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M.S. Thesis

2019

ANALYZING THE BENEFITS AND CHALLENGES OF THE BUILDING INFORMATION MODELLING AND LIFE CYCLE ASSESSMENT INTEGRATION

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B.S., Civil Engineering, IŞIK UNIVERSITY, 2019

Submitted to the Graduate School of Science and Engineering
in partial fulfillment of the requirements for the degree of
Master of Science
in
Civil Engineering

IŞIK UNIVERSITY
2019

IŞIK UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

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APPROVAL DATE: 17/07/2019

ANALYZING THE BENEFITS AND CHALLENGES OF THE BIM AND LCA INTEGRATION

Abstract

The architecture, engineering and construction (AEC) industry involves the large quantities of material and energy consumption. Previous studies show that the AEC industry consumes about 40 percent of primary energy utilization and contributes up to more than half of global GHG emissions. With the aim of decreasing these negative impacts of AEC industry on the natural environment, the integrated use of advanced technological instruments has been increasing in the last decade. One of the promising technological instrument integrations is the collaborative use Building Information Modeling (BIM) and Life Cycle Assessment (LCA) which is able to decrease negative impacts of AEC industry on natural environment in an effective and efficient manner. The objective of this MS thesis is to identify, classify and prioritize the benefits and challenges of the integrated use of Building Information Modelling and Life Cycle Assessment in the AEC industry. In order to achieve research objectives of this thesis, a comprehensive literature review, semi-structured interviews with experts and Delphi method were performed. The interrater agreement and significance-level statistics were conducted for analyzing and validating the consensus among the Delphi method participants. Results of this study provide twenty-two types of benefits and seven types of challenges for the integrated use of BIM and LCA in the AEC industry. The contributions of this thesis are a comprehensive identification, classification and prioritization of the integrated use of BIM and LCA. The results of this study may contribute to extend utilization of BIM-LCA integration in the AEC industry.

Keywords: Building Information Modelling, Life Cycle Assessment

YAPI BİLGİ MODELLEMESİ VE YAŞAM DONGUSU ANALİZİ'NİN ENTEGRASYONUNUN FAYDALARININ VE ZORLUKLARININ ANALİZ EDİLMESİ

Özet

Günümüzdeki enerji ve malzeme tüketiminin çoğunluğuna mimarlık, mühendislik ve inşaat sektörü neden olmaktadır. Yapılan çalışmalar, inşaat sektörünün birincil enerji kullanımının yaklaşık % 40'ına ve küresel sera gazı emisyonlarının yarısından fazlasına neden olduğunu göstermektedir. Geçtiğimiz on senede inşaat ve mühendislik sektörlerinin çevreye olan olumsuz etkilerini azaltmak için kullanılabilecek yeni teknolojik araçlar geliştirilmiştir. Bu yeniliklerin önde gelenlerinden bir tanesi çoğunluğuna mimarlık, mühendislik ve inşaat sektörünün olumsuz çevresel etkilerini etkili ve verimli bir şekilde azaltan Yaşam Döngüsü Analizi (LCA) ile Yapı Bilgi Modellemesi (BIM)'nin entegrasyonudur. Bu yüksek lisans tezinin amacı, Yapı Bilgi Modellemesi ve Yaşam Döngüsü Analizi entegrasyonun faydaları ve zorluklarını tespit etmek, sınıflandırmak ve önem derecelerine göre sıralamaktır. Bu tezin araştırma amacını gerçekleştirmek için kapsamlı literatür taraması, uzmanlarla yarı yapılandırılmış görüşmeler ve Delphi yöntemi uygulanmıştır. Delphi yöntemi katılımcıları arasındaki uzlaşmayı analiz etmek ve doğrulamak için değerlendiriciler arasında güvenilirlik ve anlamlılık düzeyi istatistikleri hesaplanmıştır. Bu çalışmalar sonucunda mimarlık, mühendislik ve inşaat sektöründe Yapı Bilgi Modellemesi ve Yaşam Döngüsü Analizi entegrasyonun kullanımı ile ilgili yirmi iki adet fayda ve yedi adet zorluk belirlenmiştir. Bu tezin katkıları, Yapı Bilgi Modellemesi ve Yaşam Döngüsü Analizi entegrasyonun mimarlık, mühendislik ve inşaat endüstrisinde kullanımının kapsamlı tanımlanmasını, sınıflandırılmasını ve önceliklendirilmesini sağlamaktadır. Bu çalışmanın sonuçları, mimarlık, mühendislik ve inşaat endüstrisinde Yapı Bilgi Modellemesi ve Yaşam Döngüsü Analizi entegrasyonunun kullanımının artmasına katkıda bulunabilir.

Anahtar kelimeler: Yapı Bilgi Modellemesi, Yaşam Döngüsü Analizi

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List of Abbreviations

LCA	**L**ife **C**ycle **A**ssessment
BIM	**B**uilding **I**nformation **M**odelling

Chapter 1

Introduction

The construction industry is one of the fundamental components of the economic and social development that involves the large quantities of material and energy consumption. Previous studies show that the buildings sector consumes about 40 percent of primary energy utilization [1]. Human activities are the major factor of environmental pollution. The architecture, engineering and construction (AEC) industry contributes up to more than half of global GHG emissions. The products of developing technology reduce the negative environmental impacts of humanity. The design of some of these products directly and indirectly affects the construction sector. The integration of Building Information Modelling (BIM) and Life Cycle Assessment (LCA) is one of the updated technological instruments, provides reduction of the total time spent and the improvement of the application while minimizing the environmental impacts throughout the life cycle of facility. The main objective of this research is to identify the benefits and challenges of BIM and LCA integration. The data obtained from this study will help the BIM-LCA integration to be used more efficiently and to overcome the deficiencies. And the data obtained from this study also increase the utilization of the BIM-LCA integration in the AEC industry.

