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Comparison of survey and numerical sensitivity analysis results to assess the role of life cycle analyses from building designers' perspectives

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ABSTRACT

The objective of this study is to understand the role of life cycle analysis (LCA) in building system design process based on survey inputs from building system designers and a numerical sensitivity analysis. This paper first presents findings on the perceived importance of building life cycle assessment completed by 96 practicing designers from August 2012 to April 2013. The majority of respondents, approximately 70%, work as building system designers in the U.S. The building system designers are divided into three categories: (1) enclosure system designers, (2) mechanical system designers, and (3) designers working on both systems. One of the major survey findings is that life cycle assessments are much less used in building system design than energy simulations. The primary reason for performing a life cycle analysis for a building design project is a requirement from a building owner. Furthermore, Fisher's test shows that respondents' profession, company size, and work experience have significant correlations with the deployment of energy simulations and life cycle assessments in building design projects. ANOVA-based analyses demonstrate that there is no statically significant difference among the three categories of system designer responses on the importance of building components and design selection criteria. Interestingly, the sensitivity analyses performed for the medium size DOE (Department of Energy) reference building indicate that wall assemblies have a much larger impact on building life cycle costs than window properties. The comparison between sensitivity analysis and survey results indicates that the influence of window properties on life cycle cost is over estimated by most of the surveyed participants. Overall, this study revealed that LCA is still not widely used in the building industry even though it would help address design biases toward building systems that do not deliver the expected performance.

1. Introduction

Building energy simulations (BES) and life cycle analyses (LCA) enable the comparison of different building design solutions based on the predicted building performance. The utilization of BES and LCA supports decision making during the design process to optimize building performance from a range of design variants [1]. It is necessary to further study the role of BES and LCA from the designers' perspectives, and to define the significance of BES and LCA in the design processes. There have been studies to evaluate the influence of simulation tools and performance analyses on the building design. A study investigated a set of design projects and found that the presence of building performance analysis experts in the early stages of the design process can improve the building performance [2]. Another study demonstrated that LCA could enable better early stage decision-making by providing feedback about the embodied carbon footprint for different design choices [3]. Moreover, the concept of life cycle analysis is also useful when estimating the life cycle carbon dioxide in the planning phase [4]. However, there are very few studies which focus on the utilization of BES and LCA by building designers in the practical design processes.

A number of studies have been conducted worldwide in recent years to discover the role of building performance analyses in the design process by interviewing building designers. The results of a questionnaire administered in the UK suggested that building engineers/designers tend to use more detailed energy modeling than architects, while both groups believe their simulation errors

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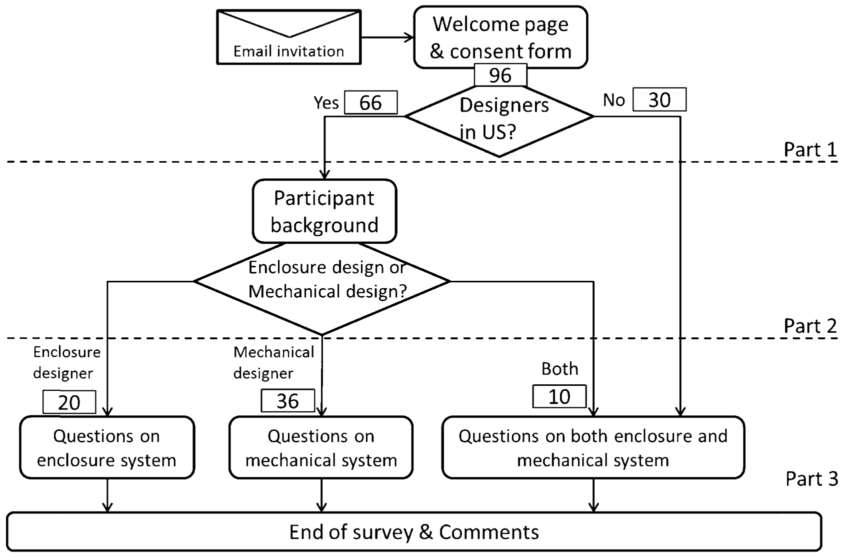

