' environmental impact at the early design stages. For example, the Athena EcoCalculator [27] provides environmental impact estimates of buildings based on minimal inputs. However, these tools provide no sensitivity analysis showing how building components' environmental impacts vary over a range of design alternatives. Lack of integration with BIM tools also reduces their utility during the early design stages.

Prior research has also neglected to conduct sensitivity analysis on the embodied impacts of building component materials and dimensions for a range of design alternatives. An early stage decision support method is lacking that shows the degree to which design choices achieve embodied impact reductions for thousands of design variations. Massing parameters, such as building shape and height, typically are not varied in environmental impact analyses of buildings. Prior studies also do not include impacts due to mechanical, electrical, and plumbing (MEP) or other service equipment or the maintenance, repair and replacement (MRR) of building components. These limitations are addressed by the proposed method.

3. Methodology

3.1. Scope

The goal of the proposed methodology is to enable designers to understand the relative environmental impact implications of building component decisions. The choices of building component material and building component dimensions (i.e. thickness) have been shown to be important in terms of contributing to a building's life-cycle environmental impact [28–30]. In addition, material and thickness choices extend to many building components, such as the foundation, cladding, walls, floors, and duct insulation. Broadness of scope and degree of impact therefore drive the selection of material and thickness as the two types of decisions used to determine which building components contribute most significantly to a building's embodied impact.

A second goal of the methodology is to create an automated or semi-automated process that provides environmental impact feedback on many building designs. Central to the method is the integration of BIM software with LCA, energy simulation, and sensitivity analysis software. Designers manually input a range of values into the BIM for a limited number of design variables. The BIM also requires input values for a limited number of constraints. The method then computationally iterates through all possible design variable values, thereby creating a large set of building designs each with an environmental impact. Data is then aggregated and analyzed in order to determine which building components consistently contribute the most to a building's embodied impact. The method is not a full integration, since LCA and energy analysis data are manually extracted from various programs prior to the iterations. Further detail on the degree of automation used in the process is presented later in the paper.

The UniFormat 2010 classification system is used in the AEC industry to classify building components within building element categories [31]. These elements refer broadly to the parts of a building. UniFormat elements within the project scope are: substructure (A), shell (B), interiors (C), and services (D). The remaining elements (equipment and furnishings (E), special construction and demolition (F), and sitework (G)) are not considered, since these decisions relate to interior aesthetics, require specialized knowledge of site conditions, or otherwise involve decisions that would be impractical to make by designers before the design development stage. A detailed description of this classification framework is presented in Section 3.2.

Fig. 1 schematically shows the complete life cycle of a typical building. The shaded area shows those phases that are included in this method. Operational phase impacts due to HVAC, lighting, plug loads, and water use have been excluded in the scope. Rather, the research focuses on embodied impacts due to building component material and dimension choices. The operational phase is limited to embodied impacts due to maintenance, repair, and replacement (MRR) of building components. As such, decisions determining a building's impact due to operational energy use from utilities are assumed to be independent from decisions determining embodied impacts. The intention of the study is to make as granular as possible those decisions determining building embodied impacts. Including the effects of building materials and thicknesses on operational energy would dilute this feedback. Therefore, operational energy use beyond MRR is excluded from the study. Coupling of these inter-life-cycle phase design decisions is a topic of future planned research. Demolition and on-site construction have also been excluded, since impacts associated with these phases have been shown to be difficult to calculate [32] and small when compared with other phases [33].

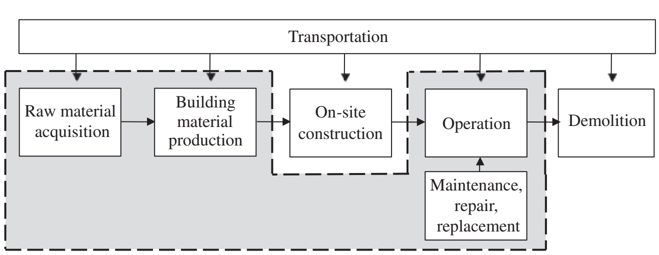


Fig. 1. Building life-cycle phases included in proposed method for reducing embodied impacts of early stage designs. Operational phase is limited to embodied impacts due to maintenance, repair, and replacement of building components.

Researchers have identified several impact categories that are useful in measuring the environmental impact of buildings. These impact categories include global warming potential, nonrenewable energy consumption, human toxicity, acidification, and eutrophication, among others [34]. Although the authors recognize the importance of all of these categories in comprehensively assessing environmental impact, this methodology considers only global warming potential. The metric used for this purpose is carbon dioxide equivalents (CO_2e) using the relevant 100-year global warming potential [35], which measures the total amount of greenhouse gas emissions of the building, considering all relevant sources. The building owner or designer could add other impact categories to the analysis as required.

3.2. Building component classification framework

The framework used to structure the building component decision-making process is based on Uniformat 2010. Table 1 outlines the assemblies and their sub-components for each of the four Uniformat elements. Material choices for each component are determined using RSMeans [36] and Athena EcoCalculator [27]. These choices are not meant to be exhaustive but rather representative of common materials for each component. The appendix enumerates the material choices (Table A) and their properties (Table B) for each building component. These properties include material densities and embodied CO_2 factors, or the amount of carbon dioxide equivalents associated with materials' feedstock energy, energy required to process the materials into building components, and fuel cycle energy for all pre-operational processes. Section 4.2 describes the software from which these factors are obtained and why these programs are chosen.

