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Life cycle environmental impact assessment to manage and optimize construction waste using Building Information Modeling (BIM)

Farzad Jalaei[a], Milad Zoghi[b] and Afshin Khoshand[b]

[a]Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Canada; [b]Department of Civil Engineering, University of Khajeh Nasir Toosi, Tehran, Iran

ABSTRACT

The construction industry has become more interested in moving towards implementing an innovative method to reduce wastes and Environmental Impacts (EIs) during the construction stage. Tools and methods represented in different frameworks to estimate construction wastes are limited to the end of life stage of building projects. A common method employed for this quantification is Life Cycle Assessment (LCA), which is globally recognized as one of the most complete methods for the environmental impact assessment of buildings. Building Information Modeling (BIM) would be an ideal platform to integrate LCA to assist in this process. However, BIM and LCA tools are currently not fully interoperable.

This research aims to represent a methodology to quantify total waste produced in the building's lifecycle. The main reasons for producing waste are examined profoundly and some solutions leading to waste reduction are proposed. Additionally, the environmental impact of the materials converted to waste is evaluated in an integrated environment by developing an add-in inside BIM tool, which calculates waste produced in each step of buildings' lifespan to be used by LCA tool. An application of an actual building project will be presented in order to illustrate the usefulness and capabilities of the developed approaches.

KEYWORDS

Building Information Modeling; Construction waste; life cycle assessment; demolition and deconstruction; Environmental Impacts (EIs)

1. Introduction

Cities are generally facing serious environmental problems mainly caused by multiple polluting industries. The construction industry is known as one of the main sources of environmental pollution in the cities. This industry depends on the extraction of raw materials. Most of the adverse EIs caused by construction industry can be attributed to the wastes from Construction and Demolition (C&D) processes (Bakshan et al., 2015; Wang et al., 2014). The C&D waste is a general term referring to any materials, which are produced as waste through different construction activities (Pacheco-Torgal, 2013). It should be noted that the most generated C&D wastes are considered as inert materials, which may not pose a threat similar to hazardous, municipal and solid wastes (Wang et al., 2004), but C&D waste could have a significant impact on the environment, including incremental greenhouse gas emissions and energy consumption, resource depletion, land deterioration and also environmental pollution (Mah et. al., 2016).

It is worth noting that the C&D waste generation not only can cause environmental problems, but also imposes extra cost for management. As presented in Table 1, generation of each ton of C&D waste forces a considerable variable cost (in addition to the constant cost) to the total cost of C&D waste management (Ibrahim, 2016).

The production of building materials creates some EIs and dissipate a large amount of energy, which are intensified through the demolition process at the end of building's life. Recently, an awareness regarding the detrimental impacts of building waste on the environment has been escalated. In most European countries, it is economically feasible to recycle up to 80-90% of the total amount of C&D waste (Lauritzen, 1998). Typically, the C&D waste comprises wood products, asphalt, walls, and prefabricated plaster products (masonry materials), concrete, brick, mosaic, tile, ceramic, cobblestone, and considerable amounts of some mixtures including metals, plastics, soil, roof cladding, insulation, paper, and plasterboard (Esin et al.,2007). The architecture, engineering and construction (AEC) industry has been witnessing an increasing demand in Building Information Modeling (BIM) used in parallel with the continuous momentum of the sustainable building movement in the last decade or so. The BIM

CONTACT Farzad Jalaei f_jalae@encs.concordia.ca

impact on design practice is significant as it introduces new processes and ways of delivering designs and construction and facilities management services. According to Kubba (2012) and Becerik-Gerber & Rice (2010), the development of a schematic model is superior to the generation of a detailed building model, allowing the designer to make a more accurate assessment of the proposed scheme, evaluate whether it meets the functional and sustainable requirements set out by the owner and increase project performance and overall quality. The introduction of BIM along with the emergence of challenging global issues like sustainability and environmental impact assessment of building requires that the design team incorporates basic performance analysis of an early design phase. Environmental performance, special quality analysis and social impact need to be incorporated into the framework by further developing the concept of virtual space and virtual building (Kam et al., 2004). The BIM helps owners visualize the spatial organization of the building and understand the sequence of construction activities and the project duration (Eastman et al., 2008). Generally, the use of BIM tools to design sustainable buildings necessitates the selection of materials and systems so that their EIs could be easily evaluated. Thus, an assessment process needs to be applied to quantify the impacts of the selected materials on the environment. The common method employed is Life Cycle Assessment (LCA) that is a tool used for evaluating environmental problems (Khasreen et al., 2009). Integrating BIM with LCA tools in the conceptual stage can help designers select components and materials that have lower EIs. This will promote sustainable development practices by recognizing the projects that implement strategies for better environmental and health performance (LEED, 2014).