Fig. 1. The structure of survey. Depending on the responses, participants follow one of four main branches: enclosure system, mechanical system, both enclosure and mechanical systems, and non-designers. The numbers in the rectangular textboxes show the number of participants that went through that particular branch.

to be minor [5]. An interview of architects and building simulation consultants in the Netherland was conducted to capture the designers' viewpoint concerning building simulation. According to the results, energy simulation plays a very limited role in the average application of advanced energy saving technology. Instead, it is used more frequently for design optimization and verification [2]. A study in Singapore revealed that the usage of performance-based simulation tools for building design evaluation in Singapore is still very limited [6]. Another research study conducted in Hong Kong and Singapore indicated that it is very important to understand the building designers' viewpoint in order to analyze the obstacle of green building development and make recommendations [7]. A survey in Sweden indicated that there is a large interest in using LCA for the economic evaluation of investment decisions. However, difficulties in achieving relevant input data, lack of experience, and incentives for consultants and contractors became the major constraints of performing LCA [8]. The survey also showed that most of the participants consider LCA a useful tool during the design phase with the most possibilities for cost reductions related to operation and maintenance. The previous studies outside of the U.S. have shown that the utilization of building performance analysis in the design process could impact the design process, design results, and decision making. However, very few studies focus on the building system designers, and analyze their perspectives of building design process. Furthermore, no research has been conducted that studies the role of BES and LCA in the design process with the designers in the U.S. as the target participants. Therefore, it is necessary to further study the role of building performance analysis from the designers' perspectives in the U.S.

Previous surveys on the building performance were used to identify general trends in the design community. However, few studies considered the building system designers as the target participants. Furthermore, numerical performance simulation methodologies were rarely used to analyze the survey results. Therefore, this study aims to understand the importance of LCA from the perspectives of the building system designers in the U.S. Moreover, this study will include statistical and numerical sensitivity analyses as important analysis methodology to provide a deeper understanding of the survey results and the role of BES and LCA in building design as well.

2. Research methodology and survey design

The objective of this study is to identify the perspective of building designers in the U.S. on BES and LCA. The methodology of the questionnaire has been considered as an effective way to collect subjective opinions [9]. Therefore, this study conducted an on-line survey to collect the viewpoint of building system designers. The results of the survey were analyzed statistically to examine the correlation between participants' background and their responses. Furthermore, sensitivity analysis is employed to further understand the survey results and numerically test the significant factors for building life cycle cost.

The survey is web-based, so responses can be effectively gathered from a large number of design professionals. Participants were recruited through email invitations to selected mailing lists as well as through direct contact with different types of building designers. The questionnaire includes four question types: (a) multiple selections of specific categories, (b) a single selection of a specific category, (c) multiple selections of a specific category, and (d) free text. Multiple selection questions usually include a textbox where participants could provide information beyond the pre-defined options.

The whole survey has three parts, as shown in Fig. 1. A welcome web page explains the purpose of the survey, procedures to be followed, possible discomforts and risks, benefits, duration, statement of confidentiality, and rights to ask questions. The potential participants are also informed that their decision is voluntary, and they have the rights to end their participation at any time and for any reason. The incentive for individuals to participate in the survey is that "the participation will be crucial in the development of the building system optimization framework." Once individuals have consented to take part in the research, the questionnaire begins with the first question, which concerns the participants' profession. The first branching separated those participants who are currently working as a designer in the U.S. from those who are not. The former group follows the questions in part 2 of the survey. The latter group is guided toward the questions for both enclosure and mechanical system in part 3 of the survey.

In part 2, the questions are geared toward understanding the general participants' background, such as the size of their company, the energy code/standard they design to, the patch they follow

Table 1
Professions of participants.

Professions of participants	
Non-designer	18 (21%)
Designer (both)	10 (12%)
Designer (enclosure)	20 (24%)
Designer (mechanical)	36 (43%)

in design, and work experience. This part also involves questions about the percentages of building designs evaluated by building energy simulation and life cycle cost estimation. The last question in part 2 divides the participants into three branches according to their roles in building design projects. The three branches are designed respectively for enclosure system engineers, mechanical system engineers, and the engineers working on both systems.