The building component classification framework includes thickness as a dimensioning variable. Specifications from several construction material and equipment supplier sources are used to determine thickness ranges. These sources are listed in the description for Table 1. The smallest minimum value and largest maximum value are identified across all sources for each subcomponent then placed into the table. Thickness ranges are not articulated for every component, namely those whose size determinations are difficult to reduce to one single thickness parameter and/or best quantified by structural analysis methods applicable to later design stages.

3.3. Analysis process

The general steps of the proposed integrated, BIM-enabled embodied impact feedback method are shown in Fig. 2. The arrows in the figure represent data dependencies between process steps.

Table 1
Building component classification framework showing building components, number of materials, and thickness parameters considered. Sources used for thickness ranges (by Uniformat element): A [36,38]; B [36,39]; C [36].

Uniformat element	Assembly	Sub-components	Number of material choices	[a]Thickness	
				Minimum (m)	Maximum (m)
[b]A: Substructure	Piles	Piles, *vapor barrier*, caps, *slab-on-grade*, grade beam, rebar, *formwork*	2, 2, 1, 1, 1, 1, 1	0.1	0.4
	Footings	Footings, *vapor barrier*, *slab-on-grade*, grade beam, rebar, *formwork*	1, 2, 1, 1, 1, 1	0.1	0.4
	Mat foundation	*Foundation, vapor barrier*	1, 2	0.2	1.8
B: Shell	Columns and beams		10	n/a	n/a
	Floor structure		12	n/a	n/a
	Roof	Roof structure, membrane, insulation, paint	10, 5, 1, 1	n/a	n/a
	Stairs	Stairs, railings	3, 3	n/a	n/a
	Cladding		7	0.02	0.08
	Exterior walls	Wall structure, insulation, membrane, gypsum, paint	5, 1, 1, 1, 1	n/a	n/a
	Glazing	*Glass, polyvinyl butyral*, frame, hardware	1, 1, 5, 1	0.007	0.02
	Doors	Door, hardware	3, 1	n/a	n/a
C: Interiors	Partitions	*Partition structure, gypsum, paint*	2, 1, 1	0.2	0.6
	Doors	Door, hardware	2, 1	n/a	n/a
	Wall finishes	*Covering, paint*	2, 1	0.005	0.02
	Flooring	*Surface, insulation*	9, 13	0.1	0.2
	Ceiling	*Plaster, gypsum, paint*	1, 1, 1	0.006	0.02
[c]D: Services	Mechanical	17 Sub-components	[d]13	n/a	n/a
	Electrical	16 Sub-components	1	n/a	n/a
	Plumbing	22 Sub-components	1	n/a	n/a
	Fire	4 Sub-components	1	n/a	n/a
	Conveying	Elevator	1	n/a	n/a

[a] Thickness ranges correspond to italicized sub-component and all material choices for that sub-component. For assemblies with multiple italic sub-components, ranges represent combined thicknesses.
[b] Substructure consists of one of the three listed assemblies. Remaining three elements consist of all listed assemblies.
[c] Large numbers of services sub-components preclude enumeration.
[d] Duct insulation is a mechanical sub-component with 13 material choices. Remaining mechanical sub-components have one material choice.

The process begins with a designer manually creating a building information model (BIM) [43]. Table 2 lists the BIM inputs in terms of constraints, variables, and assumptions. The constraints are necessary for determining the maintenance, repair, and replacement (MRR) schedule. For example, a building of one type and size located in a hot and dry climate may have very different MRR impacts than a building of another type and size located in a cold and wet climate. Minimum and maximum values are required for the variable inputs, and no material or size specifications are required. Assumptions are automatically programmed into the BIM but may be modified by the designer.

Once the BIM is created, the automated design-feedback process begins. Calculation of pre-operational carbon footprint is the first step in this process. The use of material quantity formulas is an essential part of this calculation. These formulas depend on the BIM inputs outlined in Table 2, and many were developed in consultation with senior estimators at Beck Technology, an AEC firm. Beck aggregated data from bill of material quantities on approximately one dozen of their building projects. The number of formulas totals 95 and equals the number of distinct building sub-components outlined in Table 1. Table C of the appendix provides sample formulas for each of the four building elements. The formulas are used to calculate the minimum and maximum possible quantities for each building component material. Inputs are material choice, minimum thickness, and maximum thickness as given in Table 1 as well as gross floor area and all variables and assumptions outlined in Table 2. Pre-operational carbon footprint is calculated by multiplying each quantity by the embodied CO_2e factors in Table B

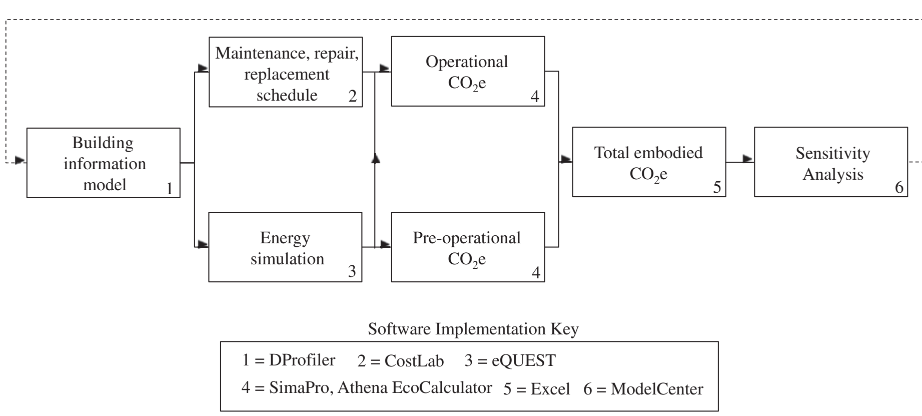


Fig. 2. Method integrating building information modeling (BIM) with embodied impact feedback involves inputting material quantities into the BIM, calculating life cycle embodied carbon footprint, then using sensitivity analysis software to determine each building component's range of impacts over many designs.