1.1 Problem Identification

Environmental pollution and destruction of nature is one of the most important problems faced by humanity recently. The rapidly developing construction sector is one of the main causes of this environmental pollution. The harmful effects resulted from construction industry, can be prevented by use of the opportunities offered by the technological developements. LCA is one of the potential technological opportunuties. Despite LCA tools are used in many different fields in the industry, with the developing software systems, it is also being used in the AEC industry. Although its use in the AEC sector has had very positive effects, its use has not yet become prevalent. Previos studies show some reasons for the low usage of the LCA. When LCA is used alone, it may be insufficient in some cases in the construction sector [2]. In construction projects, it is very important to be programmed and during the construction process the observation of the programmed stages are significant for progression. Although LCA tools are advanced methodologies for fullfilling sustainability requirements, they have some challenges about data accesibility and process follow-up, since prior studies show that these environmentally oriented tools depend on the other technologies for the effective and efficient utilization and larger capacity of storage. Storage defficiencies and data accesibility challenges can be overcome by BIM which is another innovation for structural industiry. BIM positively affects the management of the construction projects and if it is not used, some disruptions occur in the course of the project. Some problems may occur throughout construction stages including design, planning, and site management because of poor management that in return cause delays, environmental problems. Both environmental impacts and disruptions in the management of the project itself reduce productivity. BIM-LCA integration can be used to prevent such these problems.

1.2 Research Objective

The objective of this thesis is to identify the benefits and challenges of the integrated use of Building Information Modelling and Life Cycle Assessment in the architecture, engineering and construction (AEC) industry. In this study, current and future situations of the implementation were investigated as well as the benefits and challenges of this technology were examined and utilized. This paper identifies the shortcomings and challenges of BIM-LCA integration in the industry and literature. Identifying problems and investigating these problems is beneficial in order to increase the efficiency of this integration usage. This research shows that the integrated use of BIM and LCA may provide professionals in the AEC industry more accurate and faster results throughout reducing the labor force spent and achieving project objectives in less time. This paper points out that studies on BIM-LCA integration need to be intensified and that deficiencies in the sector should be eliminated. In order to eliminate the challenges of BIM-LCA integration, the use of this technological instrument should be encouraged and its use should be expanded.

1.3 Scope of the Study

After determining the topic of the master thesis as "Benefits and Challenges of BIM-LCA Integration" a extensive literature review was performed in order to get information about the subject at the starting and to limititations of the title. The literature reviews on construction projects with the BIM - LCA have been performed and the benefits and challenges of the integration examined. The deficiencies and dificulties in the construction and sustainability phases were investigated and the challenges that may come up during the implementation stage of the integration investigated. The necessary requirements and application methods for an efficient integration examined. In the second section of this master thesis study, experts which are qualified and informed about this topic were interviewed and their opinions and experiences were taken. The content of the research was customized with the data obtained from the experts and the areas to be concentrated in the literature were determined. In the third section, the two-step Delphi Method was applied. The questionnaire, which was applied with the participation of academicians and expert people, was presented for the enrinchiching the content of the study. The significance, and importance of the results were determined. After the completion of all the sections, the master thesis finalized with the result section.

1.4 Vision

The research vision of this study addresses integration of LCA methodology to BIM tools. Integration of LCA methodology to BIM technology allow professionals to analyze environmental impacts of buildings from each material used in the buildings to the entire building. The first step of integrating LCA to BIM is to identify the goal and scope of the construction project. Identification of project goal and scope includes the functional unit, system boundary and the set of building materials. The second step is to generate life cycle inventory. LCA tools such as SimaPro, Gabi and Umberto can be utilized for analyzing life cycle assessment for construction materials which ensure creating lifecycle inventory database. In order to transfer the data from inventory database into BIM tools (e.g., Revit) a converter program requires for blocking data loss and increasing data transfer speed. After transferring data, BIM tool is used for creating design alternatives and simulations. Life cycle impact assessment is performed using the data obtained from environmental analysis tools (e.g., Athena Environmental Impact Estimator, Energy Plus). After conducting life cycle impact assessment, time and cost analysis are performed using the BIM tool. The outputs are interpreted that provide classification of impacts, comparison of results and recommendations for more sustainable building, if require. The flowchart of integrating LCA to BIM is represented in Figure (1.1)