In part 3, the questions are (1) the criteria they use in the selection process of building system components and (2) the important components that they consider optimizing in order to minimize building life cycle cost. Depending on the answers given in parts 1 and 2, the four branches of participants are asked a different series of questions, focusing on enclosure system design, mechanical system design, or both. At the end of the survey, every participant is invited to provide their thoughts and comments on the survey.

3. Survey findings

The questions in this survey refer to participants' background (including professions of participants, the size of company, and work experience), the percentage of building designers using BES and LCA in the design process, the driver of life-cycle consideration, and the significant criteria and system components in building system design. Data collection lasted from September 21st, 2012 to April 22nd, 2013. A total of 104 individuals participated in the survey. Overall, 96 individuals completed the survey, whereas, 8 individuals decided to end their participation by closing their web browser somewhere in the middle of the survey. Therefore, only 96 valid responses are considered in the following analysis.

3.1. Participants' background

Table 1 shows that, when marking their professions, participants chose 21% non-designers, 43% mechanical system designers, 24% enclosure system designers, and 12% designers working on both mechanical and enclosure systems. The designers are guided to the following questions about participants' background, while the non-designers are directly taken to the questions in part 3.

Table 2 shows the size distribution of the companies participants were working in at the time of the survey. The finding is that participants mostly worked in small size (1–200 employees) design firms.

Work experience is another important aspect of the participants' background, and the results are shown in Table 3. In the valid responses of this survey, participants in the largest group (43%) had more than 20 years' work experience in the building design industry, followed by 1–5 years (21%), 6–10 years (21%), 11–15 years (9%), and 16–20 years (6%).

Table 2
The size of the company.

Company size (employees number)	
Small (1–200)	40 (61%)
Medium (201–1000)	16 (24%)
Large (1000+)	10 (15%)

Table 3
Work experience.

Work experience (years)	
1–5	14 (21%)
6–10	14 (21%)
11–15	6 (9%)
16–20	4 (6%)
20+	28 (43%)

3.2. The percentages of building energy simulation and life cycle analysis

The questionnaire also asked the designers what percentages of their projects were evaluated by building energy simulation and life cycle cost assessment. These questions required a single selection with five options indicating five frequency levels: 0–20%, 21–40%, 61–80%, 81–100%. Table 4 shows that the frequency of performing building energy simulations is more evenly distributed than the result of life cycle assessment. The projects with life cycle analysis concentrated on smaller percentages in the result. Compared to building energy simulation, life cycle assessment is much less used in building design.

3.3. The driver of life-cycle consideration

The motivation of considering life cycle assessment was evaluated using a question which allowed for multiple selections. According to Fig. 2, most building system designers indicated that the owner of the building is the major driver for performing life cycle assessment in the design process.

3.4. Significant criteria and system components in building system design

Part 3 of this questionnaire contains questions about the important criteria of component selection and the important components in life cycle assessment. Each question has 4–7 criteria/components. Options ranged from not at all important, slightly important, moderately important, very important, to extremely important, which is represented as a score of 1–5 in the analysis of results. Participants could choose only one level of importance for each criteria/component. Specifically, Figs. 3 and 4 show the results of an enclosure system design from the viewpoint of non-designer, enclosure system designer, and designers working on both enclosure and mechanical systems. Every variable has a relatively high score in this survey. However, the importance level of environmental impacts appears to noticeably decrease, when compared to others. Furthermore, Figs. 5 and 6 show the results of an enclosure system design from the perspectives of non-designer, mechanical system designer, and designers working on both enclosure and mechanical systems. Again, the importance level of environmental impacts is the lowest among all the criteria.

Table 4
Percentages of building designs evaluated by BES and LCA.