Traditionally, urban solid wastes are managed in a hierarchy that looks like an inverted pyramid. At the broad top is landfill, which is a macro solution applied at the level of the city. Very little of the waste is processed or treated in any way, and indeed have a maximum impact on the environment. At the narrow bottom of the inverted pyramid is waste minimization at source. This is a micro solution to waste management, applied at the level of an individual and household, or a business/industry at the place where the waste is generated. This research aims to focus on the concept of the “minimization at source" to reduce the amount of waste generated indeed to avoid situations where waste is generated. In order to reduce C&D waste, an integrated design technique is required because a large amount of waste can be generated due to the inappropriate design and unpredictable changes in the site (Poon et al., 2004). The BIM is considered as an effective concept to reduce the amount of waste by combining 2D and 3D factors, which are effective on the building design, with exogenous factors such as geographical location and local design conditions as a database. As a result, it can provide a unified resource for the entire information of the building (Poon et al., 2001). In the next phase, the life cycle of prevented waste is investigated to analyze the environmental impacts of waste and dissipated energy. Various LCA tools (i.e. ENVIST©, Sima pro©, ATHENA©, etc.) have been evaluated; eventually “ATHENA© Impact Estimator for Building” was selected as it has a powerful and complicated database that is prevalently used in North America and that it can evaluate all assemblies of a building based on the international LCA methodology, allowing users to modify the design, far-reaching access, supplanting materials and reporting various comparable figures and tables of EIs as the main merits of LCA tool (Jalaei, 2015).

The authors elected to use Athena Impact Estimator© for Buildings because it has the Life Cycle Inventory (LCI) dataset of the North American construction industry and because it is designed to evaluate the whole building and its assemblies based on the internationally recognized life cycle assessment (LCA) methodology. When using Athena, the focus is on analyzing the embodied energy of the architectural, structural and facility systems that are used in the 3D conceptual design. This is an important step because LCA analysis outlines how the EIs of all products should be documented and communicated to the owner. Another reason of using Athena Impact Estimator is that it reports results for the environmental impact measures consistent with the US EPA TRACI methodology including global warming potential, acidification potential, human health particulate, ozone depletion potential, smog potential, and eutrophication potential, which is commonly used in the north America while the other tools are basically use various environmental impacts assessment methods that is more suitable for European countries. Athena additionally reports various resource uses such as primary energy and water, and emissions to air, water, and land. This is an important step because LCA analysis outlines how the EIs of all products should be documented and communicated to the owner. Hoff (2008) considers that ISO 14020 calls for the implementation of a standardized format for communicating product EIs, called Environmental Product Declaration (EPD). Therefore, LCA should be applied to integrated systems in a building by combining all the EPDs of every selected component in a single environmental impact assessment. The interoperability potential of this tool also makes it to be more capable to be linked with the BIM based tools. That LCA module is connected to an external database that stores the extracted quantities of materials, which is then imported into the Athena. This paper also describes a methodology of integrating LCA capabilities to support building design at all levels of development from very early conceptual model, instead of generating LCA results only when the fully detailed BIM-based model is ready and where design and material choices have been made. The broad system perspective makes LCA as a powerful tool for environmental comparison of different options for waste management of a specific product, a material, or a complex waste flow. Therefore, the LCA has been acknowledged as a tool for waste management planning and policy-making. It is now being used in various contexts, ranging from local planning to policy-making at national and international levels (Ekvall et al., 2007). In particular, the broad perspective of LCA makes it possible to take into account the significant environmental benefits that can be obtained through different waste management processes; for example, waste incineration with energy recovery declines the need for other energy sources, material from recycling processes replaces production of virgin material, biological treatment may reduce the need for production of artificial fertilizers and vehicle fuel residues from waste incineration may replace gravel at road constructions (Birgisdottir, 2004). This integrated system is going to be used to calculate and estimate the construction wastes, which come from architectural and structural design clashes with building mechanical, electrical and pipeline facilities. These results will be compared with the real waste calculation in conventional construction methods, and the environmental impacts will be represented for both methods. The successful implementation of such a methodology represents a significant advancement in the ability to attain sustainable design of a building during the early stages to evaluate its EIs. The contribution here is to use an integrated BIM-LCA interface to estimate and calculate EIs of the wastes, which are generated from design clashes and enable design team to modify design and to select optimal types of materials from early design stages of building projects.