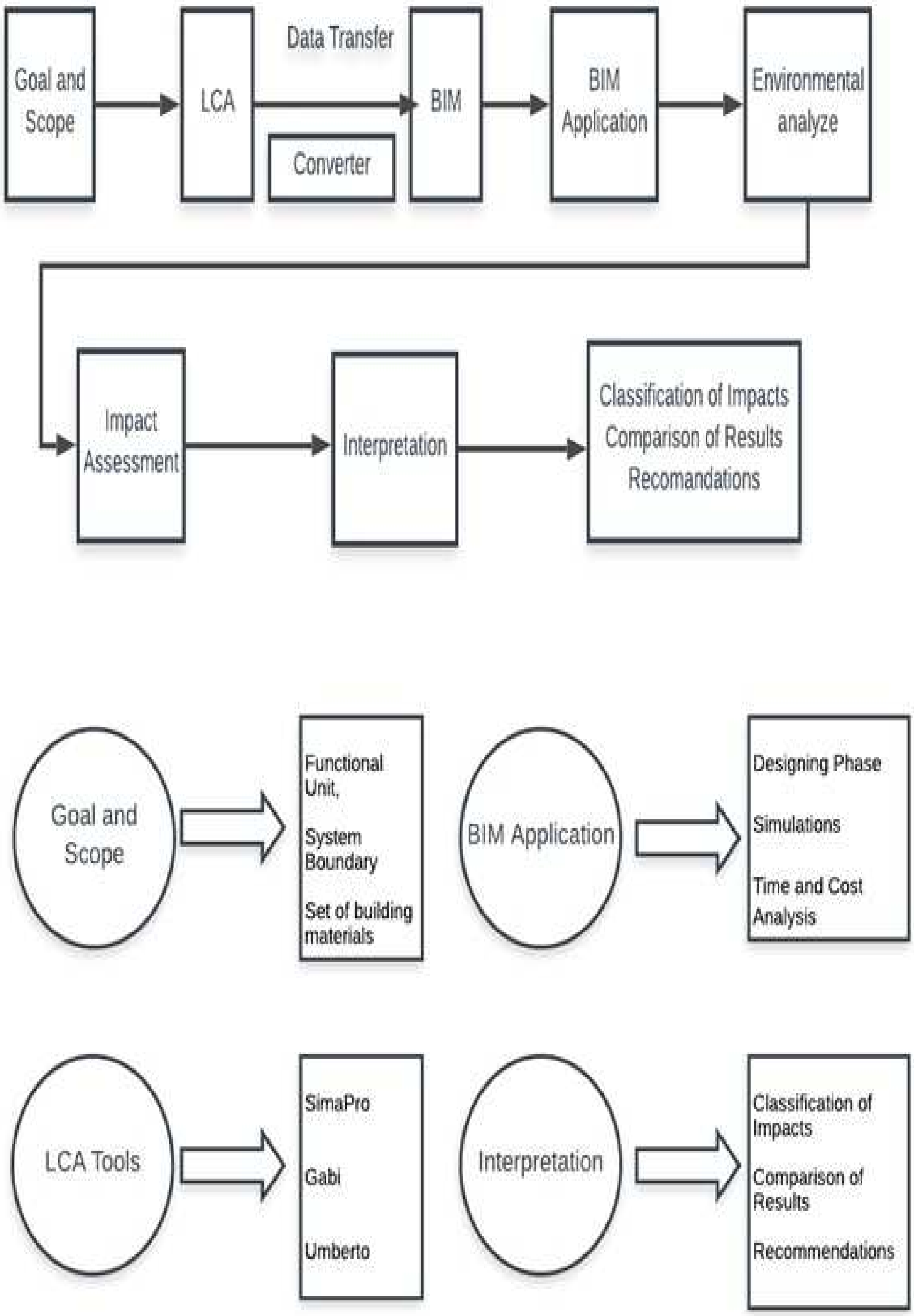

Figure 1.1: Visualization of the stages of BIM and LCA integration.

1.5 Plan of the Study

The study consists of 8 chapters. Chapter 1 explains research problem and research objective of this study. The Chapter 2, discusses the research methodology by describing the methods used for the analysis of the information obtained. The Chapter 3 presents the literature review by explaining prior studies performed to get information about the research. Chapter 4 includes informations about Delphi Method. The Chapter 5 includes the results of the benefits, challenges and risks of integration Chapter 6 discusses the integration stages of this technological platform and the necessary intermediate components.. Chapter 7 includes concluding remarks, summary of findings, thesis contributions, and further research. Chapter 8 includes references.

Chapter 2

Research Methodology

The research methodology of this study includes literature review, semi-structure interview and two staged Delphi Method to analyze the benefits and challenges of BIM-LCA integration for the AEC industry. Literature review and semi-structure interview used for the identification purpose and the Delphi Method used for the prioritization purpose. Literature review was chosen as a research technique to obtain information from different viewpoints of the previous studies. In the literature review the benefits and challenges of this integration have been determined. The deficiencies in the design, construction and sustainability phases were determined and the difficulties during the implementation phase of the proposed integration have been examined. Comparison of different researches was made in the literature to find common points from varied papers. Main reason of performing the literature review preliminarily is to collect the large amount of useful and reliable data. In the literature review, studies published between 1968 and 2019 have been investigated using the databases of Elsevier, American Society of Civil Engineers (ASCE), Science Direct, Taylor and Francis and Web of Science. A total of 38 journal articles, 6 conference papers and one book have been investigated within the literature review. The keywords in these studies are as follows; "Building Information Modelling", "Building Information Modeling", "BIM", "Building Information Model","Life Cycle Assessment", "LCA", "Building Information Modelling-Life Cycle Assessment integration", "BIM-LCA integration", "linking Building Information Modelling and Life Cycle Assessment", "integration of

Building Information Modelling with smart objects". Semi-structured interview was chosen as the other research technique in order to determine the benefits, challenges of the integration of BIM and LCA integration by obtaining experts' opinions in the subject domain. This method is an efficient way to collect information about the sector from professionals having hands-on experiences. Three experts having more than ten years of professional experiences in the BIM and LCA participated in the interviews. The interview questions can be found in the Appendix section. With the aim of achieving the prioritization purpose of this study, Delphi method was conducted. Delphi method is an interactive research technique that allows to obtain highly reliable and valid data from the experts after a detailed structured process. Delphi questionaries was prepared using the triangulation results of literature review and semi-structured interviews. Achieving valid and reliable outputs from Delphi survey rely upon the right set of experts on the subject matter [3]. Hence, Delphi panel participants was selected from (1) authors of journal articles addresing the integrated use of BIM and LCA, and (2) proffesionals having at least 2 years of experiences in BIM and LCA. Delphi questionaries was sent a total of 58 experts. 10 of them participated in survey and completed both two rounds of the Delphi method. Participation of 10 experts is enough to achieve reliable and valid outputs as 8-12 experts were suggested to conduct the Delphi survey [4]. All the experts are international that allow to analyze the subject in a holistic perspective by gathering different perspectives and experiences. An intensive effort was made to communicate with the experts. Difficulties in communication and information transfer have been encountered due to time differences between different countries and the mismatch of working hours. Hence, the Delphi survey was completed in two months. Delphi panel experts' qualification are represented in Table (2.1).

Identifier	Profession Title	Education	Exp. with BIM
R1	Civil Engineer	Ph.D.	2 Years
R2	Architect	Ph.D.	5 Years
R3	Architect	MSc	10 Years
R4	Civil Engineer	Ph.D.	15 Years
R5	Architect	Ph.D.	5 Years
R6	Architect	Ph.D.	5 Years
R7	Civil Engineer	Ph.D.	10 Years
R8	Civil Engineer	Ph.D.	5 Years
R9	Civil Engineer	MSc	2 Years
R10	Energy Systems Engineer	MSc	2 Years

Table 2.1: Expert informations about profession titles, level of educations and experience time with BIM

ID	LCA Exp.	Title	Exp. in Ind.	Country
R1	8 Years	Manager	18 Years	England
R2	3 Years	Architect	4 Years	Brasil
R3	4 Years	Research Asst.	4 Years	Austria
R4	5 Years	Professor	10 Years	USA
R5	4 Years	Architect	7 Years	USA
R6	10 Years	Architec	19 Years	Spain
R7	4 Years	Professor	5 Years	USA
R8	6 Years	Research Asst.	3 Years	Switzerland
R9	3 Years	Research Asst.	2 Years	Finland
R10	3 Years	Sustainability Eng.	2 Years	England

Table 2.2: Expert informations about experience time with LCA, titles, experience time in the industry and countries.