Proportion of the design projects	BES	LCA
0–20%	12 (18%)	35 (53%)
21–40%	22 (34%)	19 (29%)
41–60%	13 (20%)	8 (12%)
61–80%	11 (17%)	4 (6%)
81–100%	8 (12%)	0 (0%)

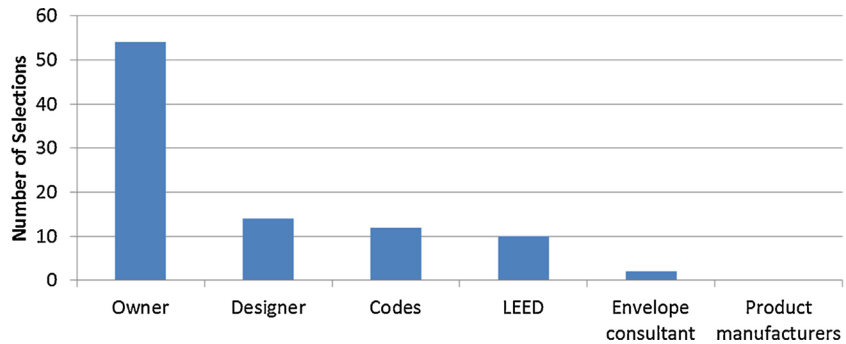

Fig. 2. The driver of life cycle consideration in building systems design process.

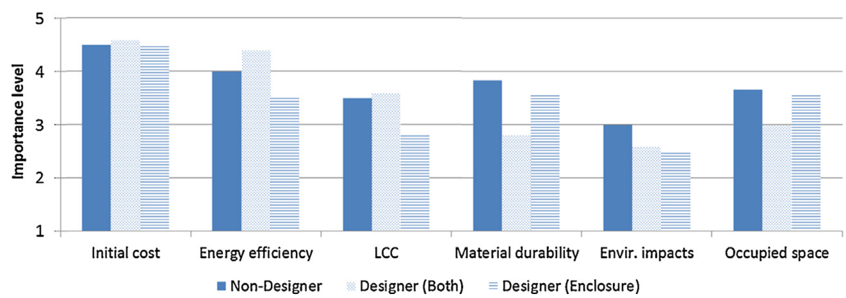

Fig. 3. Significant level of selection criteria of enclosure system components.

4. Statistical analysis

To further understand the survey results, this study uses Fisher's exact test to analyze the correlations between the frequency of building performance analysis and respondents' background. Analysis of variance (ANOVA) is employed to test if there is any significant difference among the responses of different respondent groups.

4.1. Fisher's exact test

Fisher's exact test is widely used to exam the correlations between categorical response and categorical independence. It is designed especially for the small sample in statistics [10], which is typical in building design surveys. Therefore, it is employed in this study to examine the correlation between participants' background and the percentage of performing building energy simulation and

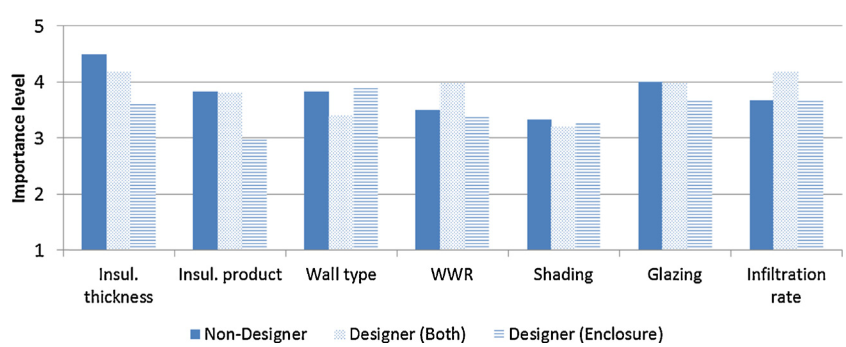

Fig. 4. Importance of enclosure system components to optimize building life cycle cost.