Table 2
BIM inputs required for integrated BIM-enabled embodied impact feedback method.

Constraints
Location
Building type
Gross floor area
Variables
Number of buildings
Number of floors
Length and width parameters determining building footprint
Window-to-wall ratio (WWR)
Assumptions
Footing depth
Bay spacing
Floor-to-floor height
Service life

of the appendix and summing the resulting impacts from the 95 sub-components.

Calculation of pre-operational embodied impacts due to the service equipment is an important sub-step of this process. These impacts comprise 60 of the 95 building component impacts and are calculated by sizing each piece of service equipment according to peak building load. An energy simulation program performs this step as follows [40]. Inputs from Table 2 are automatically passed from the BIM to the energy simulation program. Thermal zones are defined in the resulting energy simulation model as well as standard assumptions regarding building occupancy and HVAC system controls [41]. The program then calculates peak building load from these inputs and assumptions, and the result is an input to the 60 material quantity formulas. Equipment supplier documentation is used to determine whether each piece of service equipment typically increases in size as peak building load increases. Material quantities for those pieces of equipment that typically increase in size are scaled linearly according to peak building load. The resulting scaled and non-scaled material quantities are then multiplied by the CO_2e impact factors in Table B to determine the service equipment's pre-operational embodied impact.

A Maintenance, Repair and Replacement (MRR) schedule is used to determine the operational phase impacts associated with the building components. The MRR schedule is determined by manually entering all the constraints as well as the service life assumption from Table 2 into an online facility operations reference database [42]. The program returns each component's MRR dollar costs for every year of the building's operation. Equipment supplier documentation is then used to look up a typical material, material quantity, and cost for each component. Material quantities are then calculated by combining the MRR cost outputs from the operations database with the data from the supplier documentation. Material quantities are then scaled according to peak building load as described in the previous paragraph. These quantities are multiplied by a CO_2e impact factor in a similar fashion to the pre-operational impact calculation to determine the minimum and maximum MRR operational carbon footprint. The life-cycle embodied carbon footprint is then calculated by summing the pre-operational and MRR operational CO_2e impacts.

Sensitivity analysis software is then used to search the design space for the minimum and maximum possible embodied impacts due to each building component by varying the input variables from Table 2 using the pre-defined ranges [43]. The entire space is searched and the number of designs generated equals the product of the number of choices for each variable in Table 2. By generating a large number of designs, the method therefore shows how each building component's embodied impact varies across a wide range of input parameters.

The results present designers with an impact allocation scheme, which shows the minimum and maximum embodied impacts possible for each of the building components across all designs considered. The maximum possible embodied impact for a given design is first determined by selecting the material and thickness with the largest impact. A building component's minimum impact is then determined by selecting the material and thickness with the smallest impact for that component. The material and size with the largest impact are chosen for all other components. Maximum impacts are determined in a similar fashion. Minimum and maximum impacts are expressed as a percentage of a given design's maximum possible embodied impact.

Designers are also presented with an impact reduction scheme, which shows the degree to which each building component achieves reductions in embodied impact due to changes in both material and thickness. The maximum embodied impact reduction due to a change in material is calculated by subtracting the smallest possible impact from the largest possible impact. The maximum embodied impact reduction due to a change in thickness is calculated in a similar fashion. The reductions are expressed as a percentage of the entire building's maximum possible embodied impact for a given design.

The material and thickness impact reductions for each building component are calculated for all designs. The lowest and highest of these maximum values represent the range of maximum impact reductions possible across all designs for each building component. Each design's building component impact reductions are then summed, and the designs with the minimum and maximum sums represent the lowest and highest maximum impact reductions for the whole building. Histograms showing the distribution of maximum impact reductions for the building are then generated. One histogram is created for material decisions. Another histogram is created for thickness decisions. Distributions for building component material and thickness impact reductions are overlaid showing the degree to which each decision reduces a building's mean embodied impact. These distributions are generated in order of those that reduce the histogram's mean embodied impact the most to those that reduce the mean the least.

4. Implementation

4.1. Problem formulation

A mid-rise multi-building residential development is used as a case study to demonstrate the utility of the proposed method to industry practice. The development plan was provided by Beck Technology as a retrospective case study. At the time of publication, the complex was in the early design stage. The case study thus provided an opportunity to show which decisions could reduce the embodied environmental impact of the development the most in terms of building component material and thickness changes.

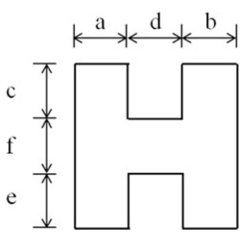
The problem formulation is described in Table 3 in terms of constraints, variables, and assumptions. Values for the constraints and assumptions are given as well as choices for the variable inputs. The total number of possible designs is 5832.

The development has a total floor area of 50,000 m^2. The variable "Number of buildings" refers to the choices for the number of individual buildings in the housing development. For

Table 3
Problem formulation showing objectives, constraints, and variables for the residential case study.