Chapter 3

Literature Review

Prior studies show that buildings produce huge scale of global dangerous gas emissions, most of the percentage of this utilization happens as part of operations during construction lifetime [5]. The number of studies conducted for sustainability has increased to reduce negative impacts of built environment. For decreasing the negative impacts of construction industry, previous studies suggested to use advanced technologies such as BIM and LCA. Moreover, the collaborated use of BIM and LCA is able to decrease construction waste while streamlining project delivery process BIM is described as a product, process and system by National Building Information Modeling Standard (NBIMS). BIM technology allows to create an accurate three dimensional (3D) digital model of a building using developed objects by identification of any potential design, construction or operational issues. This advanced technological instrument allows designers to share many complex data in a single simple model. Accordingly, BIM technology connects different disciplines which in return facilitates them to work in a simultaneous manner. BIM is an emerging technological development that facilitates every stage of construction for AEC sector. This promising technological instrument coordinates facility management activities, keeps maintenance under control, helps monitoring projects stages easily, enables preparing extensive planning phases, and encourages communication and straightforwardness among partners that altogether promote constructability of the project, increase the productivity. BIM software provides faster solutions and increases effectiveness of a project, provides better customer service and better production quality [6]. BIM enables visualization during design phase, increases communication between other departments and provides cost estimating and material qualification [1]. LCA is defined as a comprehensive methodology which allows determining the environmental and resource impacts of a material, product, or even a whole building throughout its entire life cycle from the extraction of resources to the disposal of the item [7],[8]. LCA enables to examine impacts of material selection decisions by tabulating energy and water demand as well as emissions to air, water, and land over the entity's whole life cycle [9]. LCA tools, such as SimaPro and Athena, are able to calculate the total amount of environmentally hazardous substance generated throughout the construction process of a facility which in return to mitigate negative impacts of buildings on the natural environment. Although LCA tools are advanced methodologies for fulfilling sustainability requirements, LCA systems have some problems about data accessibility. Prior studies show that these environmentally oriented tools depend on the other technologies for the effective and efficient [5]. The usage of LCA in the sector is not widespread because of; lack of specialized labor, complexity of assessment tools and unpractical manual data input [10].

3.1 Benefits of BIM-LCA Integration

Review of the literature show that, the integration of BIM-LCA contributes to the reduction of the total time and the improvement of the application while minimizing the environmental impacts throughout the life cycle of facility. With combining these two technological instruments, designers can observe possible embodied energy and global warming potential at the early stages of the planning process inside of the full building analysis [11],[12].By the use of this environment-oriented technological framework, BIM and LCA can eliminate the difficulties of each other with using the good features to compensate to the missing feature of the other [2]. While BIM technology helps minimization of LCA's challenges and deficiencies (e.g., storage capacity), LCA is able to reduce the negative environmental impacts of the projects by integrating into BIM. Life Cycle Assessment tools without BIM automation are long and complex [13]. One of the LCA's software difficulties is storage capacity. BIM provides effective solutions to LCA's storage problem with the ability to work on large files. BIM also allows professionals to organize the project schedule by mitigating the possible design errors that in return provide LCA to recognize and develop solutions to the challenges which will face throughout the life cycle of the project. LCA tools, enables BIM to be enriched as content. This integration provides early decision-making process which helps LCA to be active in beginning of the project and high potential for assessing decision making process for early stages [14], [5], [11]. The use of BIM with LCA reduces the environmental expenditure in the early stages of design [14]. The main benefit of this association is to reduce negative environmental impacts. The BIM-LCA integration allows finding the main causes of the problems and minimizing these problems. At the beginning of the project, it is possible to calculate future damages. BIM-LCA integration is an efficient mechanism for operational carbon emission analyses. The emission of carbon dioxide during construction can be monitored, this feature allows to take precautions and helps avoiding to generate unnecessary carbon dioxide to atmosphere. Due to the measures taken, the emission of carbon dioxide during construction will decrease. And also researches, supports the argue that harmful gas emission reduces with the use of the BIM-LCA integration [13]. Integration of BIM-LCA enables monitoring the total amount of energy used during construction, with this specialty detailed energy analysis becomes feasible [6]. This collaborative technological framework helps to detect unnecessary used energy and to regulate this energy usage. Reducing the unnecessary energy used, as well as reducing environmental problems decreases, the total energy consumption during the project time [9]. The negative impact of the AEC industry on global warming is also reduces with less carbon dioxide emission and minimal energy consumption. Total global warming potential decreases with the use of LCA tools which integrated with BIM [15]. Apart from the fact that the BIM-LCA integration allows to decrease negative environmental impacts of built environment. Additionally, this technological framework creates more effective working platform by avoiding software deficiencies [5]. LCA tools have difficulty in obtaining numerical data single-handedly. When it is used with BIM, this deficiency is eliminated. BIM resolves the problems that LCA tools are experiencing to obtain numerical data in the field [6]. Quantitative performance predictions become available for LCA tools with the use of BIM [6]. BIM-LCA integration enables determining the properties of the materials in buildings and adjusting the amount of the material during construction. Hence, this integrated technological framework helps the selection of the material. For reducing the negative

effects on natural environment, a detailed examination is made for material selection that allows designers to choose less-emitting materials for the construction processes. Accordingly, use of more sustainable materials in building production and renovation increases. With the use of this integration, designers gain opportunity for investigating different alternative materials [16], [14]. Examining different alternatives enables comparison in order to find the best solution. By this manner, difficulties encountered in other projects are examined and allow measures to be taken against them. Different methods have been used to understand the benefits and challenges of this integration. One of them is literature review. The literature review was used to obtain tangible data. According to the comprehensive literature review, a total of 22 benefits for the integrated use of BIM and LCA were identified that are represented in Table (3.1).