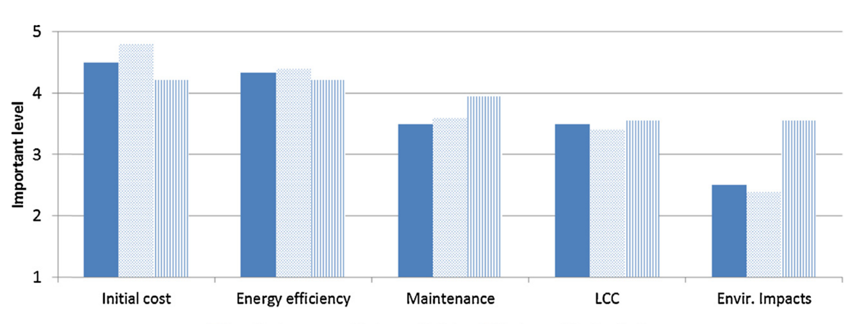

Fig. 5. Significant level of selection criteria of mechanical system components.

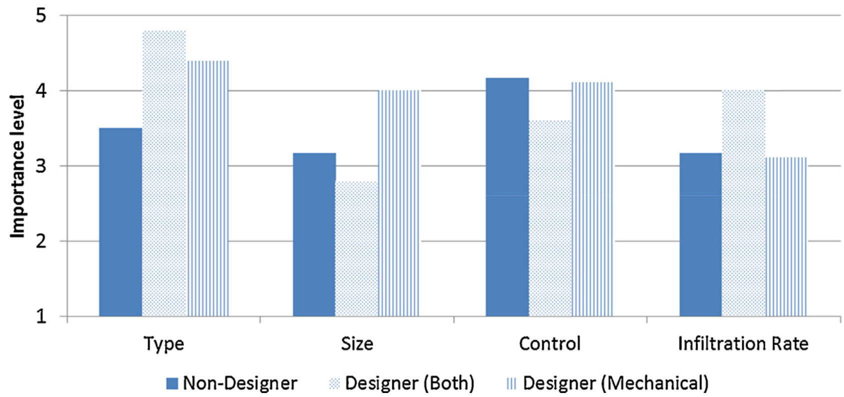

Fig. 6. Importance of mechanical system components to optimize building life cycle cost.

life cycle assessment. In this analysis, the tested response and independence have a correlation of *P*-value less than 0.05. Furthermore, Table 5 shows the *P*-values between different groups of response and independence. The results indicate that participant profession is correlated with the percentage of building energy simulations and life cycle assessments performed in the building design process. The results showed that the designers working on both enclosure and mechanical systems perform a larger number of building analyses in their design projects than the other two groups. The company size is correlated with the proportion of energy simulation frequency usage. The detailed information indicates that small-sized design companies use more frequently energy simulation in their projects, compared to large and medium-sized companies. Statistically, work experience of participants has impact on the frequency of using life cycle assessment, rather than the frequency of using energy simulation. The results of this survey showed that the designers with less work experience (less than 10 years) tend to have a larger percentage of life cycle analysis projects. This is probably due to the fact that the life cycle assessment is a concept relatively recently brought to the building industry. The introduction of LCA roughly coincides with the time period when the group with the highest frequency of LCA project deployment started to work in the industry.

4.2. ANOVA

All of the groups reported similar answers for the questions about significant criteria and system components in building design. Therefore, ANOVA is employed to examine the differences among the perspectives of these three groups. Specifically, Table 6 shows the *P*-values of the ANOVA tests for each criteria/component. According to ANOVA, only two out of these twenty-two variables have a *P*-value less than 0.05: mechanical system type and size. Designers for both enclosure and mechanical systems, closely followed by the group of mechanical system designers, consider mechanical system type an important component in building life cycle optimization process. Statistically, the importance of the mechanical system type from the non-designers' perspective is significantly lower than the importance level identified by the other groups. Similarly, the attention to the mechanical system size of non-designers and designers of both systems is significantly lower than that of mechanical designers. The ANOVA test indicates that there is no statistically significant deference among these three groups in terms of the perspectives of the tested variables in this survey.

Table 5
Fisher's exact test (*P*-value).