Table 1. Average management unit cost of components of C&D waste (Ibrahim, 2016).

Material type	Flat fee ($)	Variable fee ($/ton)
Co-mingled	220.00	78.00
Wood	220.00	75.00
Cardboard	220.00	70.00
Gypsum/Drywall	220.00	89.00
Concrete/Masonry/Asphalt	350.00	0.00
Steel/Metal	0.00	−75.90

2. Literature review

The data available in different cities (Table 2) indicate that significant amount of C&D wastes is generated during construction activities in different regions of the world (varied from 18 kg capita/year to 842 kg capita/year). Furthermore, the quantity of C&D wastes can be predicted to continually increase (with the C&W generation of 16.2 million ty-1 which means 1.77 t m^2 or 3.62 kg capita/year, which is owing to the rapid sustainable urbanization (Management, 2014).

The C&D waste management is an emerging field in construction industry to reduce the negative impacts of construction activities on the environment, which is considered as one of the key factors of successful sustainable development (Lu & Yuan, 2011). Although many studies have been conducted to improve C&D waste management, there are still many limitations in this area to be resolved. One of the most important challenges here is poor design quality (Jaillon et al., 2009; Gavilan et al., 1994), inefficient material handling (Poon et al., 2004), and improper procurement and planning (Formoso et al., 2002). Inappropriate design decision-making and unexpected design changes have been shown to increase the quantity of C&D waste by 33% (Innes, 2004). Thus, these issues should be improved or

Table 2. C&D waste generation in different countries/regions (Management, 2014).

Country/Region	C&D waste generation (kg/capita.year)	References
Greece	191	Fatta et al., 2003
Kuwait	800	Kartam, Al-Mutairi, Al-Ghusain, & Al-Humoud, 2004
Thailand	18	Kofoworola & Gheewala, 2009
Portugal	400	De Melo, Goncalves, & Martins, 2011
China / Shanghai	842	Ding & Xiao, 2014)
USA / Florida	471	Cochran, Townsend, Reinhart, & Heck, 2007
Taiwan	110	Hsiao, Huang, Yu, & Wernick, 2002