3.2 Challenges of BIM-LCA Integration

According to the literature review, seven types of challenges were identified for the integrated use of BIM and LCA. One of the challenges of this integrated framework is the lack of standardization for the LCA procedures [14], [10], [11]. Since the AEC sector does not have strict guidelines and standardizations about LCA that makes difficult to disseminate the use of BIM-LCA. Creating specific

Identifier	Benefits of BIM and LCA integration	References
B1	Reducing the environmental expenditure in the early stages of design	[5], [14],
B2	Integration in decision makng process	[5], [17], [14],
B3	Collaborative work between stakeholders	[14],
B4	Possibility of comparing different alternatives	[14], [2], [16],
B5	High potential for assessing decision making process for early stages	[14], [5], [11], [12]
B6	Improving environmental performance	[9], [10], [12],
B7	Detailed energy analysis	[16], [10], [11], [6], [13],
B8	Efficient mechanism for operational carbon emission analyses.	[13], [2],
B9	Observing carbon emission while transportation of materials.	[17], [12],
B10	Instant feedback about LCA performance for structures	[2];
B11	Reduction of carbon emission in structure process	[9], [2], [11], [13],

Identifier	Benefits of BIM and LCA integration	References
B12	Scientific assessment environmentally while construction process	[11], [2], [5], [6],
B13	Quantitative performance predictions for LCA tools	[10], [6],
B14	Conducting daylight analysis	[10], [6],
B15	Investigating the water harvesting potential	[10], [6],
B16	BIM-based sustainability softwares provide very quick results	[6], [13],
B17	Decrease of the total energy consumption	[11], [12], [9],
B18	Decrease of the total waste after demolition	[11],
B19	Less emiting material usage (paints and coating)	[6],
B20	Water use reduction	[6],
B21	Use of more sustainable materials in building production and renovation	[12],
B22	Decreases the global warming potential	[11], [12], [9]

Table 3.1: Benefits of the BIM-LCA Integration.

regulations on the subject will be beneficial in increasing use and reducing environmental negative impacts [5]. Except some updated programs like Revit, other difficulties occur while using tools because these systems are designed separately and trying to be used simultaneously. The interoperability is not completely arranged between LCA and BIM [14], [18] . The number of sustainable-based BIM tools in the market is not very high [12]. This situation creates difficulty of finding a way for using sustainable BIM-based tools ([10], [18]). The potential of working with information systems in the AEC sector is increasing. Although this potential is not entirely be used, it is signaling that the prevalence will increase. As tools are used, their deficiencies will be improved. One of the other shortcomings is the complexity of the required data and available tools [10]. BIM can be used for increasing the storage capacity of LCA that allows more information to be stored. However, the difficulties result from the lack of strict regulations on how to process this stored data. The other challenge of BIM-LCA is lack of comparable studies in the literature [11], [12] that makes difficult to take measures and to find proper solutions. Challenges of this integrated framework is represented in Table (3.2)

The dynamic model in this algorithm consists of drift and diffusion. Drift is deterministic motion defined with velocity and acceleration, and is common for all particles of a partition. Diffusion on the other hand is Brownian motion; random movements that split particles at the identical state and enable search in the image space through random walk.

Identifier	Challenges of BIM-LCA Integration	References
C1	Lack of standardization of LCA procedures	[10], [11],
C2	Interoperability is not fully prepared between LCA and BIM	[14], [18], [10],
C3	Difficulty in data transfer	[10], [18],
C4	Difficulty related to the techniques for mapping objects	[10],
C5	Complexity of required data an avaliable tools	[10],
C6	Lack of comparable studies in literature	[11], [12],
C7	Scarcity of available product data in design phase for LCA tools	[12],

Table 3.2: Challenges of the BIM-LCA Integration.

Chapter 4

Delphi Method

Delphi method is an interactive expert oriented research technique which allows for gathering rational judgments from a preselected group of independent experts (i.e., panel participants) through series of systematic questionnaires on a specific topic. According to the requirements of this structured methodology, the personal information of the panel participants should be kept confidential and these participants should complete Delphi process independently from each other[19]. Considering the reasoning mechanism of Delphi method, the survey may involve multiple panel rounds with the aim of achieving consensus among the experts. After each round, the information (e.g., feedback, scoring) are gathered from the experts. The data gathered from the previous round is shared with the participants in the next questionnaire. This procedure is reiterated in each round until achieving consensus among Delphi panel participants. At the end of the Delphi survey, the results of the last round are shared with panel participants. This expert-oriented interactive research technique is widely used for achieving consensus in cross-field topics or for state-of-the-art and complex concepts [3]. In this integrated research study, Delphi method is utilized for prioritizing the identified benefits and challenges of BIM-LCA integration. The Delphi questionnaires were prepared using the triangulation results of literature review and semi-structured interviews. In this research, Delphi survey was conducted in two rounds because 2-3 iterated rounds are suggested to be conducted for reaching consensus among the panel participants [4]. A list of benefits and challenges of BIM-LCA integration were distributed to the Delphi panel participants. In the first round, Delphi panel experts were asked for scoring the benefits and challenges of BIM-LCA integration. In this Delphi survey, a five-point Likert-scale was used as a grading system. In the grading system used for prioritizing the benefits of BIM-LCA integration, "1" corresponds to "minimum positive effect" and "5" refers to "maximum positive effect". In the grading system used for prioritizing the challenges of the BIM-LCA integration, "1" represents the "minimum negative effect" and "5" corresponds to "maximum negative effect". Mean, median and standard deviation values were acquired from the data assembled from the Delphi experts. The reason for calculating mean and median values is analyzing the central tendency. Mean and median values are also used for ranking the benefits and challenges of BIM-LCA integration. The reason for calculating the standard deviation value is analyzing the group consensus [20]. The standard deviation value is less than 1 shows that the Delphi panel participants have common thoughts on the topic and achieve high level of consensus [21]. The standard deviation values of twenty benefits and five challenges are less than 1 that indicates high level of consensus was achieved. In the second round, mean values of the first round were shared with the Delhi experts by asking them for re-scoring the benefits and challenges of the BIM-LCA integration considering the mean values of each benefit and challenge. Mean values were utilized for prioritizing the benefits and challenges of BIM-LCA integration. If the mean values of each benefit and/or challenge are equal, median values were utilized for ranking. In addition to mean, median and standard deviation values, significance and agreement levels of each benefit and challenges of BIM-LCA integration were calculated. In order to determine significance levels, the mean value is used of each benefit and challenge of BIM-LCA integration. Benefits and challenges with a mean value less than 1.5 were considered as "not important". Benefits and challenges with a mean value between 1.51 and 2.50 are defined as "somewhat important", between 2.51 and 3.50 are defined as "important", between 3,51 and 4,50 identified as "very important". The benefits and challenges with a mean value between 4,51 and 5 described as “extremely important”. ” [22]. For determining the agreement levels, ” the interrater agreement statistics” (rwg) were calculated for each benefit and challenge of BIM-LCA integration. rwg values between ”0” and “0.30” are defined as “lack of agreement”, rwg values between “0.31” and “0.50” are defined as ”weak agreement”, rwg values between “0.51” and “0.70” are identified as ”moderate agreement”, rwg values between “0.71” and “0.90” are defined as ”strong agreement” and rwg values between “0.91” and “1” are defined as ”very strong agreement” [22]. Eq.(4.1) shows the interrater agreement statistics formula. In order to analyze and validate the consensus reached by the experts in the second Delphi round for each benefit and challenges of BIM-LCA integration, the interrater agreement statistics formula was applied [22], [23],[20] .