Constraints
Location = confidential
Building type = residential mid-rise
Gross floor area = 50,000 m^2

Variables
Number of buildings = 3, 4
Number of floors = 5, 6, 7, 8
Shape parameters:



a = 0 m, 15 m, 30 m
b = 10 m, 20 m, 30 m
c = 0 m, 15 m, 30 m
d = 10 m, 30 m, 50 m
e = 0 m, 15 m, 30 m
f[a]

Window-to-wall ratio = 0.15, 0.325, 0.50

Assumptions
Footing depth = 2 m
Bay spacing = 9 m
Floor-to-floor height = 3.6 m
Service life = 30 years

[a] Shape parameter "f" is dependent on the other five shape parameters. Minimum possible value for "f" is 15, and maximum possible value is 30.

a given design, each building is identical in terms of values selected for the variables as well as the material and thickness selected for each building component. Six shape parameters determine the form of the building. Peak building load is used to size the service equipment and determine the MRR impacts for every possible combination of number of floors and number of buildings, using the process described in Section 3.3. Embodied carbon footprint ranges and reductions due to building component material and thickness changes are calculated in terms of CO_2e as described in Section 3.3. Internal loads and the weekly operating schedule are determined from the 2009 ASHRAE Fundamentals [41]. Since orientation is constrained in this study to a single value, orientation is not included as a variable in the problem formulation and therefore does not influence changes in embodied impact.

4.2. Software integration

The various software components used to implement the BIM-enabled embodied impact feedback method are shown in Fig. 2. Descriptions of the software, pros, cons, and alternatives are discussed in the following section.

DProfiler is used as the selected BIM software [44]. The program is a conceptual level building modeler and is useful for early design stages. The program provides detailed material quantity and energy analysis feedback given minimal building design inputs. Heuristics programmed into the software compute building component material quantities. The program outputs a detailed BIM with fewer inputs than is typically required by alternative BIM programs such as Revit [45]. Another advantage of DProfiler is that the BIM created by the program is automatically exported to eQUEST, an energy simulation program [40]. This export occurs entirely within DProfiler without any user interface with eQUEST. Linkage of the BIM and energy model configuration is therefore useful for the method developed in this paper since users receive energy analysis feedback on BIM inputs without having to separately create an energy simulation model. A number of limitations exist with the computational architecture shown in Fig. 2. DProfiler has limitations in terms of the range of geometric forms that it can create. DProfiler's building wizard tool is used to implement the method in Fig. 2, and BIM geometries are limited to fairly simple orthogonal building shapes such as the H-shaped figure shown in Table 3. Complex or freeform architectural shapes are currently not accommodated by the software. Limitations of eQUEST include long run times, meaning it may take several days to execute the method shown in Fig. 2 for thousands of runs. The program also does not model natural ventilation, operable windows, or thermal comfort. However, the proposed method includes only MRR operational impacts and so is not affected by these limitations.

SimaPro is the LCA software used to obtain many of the CO_2e impacts outlined in Table B [37]. As described in Section 3.3, these factors are critical for converting building component material quantities into embodied impacts. SimaPro is chosen because the software contains impact factors for many different building materials, and these impacts correspond to the life-cycle phases scoped in the method and outlined in Fig. 1. SimaPro is provided the quantity of building component material as an input and returns kg CO_2e per kg of material. A limitation of the program is that the software does not computationally integrate into the method proposed in Fig. 2. Instead, the CO_2e impact factors must be manually extracted and placed into Excel.

Athena EcoCalculator is also used to obtain some of the CO_2e impact factors in Table B [27]. The program is helpful for estimating impacts of structural assemblies, such as columns and beams, interior walls, or the roof structure. The tool scales impacts by building gross floor area rather than a building component thickness parameter. This scaling method is especially useful during the early stages of building design when very limited information is known about a building such as structural requirements. The tool integrates well with the proposed method, since gross floor area is a required input in Table 3. As with SimaPro, however, the program does not computationally integrate into the proposed method and CO_2e impact factors are manually extracted and placed into Excel.

CostLab is the online facility operations reference database used to calculate MRR impacts [42]. The software creates an MRR schedule comprised of a detailed list of building components within its database. LCA tools do not provide such detailed MRR information. CostLab works well with the proposed method since the program takes as inputs the constraints outlined in Table 2. Since the program is not an LCA tool, impacts are output in terms of dollar costs instead of CO_2e for every component for every year of a building's operation. Therefore, the program is cumbersome to work with since dollar costs must be converted to embodied impacts as described in Section 3.3. In addition, since the program does not computationally integrate into the proposed method, BIM inputs are manually entered and cost outputs are manually extracted and placed into Excel.

Excel is used to perform simple mathematical operations on the material quantities that determine the embodied carbon footprint of each building design [46]. Data is manually extracted from the various software sources as described above and Excel formulas are used to perform the operations for each iteration.

ModelCenter is the sensitivity analysis software used to integrate DProfiler and Excel into a common environment [43]. The program's ScriptWrapper utility enables users to integrate or "wrap" different software components using a scripting language. In this work, DProfiler is wrapped with ModelCenter to allow the programs to communicate with each other in terms of inputs and outputs. Phoenix Integration, Inc. has wrapped Excel with ModelCenter, thereby allowing DProfiler and Excel to communicate with each other. The program's "Design Explorer" tool allows sensitivity analysis to be performed on a large design space by computationally iterating through all possible designs. Ranges for design variables are articulated either as a continuous range or as a discrete set. Table 3 lists the discrete set of variable choices used for the case study. The program iterated through all 5832 designs in order to determine the minimum and maximum embodied impacts for each building component. Choosing every single integer value for each variable in Table 3 between the minimum and maximum given values would require significant memory and several weeks of computer processing time. Due to these constraints, only the lower bound, upper bound, and mid-point value of each variable range were chosen as shown in the table. Limiting the selection of parameter values in this way does not affect results, since sensitivity analysis is concerned with determining only minimum and maximum possible embodied impacts.