P-value	Participants profession	Company size	Work experience
Percentage of performing energy simulation	0.008	0.001	0.180
Percentage of performing life cycle assessment	0.000	0.466	0.024

5. Numerical sensitivity analysis

To examine significant factors for building life cycle cost, this study also performed sensitivity analysis based on new-constructed medium size DOE reference office building [11]. Considering the influence of the local weather on building design and construction, this study included ASHRAE (American Society of Heating Ventilating and Air Conditioning Engineers) climate zones 1A (very hot), 5A (cool), and 8 (subarctic). The representative cities in these climate zones are Miami, Chicago, and Fairbanks. Table 7 shows the enclosure information in the base case, which is also the

Table 6
ANOVA (*P*-value).

Variables	*P*-value
Enclosure system	
Criteria in selection process	
Initial cost	0.954
Energy efficiency	0.097
Life cycle cost	0.296
Material durability	0.194
Environmental impacts	0.650
Occupied space	0.547
Optimized component	
Insulation thickness	0.197
Insulation product	0.341
Wall/roof/floor type	0.635
Window-to-wall ratio	0.656
Shading	0.967
Glazing	0.812
Infiltration rate	0.582
Mechanical system	
Criteria in selection process	
Initial cost	0.218
Energy efficiency	0.848
Maintenance	0.488
Life cycle cost	0.947
Environmental impacts	0.063
Optimized components	
Mechanical system type	0.005
Mechanical system size	0.017
Mechanical system control	0.511
Infiltration rate	0.181

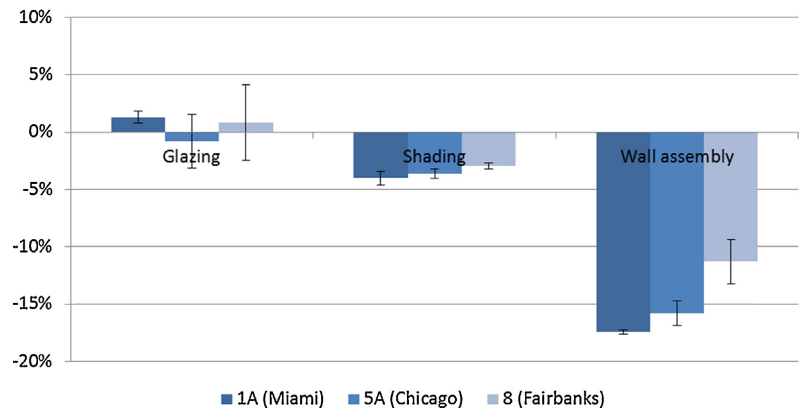

Fig. 7. Average percentage differences and standard deviations by the options of window glazing, shading, and wall assembly in three climate zones, when building has 50 years life span.

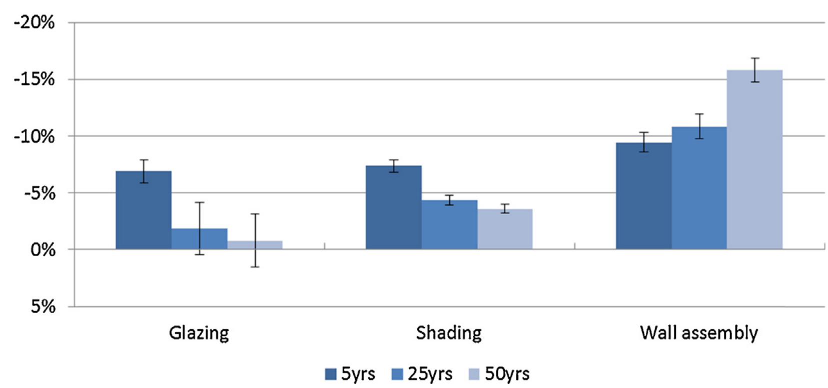

Fig. 8. Average percentage differences and standard deviations by the options of window glazing, shading, and wall assembly in Chicago (climate zone 5A), when building has different life span (5 years, 25 years, 50 years).

Table 7
Base case of medium size DOE reference office building.