$$1 - (2(Z^2))/((A + B)xM - (M^2) - (AxB))xn/(n - 1) \tag{4.1}$$

In this formula, rwg denotes the interrater agreement of that benefit or challenge of BIM-LCA integation, “A” signifies the maximum scale value (i.e., 5), “B” represents minimum scale value (i.e., 1), “M” refers to the mean value of that benefit or challenge of BIM-LCA integration, “n” stands for the sample size of panel participants which is ten in this research, and sigma indicates the standard deviation value. The results from the second round of Delphi survey can be found in the Table (4.1) and (4.2) The tables show mean, median and standard deviation values, as well as agreement levels and significance levels of each benefit and challenge of BIM-LCA integration. The results from the first step of the Delphi method are represented in the “Appendix” section. In the second round of the Delphi survey, the number of common ideas among experts increased. “The weak agreement” number decreased from 8 to 3 for benefits and 2 to 1 for challenges.

No	Benefit	Mean	Med.	Std. Dev.	rwg	Agr. Level	Sgn. Level
B2	Integration in decision making process	4,8	5	0,42	0,582	ext. imp.	mod. agr.
B4	Possibility of comparing different alternatives	4,8	5	0,42	0,582	ext. imp.	mod. agr.
B5	High potential for assessing decision making process for early stages	4,8	5	0,42	0,582	ext. imp.	mod. agr.
B10	Instant feedback about LCA performance for structures	4,7	5	0,63	0,356	ext. imp.	weak agr.
B1	Reducing the environmental expenditure in the earlystages of design	4,6	5	0,52	0,662	ext. imp.	mod. agr.
B8	Efficient mechanism for operational carbon emission analyses.	4,4	4	0,52	0,761	very imp.	str. agr.
B13	Quantitative performance predictions for LCA tools	4,4	4	0,66	0,616	very imp.	mod. agr.
B14	Conducting daylight analysis	4,4	4	0,52	0,761	very imp.	str. agr.
B6	Improving environmental performance	4,2	4	0,48	0,838	very imp.	str. agr.
B3	Collaborative work between stakeholders	4,1	4	0,83	0,556	very imp.	mod. agr.
B22	Decreases the global warming potential	4,1	4	0,83	0,556	very imp.	mod. agr.
B15	Investigating the water harvesting potential	4	4	0,71	0,698	very imp.	mod. agr.
B21	Use of more sustainable materials in building production and renovation	4	4	0,8	0,616	very imp.	mod. agr.

No	Benefit	Mean	Median	Std. Dev.	rwg	Agr. Level	Sgn. Level
B11	Reduction of carbon emission in structure process	3,8	5	1,06	0,398	very imp.	weak agr.t
B16	Possibility of comparing different alternatives	3,8	4	0,52	0,855	very imp.	str. agr.
B7	High potential for assessing decision making process for early stages	3,7	4	0,98	0,507	very imp.	mod. agr.
B12	Instant feedback about LCA performance for structures	3,7	4	0,78	0,688	very imp.	mod. agr.
B17	Reducing the environmental expenditure in the earlystages of design	3,7	3,5	1,12	0,357	very imp.	mod. agr.
B9	Efficient mechanism for operational carbon emission analyses.	3,6	4	0,63	0,804	very imp.	str. agr.
B18	Quantitative performance predictions for LCA tools	3,5	4	0,9	0,611	imp.	mod. agr.t
B19	Conducting daylight analysis	3,5	3,5	0,75	0,734	imp.	str. agr.
B20	Improving environmental performance	3,2	3,5	0,94	0,598	imp.	mod. agr.

Table 4.1: Delphi Survey Round 2 Results for Benefits of BIM and LCA Integration(Mean. median, standart deviation, agreemnet levels and significance levels has shown.

No	Challenge	Mean	Median	Std. Dev.	rwg	Agr. Level	Sgn. Level
C2	Interoperability is not fully prepared between LCA and BIM process	4	4	0,85	0,567	very imp.	mod. agr.
C1	Lack of standardization of LCA procedures	3,8	4	0,42	0,906	very imp.	very str. agr.
C7	Scarcity of avaliable product data in design for LCA tools	3,7	4	0,85	0,629	very imp.	mod. agr.
C3	Difficulty of finding a way for using sustainable BIM-based tools	3,5	3,5	0,53	0,865	imp.	str. agr.
C5	Complexity of the required data and available tools	3,4	3,5	1,11	0,357	very imp.	weak agr.
C4	The difficulty related to techniques for mapping objects	3,3	3	1,28	0,246	important	lack of agr.
C6	Lack of comparable studies in literature	2,7	3	0,62	0,823	imp.t	str. agr.