4.3. Results and discussion

The proposed method was applied to the case study project to determine in which building components embodied impacts are concentrated as well as which design decisions achieve the greatest reductions in embodied impact.

Table 4 presents the impact allocation and impact reduction schemes described in Section 3.3. Tables 5 and 6 regenerate the impact reductions after each material and thickness decision, respectively, are made. The results show how the range of embodied impacts is steadily reduced as decisions are made in order from those achieving the greatest embodied impact reductions to those achieving the least reductions. The results are not meant to suggest that making decisions in a certain sequence – from those achieving the greatest impact reduction to those achieving the least – can help designers arrive at a best or improved design in terms of lowered embodied impact. Rather, the results are meant to help designers visualize the potential reductions for each building component so that they can understand which decisions consistently contribute to a building's embodied impact then focus on making choices for those decisions that matter the most.

The impact allocation scheme shows that the range of impacts is very large for building components in all four of the elements. The total embodied impact can potentially be concentrated in any of these elements, as long as materials and thicknesses with minimum embodied impact are chosen for components in each of the other elements. Each element may contribute over 50% of the

Table 4
Impact allocation scheme shows minimum and maximum embodied impacts for each building component, and impact reduction scheme shows impact reductions due to material and thickness changes.

		Impact allocation scheme		Impact reduction scheme			
		(as % of total embodied impact)		Material change (as % of max embodied impact)		Thickness change (as % of max embodied impact)	
Uniformat element	Assembly	Minimum impact	Maximum impact	Min impact reduction	Max impact reduction	Min impact reduction	Max impact reduction
Whole building				**62.95**	**74.94**	**19.98**	**37.33**
A: substructure		**0.21**	**55.07**	**7.77**	**19.65**	**0.33**	**2.03**
	Piles	1.35	51.51	7.77	19.65	0.33	0.63
	Footings	11.13	55.07	n/a	n/a	0.33	0.63
	Mat foundation	0.21	10.68	n/a	n/a	0.85	2.03
B: shell		**2.22**	**78.97**	**21.17**	**49.64**	**6.03**	**27.27**
	Columns and beams	0.27	19.18	2.59	4.50	n/a	n/a
	Floor	0.29	25.77	3.74	7.31	n/a	n/a
	Roof	0.02	2.78	0.36	0.47	n/a	n/a
	Stairs	0.00	2.13	0.25	0.50	n/a	n/a
	Cladding	0.01	68.47	6.78	35.08	5.10	26.39
	Exterior walls	0.24	30.38	0.97	5.15	n/a	n/a
	Glazing	0.35	55.61	0.60	7.52	0.22	3.17
	Doors	0.00	0.13	0.01	0.03	n/a	n/a
C: interiors		**5.42**	**70.27**	**14.98**	**26.23**	**8.61**	**13.82**
	Partitions	0.92	39.40	6.81	12.20	n/a	n/a
	Doors	0.00	0.44	0.05	0.09	n/a	n/a
	Wall finishes	0.89	23.40	1.35	1.81	2.02	2.5
	Flooring	0.18	44.69	6.77	12.13	3.76	6.73
	Ceiling	1.95	30.78	n/a	n/a	2.69	4.81
D: services		**8.06**	**70.27**	**1.09**	**1.94**	**0.00**	**0.78**
	Mechanical	4.12	42.62	1.09	1.94	0.00	0.57
	Electrical	2.96	24.10	n/a	n/a	0.00	0.2
	Plumbing	0.84	6.72	n/a	n/a	0.00	0.01
	Fire	0.03	0.21	n/a	n/a	n/a	n/a
	Conveying	0.05	0.38	n/a	n/a	n/a	n/a

Table 5
Material decisions for each building component are ranked from those with the greatest potential to reduce a building's embodied impact to those with the least potential.

Material decision number	Assembly (specific component)	Minimum impact reduction[a]	Maximimum impact reduction[a]
1	Cladding	38.86	59.70
2	Substructure (vapor barrier, piles)	29.71	44.23
3	Partitions	22.89	32.03
4	Flooring surface	16.11	21.75
5	Floor structural assembly	10.76	17.28
6	Column and beam structural assembly	6.50	14.52
7	Window assembly	5.39	8.37
8	Wall assembly	3.14	4.78
9	Wall finishes	1.41	2.97
10	Mechanical system (duct insulation)	0.71	1.03
11	Roof assembly	0.32	1.00
12	Stairs	0.07	0.12
13	Interior doors	0.01	0.03
14	Exterior doors	0	0

Therefore, no impact reduction is possible once the final decision has been made.
[a] Material impact reduction ranges reflect the reduction in embodied impact possible *after* each decision has been made.

Table 6
Thickness decisions for each building component are ranked from those with the greatest potential to reduce a building's embodied impact to those with the least potential reduction.