Parameter	Value
Floor area	4982 m^2, 53,628 ft^2
Number of floors	3
Wall assembly	ASHRAE 90.1-2004 requirements, non-residential wall
Glazing	ASHRAE 90.1-2004 requirements
Glazing fraction (WWR)	0.33
Shading	No
System type	Packaged VAV systems
Heating source	Gas furnace
Cooling source	Air-cooled direct expansion
Air distribution and terminal units	VAV terminal box with reheat coil
Thermostat setpoint	75 °F Cooling/70 °F Heating
Average lighting power density (W/m^2)	8.87
Average plug-load power density (W/m^2)	8.07
Average occupancy density (m^2/person)	18.6

Plus basement (not included in the table number) [11].

Table 8
The options of the parameter considered in the sensitivity analysis.

Parameter	Option
Window glazing	Single, double, lowE
Shading	Overhang, interior blind, exterior blind, interior screen, exterior screen
Wall assembly (including insulation)	CIP concrete with fiberglass/foamglass/EPS/XPS Concrete block with fiberglass/foamglass/EPS/XPS

default setting in DOE reference model. The simulation is carried out by EnergyPlus, while the initial cost accounts for the data from RS Means [12,13].

The sensitivity analysis focuses on enclosure system components. The options are selected according to the available data in the ASHRAE standard and RS Means, shown in Table 8. Fig. 7 shows the average differences and standard deviations of the 50-year life cycle costs caused by different options of window glazing, shading, and wall assembly in three climate zones. The life cycle cost calculations follow a procedure outlined in the literature [14]. The LCA results indicate that wall assembly has a much larger impact on building life cycle costs across all three different climate zones. The changes of the envelope components also show larger impacts on the building's 50-year life cycle cost in hot climate than it is in relatively colder climates. Fig. 8 presents the average percentage differences and standard deviations caused by changing envelope components in Chicago (climate zone 5A). The results illustrate that the changes of wall assembly, including insulation material, have a large impact on life cycle costs as the building has longer life span. Oppositely, window glazing and shading are less influential on life cycle cost as the building's life span increases.

6. Conclusions

This study gathered a snapshot of the current perspective of building professionals on life cycle assessment and energy simulations. The online survey gathered responses from a representative sample of 96 building system professionals involved in enclosure and HVAC system design. At the time of this study, 12% of the survey participants performed building energy simulations in 81–100% of their projects, while none of the participants indicated that they performed life cycle assessments as frequently. Furthermore, 18% of the participants indicated that they use energy simulations in 0–20% of their projects, while 55% of the participants selected this low frequency for the life cycle assessment. These results show that life cycle assessments are much less frequently used in building system design than energy simulations. The survey also indicates that the main driver for doing life cycle assessment is the building owner.

The survey also investigated the importance of different criteria and components in life cycle analysis from a designer's point of view. The importance of every criterion was very high in the process of building system design from the perspectives of surveyed participants. However, there was a noticeably higher bias toward the importance of environmental impacts in the building design process. These survey inputs were analyzed by two types of statistical analysis methodologies. First, Fisher's exact test examined the correlations between the frequency of building performance analysis and the respondents' background. The respondents' background has a significant correlation with the frequency of performing energy simulations and life cycle assessment in their projects. Company size also had a statistically significant impact on the energy simulation usage frequency. The designers with less than 10 years of work experience tend to be more likely to perform life cycle analysis in their projects. Moreover, ANOVA-based analysis examines whether a statically significant difference among the perspectives of different designer groups exists. The analysis demonstrated that different groups have very similar answers to most of the questions covering important components and selection criteria.

A sensitivity analysis was also performed in this study to theoretically find the significant building components in life cycle analysis. The analysis is based on a new-constructed medium size DOE reference building located in three different climate zones. In contrast to the survey results, the sensitivity analysis demonstrated that the changes in wall assembly have a strong impact on life cycle costs in all examined climate zones. With colder climates and longer life spans, the wall assembly became even more important for building life cycle cost. The comparison between sensitivity analysis and survey results indicates that the influence of window properties on life cycle cost is over estimated by most of the participants. Overall, this study revealed that LCA is still not widely used in building industry even though it would help address design biases toward building systems that do not deliver expected performance.

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