Table 4.2: Delphi Survey Round 2 Results for Challenges of BIM and LCA Integration(Mean. median, standart deviation, agreemnet levels and significance levels has shown.

According to the results obtained from the second round of Delphi Survey, significance levels of 6 benefits (B8, B14, B6, B16, B9, B19) are identified as "strong agreement". 13 benefits (B2, B4, B5, B1, B13, B3, B22, B15, B21, B7, B12, B18, B20) are identified as "moderate agreement" and three benefits (B1, B14, B18) are described as "weak agreement". The significance levels of the Delphi results show that 5 of the benefits (B2, B4, B5, B10, B1) are defined as "extremely important", 14 of the benefits (B8, B13, B14, B6, B3, B22, B15, B21, B11, B16, B7, B12, B17, B9) are defined as "very important" and 3 of the benefits (B18, B19, B20) are defined as "important". According to the Delphi results agreement levels of one challenge (C1) is defined as "very strong agreement". Agreement levels of two challenges (C3, C6) are identified as "strong agreement". Two of the challenges (C2, C7) are defined as "moderate agreement", one challenge (C5) is identified as "weak agreement" and one challenge (C4) is defined as "lack of agreement". The significance levels of three challenges (C1, C2, C7) are defined "very important", another three challenges (C3, C4, C5) are identified as "important" and the last challenge (C6) is defined as "somewhat important"

Chapter 5

Discussion

In this section, the results obtained from Delphi Method are discussed by explaining experts' comments and suggestions. According to the results "integration in decision making process" (B2) has the highest mean value with 4,8 in the second round of Delphi method. The value of the mean value gained from first round increased with the second questionnaire. According to expert comments, the use of BIM integration with LCA has a positive effect on planning of the construction projects. Another benefit which is "high potential for assessing decision making process for early stages" (B5) covered by the similar subject has also high average with the value of 4,7. This benefit has the third highest mean value in the list of all benefits. In construction projects, it is very important to set the calendar at an early stage. This integration can play an effective role in planning the process before construction process initiates. "Possibility of comparing different alternatives" (B4), is one of the benefits of the BIM-LCA integration, which has a mean value of 4,8. According to experts' comments, development of different technologies allows for creating various alternatives which in return achieve more sustainable and efficient results by comparison of the alternatives. In this way, the programmability and sustainability of the project can be improved. One of the most important software benefits is "instant feedback about LCA performance for structures" (B10). This benefit is in the fourth place in the list of benefits with the mean value of 4,6. Experts indicated that monitoring the feedbacks of LCA tools in the project is not effective when LCA used alone. In order to solve this problem, applying BIM-LCA integration is highly suggested in the previous studies and subject oriented experts. According to the experts, monitorization of changes in performance provides an opportunity to react negative situations early. "Reducing the environmental expenditure in the early stages of design" (B1) is another benefit of BIM-LCA integration. This benefit is in the fifth place in the list of benefits with the mean value of 4,6. The reason for its high mean value could be that the most important benefits of LCA tools are related to environment and the integrated use with BIM minimizes the environmental impacts of the AEC industry. Another benefit of the BIM-LCA integration is "efficient mechanism for operational carbon emission analyses" (B8). This benefit is in the sixth place in the list of benefits with the mean value of 4,4. According to the experts' comments, the emission of carbon gas is one of the most damaging causes of nature today; therefore, the integration of BIM with LCA is useful for minimizing this released gas. Another benefit of the BIM-LCA integration is "quantitative performance predictions for LCA tools". This benefit is in the seventh place in the list of benefits with the mean value of 4,4. Experts highlighted that BIM software (e.g., Revit) provide a performance prediction with LCA integration. Knowledge about the performance of the work is very important for the course of the project that can be provided by BIM-LCA integration. Another benefit of the BIM-LCA integration is "conducting daylight analysis". This benefit is in the eighth place in the list of benefits with the mean value of 4,4. Experts indicated that this feature of BIM-LCA integration allows for the adjustment of working hours and programming depending on weather conditions. According to the results, "decreases the global warming potential" has the ninth highest mean value with 4,1. The reason why this feature taken so important by experts is that it reduces the risk of global warming which is classified one of the most important problem of our era. The environmental impacts of LCA vehicles were transferred to the AEC sector with BIM. "Investigating the water harvesting potential" is the other benefit of BIM-LCA integration which has the tenth highest mean value with 4,0. Experts indicated that, investigating the water harvesting potential is useful for monitoring the amount of water used and minimizing this amount. According to the experts' comments, the BIM-LCA integration should be expanded to reduce the negative impact of built environment on natural environment while mitigating the use of water resources. In addition to its benefits, the challenges of the BIM-LCA integration have been evaluated with numerical data gathered from Delphi survey and expert opinions. The results show that mean values of all challenges for BIM-LCA integration increase in the second round of Delphi survey. One of the challenges of BIM-LCA integration is "interoperability is not fully prepared between LCA and BIM" (C1) which achieve the highest mean value among the challenges of BIM-LCA integration. The mean value of this challenge is 4. Although there are many different alternative software, difficulties in the compatibility of these new technologies and data transfer are highlighted by experts and researches focusing on this subject domain. Although some products have been introduced to the market in recent years, this challenge can be overcome by developing new advanced software as more advanced products still need to be spread in the market. One of the other challenges which has the second highest mean value is "lack of standardization of LCA procedures". The mean value of this challenges is 3,8. Experts indicated that this challenge can be solved by state-sponsored laws and official specifications. Along with these changes, the use of BIM-LCA integration will be bound to certain standards. With the standardizations the use of this promising integration will increase and expand in the AEC industry. The specifications and guidelines will pave the way for the use of this integration. The least significant challenge in this study is "lack of comparable studies in literature" with the mean value of 2,7. According to the expert's comments, there are studies focusing on each subject domain separately. For this reason, this challenge has lower negative impact compared with the other challenges of BIM-LCA integration. This challenge could be eliminated as the industry develops in the future.