Thickness decision number	Assembly	Minimum impact reduction[a]	Maximum impact reduction[a]
1	Cladding	10.67	16.67
2	Flooring surface	6.69	10.09
3	Ceiling	3.82	6.98
4	Wall finishes	1.56	4.69
5	Substructure	0.24	3.66
6	Window assembly	0.00	0.78
7	Mechanical system	0.00	0.21
8	Electrical system	0.00	0.01
9	Plumbing system	0	0

Therefore, no impact reduction is possible once the final decision has been made.
[a] Thickness impact reduction ranges reflect the reduction in embodied impact possible *after* each decision has been made.

development's embodied impact, depending on the design under consideration.

In terms of the impact reduction scheme shown in Table 4, both material and thickness changes can potentially lower embodied impacts by large amounts for many building components in the substructure (UniFormat Element A), the shell (Element B), and the interiors (Element C). Fourteen of the 21 components' maximum impacts are greater than 10% of the total embodied impact, and six are greater than 40%. The largest impact changes are seen in cladding material (reduced from 35% to approximately 7% of the maximum possible total embodied impact), cladding thickness, piles material, glazing material, and flooring material. Designers should be aware of the material and thickness choices for these building components during the early design stages. In contrast, changes to materials and thicknesses are not important for all of the services components within UniFormat Element D, suggesting designers need not focus on these decisions during the early design stages.

Tables 5 and 6 regenerate the impact reductions after each material and thickness decision, respectively, is made. The results show how the range of embodied impacts is steadily reduced as decisions are made in order from those achieving the greatest embodied impact reductions to those achieving the least reductions. The tables confirm the results from Table 4. Tables 5 and 6 show that large reductions can be achieved for both material and thickness decisions for building components in UniFormat Elements A, B, and C. In terms of material choice, the greatest reductions are achieved for cladding, substructure, partitions, and flooring surface. In terms of thickness choice, the greatest reductions are achieved for cladding, flooring surface, ceiling, and wall finishes.

Figs. 3 and 4 are histograms illustrating the distributions of embodied impact reductions across all 5832 designs before any decisions have been made, after the first decision achieving the greatest reduction has been made, and after the second decision achieving the next greatest reduction has been made for material and thickness choices, respectively. Section 3.3 described how these histograms are generated. The impact ranges for each decision correspond to the minimum and maximum impact reduction values in Tables 5 and 6. The rightmost distributions in Figs. 3 and 4 show the potential for reducing a building's maximum total embodied impact *before* any material or thickness decisions have been made. For Fig. 3, anywhere from a 63% to 75% reduction in the building's maximum total embodied impact is possible, depending on the particular set of design parameters selected from Table 3. Once the cladding material decision has been made, the impact due to cladding is subtracted from the total impact, and between 39% and 60% of the remaining embodied impact can be reduced. This process continues in a similar fashion for the remaining 13 material decisions until no impact reduction is possible once the final decision has been

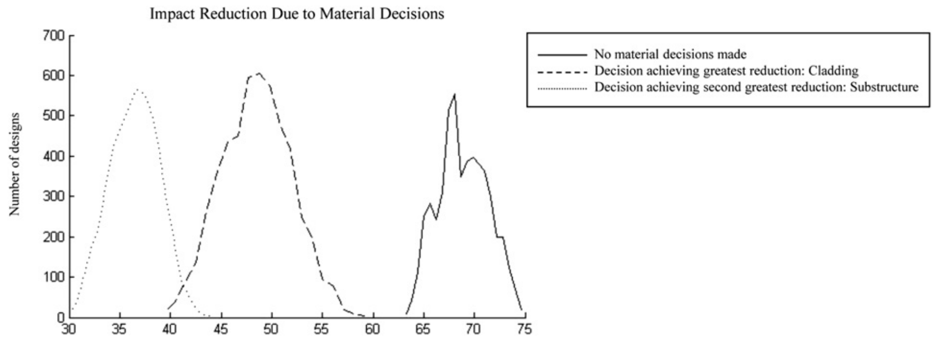


Fig. 3. Distributions across 5832 designs show which material decisions achieve the most significant embodied impact reductions.

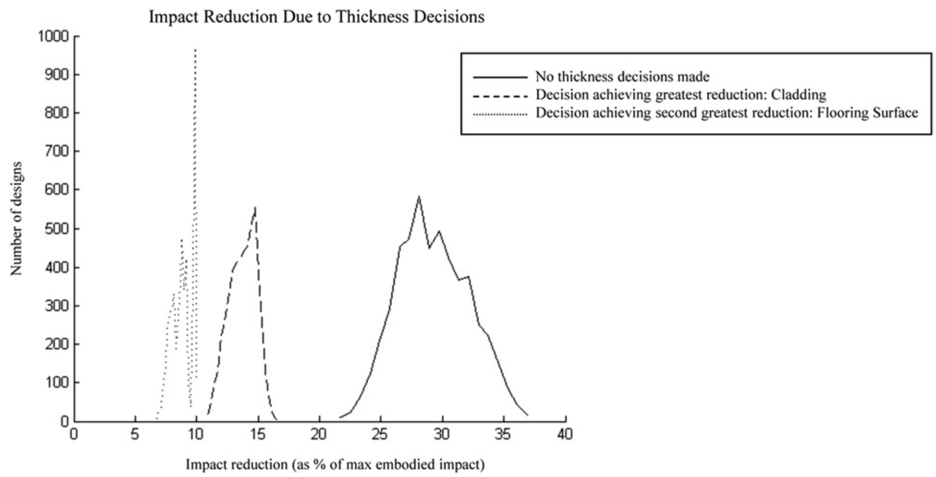


Fig. 4. Distributions across 5832 designs show which thickness decisions achieve the most significant embodied impact reductions.

made. Results for the thickness decisions are presented in a similar fashion, with anywhere from a 20% to 37% reduction in the building's total embodied impact possible depending on the design configuration. The histograms allow designers to visually determine during the early design stages which building components are most important in terms of achieving embodied impact reductions through material and thickness choices.

Tables 4–6 and Figs. 3 and 4 together show that significant embodied impact reductions can be achieved in the substructure, shell, and interiors of the case study building. The largest reductions for material changes are cladding, substructure, and partitions, and the least important material decisions are related to the doors, stairs, and service equipment. The largest reductions for thickness dimension changes are cladding, flooring surface, and the ceiling, and the smallest reductions are for the window assembly and service equipment. The impact reduction schemes for material and thickness dimensions taken together suggest that significant reductions in the building development's embodied impact cannot be achieved by making decisions for the wall finishes or service equipment.

The distributions show the relative importance of making a decision for one building component over another. Designers are provided with intuition on which decisions frequently achieve significant embodied impact reductions. By postponing material and thickness decisions achieving smaller reductions to the design development stage, designers would avoid expending effort on inconsequential decisions during the critical early design stages. The method ultimately allows designers to focus their efforts during the early design stages on those decisions that are most likely to decrease a building's life cyle embodied environmental impact.

5. Conclusions

A BIM-enabled decision support method is proposed that helps designers predict which decisions most critically determine a building's embodied impact. The automated method integrates BIM, LCA, energy simulation, MRR scheduling, and sensitivity analysis software. The framework is well suited for the early design stages as very few inputs are required, and the method can quickly iterate across many building designs thereby presenting a number of design alternatives.

A case study analysis is presented in order to show how designers can understand which building component decisions consistently contribute the largest to a building's embodied impact. Results are presented in the form of an impact allocation scheme, an impact reduction scheme, and histograms showing the distributions of embodied impacts for many designs. The results rank building components from those achieving the greatest to least embodied impact reductions. A building's embodied impact can potentially be concentrated in the substructure, shell, or interiors. Embodied impacts due to service equipment are small, whereas cladding material and thickness choices are consistently the most significant, regardless of building design configuration. A designer should focus during the early design stages on these decisions that achieve a large embodied impact reduction and defer less important decisions to the design development stage.

The scope of this method is limited to building components for which dimensional thickness ranges can be predicted at the early design stages. Future work will consider additional sizing parameters besides thickness in order that structural components and service equipment may be included in the sizing decisions. Operational impacts do not include impacts from HVAC or lighting equipment, plug loads, or water use. Future research will consider the effects that orientation and thermal properties of the building envelope have on operational energy use in order to develop a more comprehensive understanding of the relationship between early stage design decisions and life-cycle environmental impacts. Finally, the validation of the method is currently limited to a single case study involving a particular building type, size, location, and geometry. Additional case study applications will be required to comment more generally on the performance and robustness of the proposed decision support method.

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Appendix

Table A
Material alternatives considered in quantifying embodied impacts of building components.

Building component	Material alternatives
Piles	Steel pipe, precast concrete
Vapor barrier	Polyethylene plastic sheeting, polypropylene cloth
Columns and beams	Concrete column/concrete beam, concrete column/glulam beam, concrete column/LVL beam, concrete column/WF beam, HSS column/glulam beam, HSS column/LVL beam, HSS column/WF beam, WF column/glulam beam, WF column/LVL beam, WF column/WF beam
Floor structure	Glulam/plywood decking, precast hollow-core/concrete topping, wood I-joist/plywood decking, open-web steel joist/concrete topping, open-web steel joist/plywood decking, precast double-T/concrete topping, steel joist/concrete topping, steel joist/plywood decking, suspended concrete slab/concrete topping, wood joist/plywood decking, wood chord and steel web truss/plywood decking, wood truss/plywood decking
Roof	Precast hollow-core concrete, precast concrete double-T, suspended concrete slab, open-web steel joist w/steel decking, open-web steel joist w/wood decking, glulam joist with plank decking, wood I-joist w/WSP decking, solid wood joist w/WSP decking, wood chord/steel web truss with WSP decking, wood truss (flat) with WSP decking
Roof membrane	EPDM, PVC, modified bitumen, 4-ply built-up roofing system, steel roofing system
Stairs	Precast concrete, wood, steel
Railings	Wood, precast concrete, aluminum
Cladding	Brick, steel, stucco, vinyl, wood, limestone, concrete
Wall structure	Concrete block, cast-in-place concrete, steel stud wall, curtainwall: opaque glazing, curtainwall: metal spandrel panel
Window frame	Aluminum, steel, PVC, wood-metal, wood
Exterior doors	Steel, wood-glass-steel, wood-steel
Partitions	Steel stud wall, concrete block
Interior doors	Wood, steel
Wall coverings	Ceramic wall tile, vinyl
Flooring surface	Ceramic floor tile, stone floor tile, cement facing tile with fiber, cement cast plaster floor, neoprene, polyacrylate with ground granite, polyurethane with vinyl chips, carpet tile with nylon, laminated veneer wood
Floor insulation	Blown cellulose, extruded polystyrene, polystyrene foam slab, cork slab, foam glass, glass wool mat, glass wool (fleece), rock wool, rock wool (fleece), rock wool (packed), tube insulation (elastomere), urea formaldehyde foam slab, urea formaldehyde in situ foaming
Duct insulation	Blown cellulose, extruded polystyrene, polystyrene foam slab, cork slab, foam glass, glass wool mat, glass wool (fleece), rock wool, rock wool (fleece), rock wool (packed), tube insulation (elastomere), urea formaldehyde foam slab, urea formaldehyde in situ foaming

Table B
Material(s) associated with each building component and material properties used to quantify building component embodied impacts.