Chapter 6

Conclusion

This thesis identifies, classifies and prioritizes the benefits and challenges for the integrated use of the BIM-LCA in the AEC industry. In order to identify and classify the benefits and challenges of the BIM-LCA integration, literature review and semi-structured interviews were performed. In order to prioritize the benefits and challenges of the BIM-LCA integration, a two round Delphi method with ten experts was conducted. Results of this study provide twenty-two types of benefits and seven types of challenges for the integrated use of BIM and LCA in the AEC industry. The contributions of this thesis are a comprehensive identification, classification and prioritization of the integrated use of BIM and LCA. The results of this study may contribute to extend utilization of BIM-LCA integration in the AEC industry.

According to the results of the study, "integration in decision making process" is ranked as one of the most important benefit of the BIM-LCA integration. In order to make progress in the design phase of the projects and to make the necessary moves during the project delivery process, the use of this integration should be expanded. Results show that "possibility of comparing different alternatives" is the other important benefit of BIM-LCA integration. Considering the experts' comments, the technological developments allow the best results for the moves to be made within the projects. Hence, possibility of alternative outcomes from different solution ways is highly important. The integrated use of BIM-LCA allows users to make comparisons of alternative outcomes from different solution ways. This integrated technological instrument makes it possible to doing the right moves in the right times during construction.

The BIM and LCA integration provides quantitive performance predictions for designer which is a usefull feature in the design phase. Additionally, this integrated instrument can be used for obtaining numerical data. The BIM and LCA integration has many important features like minimizing the negative environmental impacts and contributes to the operation of the project. This environmentally oriented technological instrument plays an effective role in every stage of the project delivery process. The BIM and LCA integrated technology helps planning and programming at the beginning of the project. This integrated technological instrument enables follow-up during the project process and once the project is completed, this integration contributes to the sustainability phase. Accordingly, the integrated use of BIM and LCA allows for more systematic and programmed prevention of environmental negative impacts. The most efficient information to be obtained from this thesis is that BIM-LCA integration enables systematic and programmed operation while minimizing environmental negative effects for the AEC sector.

This research is a valuable resource for helping investors who want to learn about BIM and LCA integration for the AEC industry. This study helps the construction industry to gather information about the benefits and challenges of BIM-LCA integration and to decide whether to invest in this direction or not. The benefits of the BIM-LCA integration should be used in the most effective way and steps should be taken to eliminate the difficulties and challenges. A future direction could be conducting a case study in a project by examining the use of BIM-LCA integration within the sector and comparing with the results of the data provided in this thesis.

According to the studies, the cost of BIM and LCA is high; therefore, demand of using both technologies is low. BIM-LCA integration needs to be turned into an open source in order to be more widely used in the industry and to be easily accessible for everyone. Being open source of BIM and LCA would ensure professionals to overcome their challenge by creating new ideas from the increased amount of users. These open source technologies will be beneficial for the development of the construction sector. Expanding the use of BIM-LCA integration in the AEC industry would allow to reduce the negative environmental impact of the construction sector and lead to better management of the project process.

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Chapter 7

Appendix

Identifier	Benefit	Std. Dev.	rwg	Agr. Level	Sign. Level
B1	Reducing the environmental expenditure in the early stages of design	0,474	0,77	extremely important	moderate agreement
B2	Integration in decision making process	0,436	0,69	extremely important	moderate agreement
B3	Collaborative work between stakeholders	0,787	0,6	very important	moderate agreement
B4	Possibility of comparing different alternatives	0,626	0,51	extremely important	weak agreement
B5	High potential for assessing decision making process for early stages	0,436	0,69	extremely important	weak agreement
B6	Improving environmental performance	0,655	0,7	very important	moderate agreement
B7	Detailed energy analysis	0,996	0,49	very important	weak agreement
B8	Efficient mechanism for operational carbon emission analyses.	1,044	0,35	important	weak agreement

Identifier	Benefit	Std. Dev.	rwg	Agr. Level	Sign. Level
B9	Observing carbon emission while transportation of materials.	1,224	0,31	important	weak agreement
B10	Instant feedback about LCA performance for structures	0,664	0,55	very important	moderate agreement
B11	Reduction of carbon emission in structure process	1,006	0,46	very important	weak agreement
B12	Scientific assessment environmentally while construction process	0,778	0,69	very important	moderate agreement
B13	Quantitative performance predictions for LCA tools	0,626	0,65	very important	moderate agreement
B14	Conducting daylight analysis	1,319	0,53	very important	moderate agreement
B15	Investigating the water harvesting potential	1,063	0,49	important	weak agreement
B16	BIM-based sustainability softwares provide very quick results	0,749	0,73	importan	strong agreement
B17	Decrease of the total energy consumption	1,063	0,42	very important	weak agreement
B18	Decrease of the total waste after demolition	0,901	0,61	important	moderate agreement
B19	Less emitting materials (paints etc.)	0,863	0,66	important	moderate agreement
B20	Water use reduction	0,939	0,6	important	moderate agreement
B21	Use of more sustainable materials in building production and renovation	0,797	0,62	very important	moderate agreement
B22	Decreases the global warming potential	0,835	0,55	very important	moderate agreement

Table 7.1: Delphi Survey Round 1 Results for Benefits of BIM and LCA Integration(standart deviation, agreemnet levels and significance levels has shown).

1	What are the benefits of LCA-BIM integration for the AEC industry?
2	What are the challenges of LCA-BIM integration for the AEC industry?
3	What kind of mitigation can be utilized to overcome the challenges of BIM-LCA integration?
4	How can professionals make the BIM-LCA integration more efficient?
5	What kind of technological instruments can be utilized for the BIM-LCA integration?
6	How can the use of BIM-LCA integration be promoted in the AEC industry?
7	Which softwares and/or tools do you suggest for decreasing problems encountered while converting data obtained from LCA to BIM?
8	Do you have any other suggestions and/or feedback you would like to share about this subject domain.

Table 7.2: Semi-Structured Interview Questions.