Material	Building component(s)	Density (kg/m^3)	Embodied impact factor ($kg\ CO_2e/kg$ material)
Concrete	Mat foundation	2400	0.050
Concrete	Footing	2400	5.15
Concrete	Piles, pile caps	2400	0.12
Concrete (precast)	Grade beams, stairs, railings, cladding	2400	0.121
Concrete	Slab-on-grade	2400	0.065
Steel	Rebar	8000	1.03
Steel	Piles, stairs, cladding	8000	1.89
Steel (stainless)	Gutter	8000	3.38
Brass	Service equipment (various)	8400	2.34
Cast iron	Service equipment (various)	7000	2.34
Limestone	Cladding	2500	0.019
Limestone	Flooring	2500	0.37
Stucco	Cladding	800	0.070
Copper	Gutter	8930	1.81
Brick	Cladding	2403	1.13
Neoprene	Flooring	1230	2.46
Polyethylene	Vapor barrier	950	1.58
Fiberglass	Pipe insulation	26	1.50
Flat glass	Glazing	2310	1.06
Polyvinyl butyral	Glazing	1100	6.98
Vinyl	Gutter, cladding	580	2.37
Vinyl	Wall coverings	1360	1.80
Ceramic tile	Wall coverings, flooring	1360	0.74
Acrylic paint	Wall coverings	1200	2.66
Aluminum	Gutter, railings	2700	11.4
Wood (Douglas fir)	Formwork	600	1.02
Wood (Douglas fir)	Gutter	600	0.29
Wood	Stairs, railings, cladding, flooring	600	0.33
Polyurethane foam (high density)	Flooring	400	4.04
Polypropylene (vapor retarder)	Vapor barrier	946	1.68
Polyacrylate terrazzo	Flooring	1054	3.23
Carpet tile	Flooring	74	6.78
Blown cellulose	Floor insulation, duct insulation	56	0.35
Extruded polystyrene	Floor insulation, duct insulation	30	10.1

Table B (*continued*)

Material	Building component(s)	Density (kg/m^3)	Embodied impact factor ($kg\ CO_2e/kg$ material)
Polystyrene foam slab	Floor insulation, duct insulation	30	3.36
Cork slab	Floor insulation, duct insulation	110	1.09
Foam glass	Floor insulation, duct insulation	110	1.50
Glass wool mat	Floor insulation, duct insulation	40	1.40
Glass wool, fleece	Floor insulation, duct insulation	40	2.79
Rock wool	Floor insulation, duct insulation	46	1.00
Rock wool, fleece	Floor insulation, duct insulation	28	1.12
Rock wool, packed	Floor insulation, duct insulation	100	1.05
Tube insulation, elastomere	Floor insulation, duct insulation	75	4.16
Urea formaldehyde foam slab	Floor insulation, duct insulation	20	2.71
Urea formaldehyde foam, in situ foaming	Floor insulation, duct insulation	20	2.85

Table C
Sampling of material quantity formulas developed for each building component.

Uniformat element	Assembly	Sub-component	Material quantity formula[a]
A: substructure	Piles	Piles	Density × slab area[b] × slab depth
		Vapor barrier	Density × thickness × (slab area[b] + perimeter[c] × footing depth[d])
		Slab-on-grade	Slab area[b] × thickness
		Grade beam	Density × perimeter[c] × 4
	Footings	Footings	Density × slab area × 0.2
	Mat foundation	Foundation	Slab area[b] × slab depth
B: shell	Columns and beams	Columns and beams	Gross floor area[e] + roof area
	Floor	Floor structure	Gross floor area[e] − slab area[b]
	Roof	Roof structure	Slab area[b,e]
	Cladding	Cladding	Density × thickness × (1 − WWR) × perimeter[c] × height[f]
	Exterior walls	Wall structure	(1 − WWR) × perimeter[c] × height[f]
C: interiors	Partitions	Partition structure	Gross floor area[e] × 1.5
	Wall finishes	Covering	Density × thickness × (gross floor area × 2.55 + perimeter[c] × height[f])
	Flooring	Surface	Density × thickness × gross floor area
	Ceiling	Gypsum + paint	Gross floor area[e] + roof area
D: services[g]	Mechanical	Air conditioner	Gross floor area
	Electrical	Compact fluorescent	Gross floor area
		Lighting fixture	
		Ballast and lamps (glass tube)	
	Plumbing	Circulator pump	Gross floor area
	Fire	Fire extinguisher	Gross floor area
	Conveying	Elevator	Gross floor area

[a] All material quantities are multiplied by number of buildings, a parameter given in Table 2.
[b] Slab area = gross floor area/number of floors.
[c] Perimeter is determined by length and width parameters, as given in Table 2.
[d] Constraint is outlined in Table 2.
[e] Parameter(s) are inputted into Athena EcoCalculator.
[f] Height = number of floors × floor-to-floor height.
[g] Section 3.3 describes how an online facility operations reference database takes as inputs gross floor area as well as the other constraints and service life assumption outlined in Table 2 and returns impacts.

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