eliminated for more efficient waste management. Information and communication technology (ICT), including spatial technologies, identification technologies, data acquisition, and data communication technologies, can eliminate wastes (Hannan et al., 2015). Building information modeling (BIM) is considered as one of the spatial and data communication concepts, which is commonly used in the architecture, engineering, and construction (AEC) industry and can be systematically and efficiently integrated with identification and data acquisition technologies (NIST, 2012). The BIM enhances the quality and accuracy of design and construction, thereby preventing errors, duplications, and unpredictable changes in design. These include improving and enhancing simulation and analysis, coordination and communication for collaborative working, lifecycle information assessment, and sustainable design across project lifecycle, indicating that the current use of BIM brings benefits throughout a project lifecycle (Liu et al., 2015). In addition, the BIM-based design validation, which involves clash detection and design review, could reduce the rate of design errors and rework, thereby reducing the amount of construction waste on site by 15% (Won et al., 2016). Multiple researches have been carried out on the design system based on BIM and other management methods in order to reduce waste (Hamidi et al., 2014). Won et al. (2016) developed a database for the materials originated from the building demolition through BIM. In addition, Hamidi et al. (2014) proposed waste management system after demolition using BIM. Cheng and Ma (2013) used BIM concept to estimate demolition waste and disposal charging fee in addition to arrange trucks for waste collection system. Jrade and Jalaei (2013) described a methodology emphasizing the integration of the BIM, Management Information Systems and LCA that can be used to implement sustainable design for proposed buildings at their conceptual stage all the while taking into consideration their EIs. Won et al. (2017) proposed their BIM-based approaches to efficient construction waste management and minimization, including how the limitations in C&D waste management and minimization processes and technologies can be addressed by implementing BIM in AEC projects, which should be involved, and that information should be generated and exchanged between project participants through in-depth literature review. Liu et al. (2015) represented the first attempt to develop a design decision-making framework in improving construction waste minimization performance through BIM. The potential use of BIM to drive out construction waste in building design was investigated through a questionnaire survey and follow-up interview with the top 100 architectural practices in the United Kingdom. The questionnaire results revealed that BIM was not frequently used in building design in general and for construction waste management in particular, where only 28 out of 50 responding architects had used BIM for sustainable building design. However, results showed that there is an agreement on the potential use of BIM for construction waste management during design stages, including BIM-aided coordination to reduce conflicts between disciplines, reduce rework, clash detection for error reduction, enhance communication and integration, increase the ability to quantify and test numerous design options of varying waste reduction performance and to improve the quality of knowledge for construction waste management decision making. However, there is a complete absence of investigation on the development and review of tools and methodologies that use BIM to support the construction waste management decision making during design. In spite of the appropriate results obtained from the aforementioned researches, the focus was on the management of C&D waste rather than the reduction of the main factors contributing to its creation. Such reduction requires more concentration on the identification of the chief factors (Won et al., 2016). Rajendran and Gomez (2012) claimed that wastes could be reduced or eliminated totally by concentration on waste sources. Designing-out-waste could be achieved using the BIM-based tools. Ahankoob et al. (2012) evaluated the potential BIM functionality in reducing waste associated with profound analysis of various factors of its creation and impacts. Reassessment of the design procedure has been proposed to prevent design errors, reworks, prefabricated materials and elimination of inappropriate interactions (i.e. clash detection). Won (2016) examined a method to determine the amount of construction waste, which might be generated due to design errors, within the BIM-based design. This research detected 517 errors, including illogical design, discrepancy between drawings and omissions; 129 errors (25%) might have led to rework and production of building waste. In the two assessed buildings, the amount of waste was reduced using BIM up to 15.2% and 4.3%, respectively.

Building maintenance is considered as one of the main facets of facility management (Barrett and Baldry, 2009) and it can be used for construction industry simultaneously (Ali et al., 2006). However, there is insufficient attention in this area due to the non-core function of facility management on provider service (Waheed and Fernie, 2009). Building maintenance is typically considered over quite a long period. The residents of buildings need to seek after the providers' companies to maintain major components constantly (Nummelin et al., 2011). During the operational stage, functions like heating, cooling, lighting and water use, as well as the introduction of new products such as paints, stains, floor coverings and other interior finishes are required to be taken into account. We should also consider the fact that a building may be remodeled or reconfigured several times over its life (a form of reuse), with changes to interior partitions and possibly the addition of new products or systems. Regarding the maintenance, some parts of a building would be altered (i.e. by painting), but other parts may not be seen or touched until the building is demolished. The maintenance phase included all the life-cycle elements needed during the maintenance stage. These include the use of building materials, construction activities, and waste management of discarded building materials (Ragheb, 2011). Large quantities of solid waste is generated during maintenance and refurbishments, and large quantities of natural resources are again consumed for new materials as well and thereby all the prior stages to maintenance are repeated creating even more impacts on the environment (Ngwepe, 2015)

The BIM capabilities help to share both information and knowledge-based techniques (case-based reasoning) to provide benefits to users and stakeholders within this stage (Motawa and Almarshad, 2013). The BIM-based deconstruction leads to effective cooperation between stockholders and provides clear access to entire information, controls, and observation of construction levels (Grilo and Jardim-Goncalves, 2010). Deconstruction means separating completely or partially the building components simplifying reuse and recycling of materials (British Land, 2010). In the design for deconstruction method, after the end of each building's lifespan, the minimum amount of waste is expected to be produced. Typically, studies have been conducted in this area emphasizing waste's cost estimation (Yuan et al, 2011) and the amount of waste in the demolition stage (Masudi et al., 2012). However, only a few studies focused on reducing the waste generation at the early design stage. Given the fact that the greatest amount of building waste is produced while the building lifespan is ended (DEFRA, 2012), it is essential to plan for the whole building lifespan. Olugbenga investigated the details of BIM development according to the building deconstruction assessment system (DAS-BIM) in order to represent a benchmark for building deconstruction at the design stage (Akinade et al., 2015). According to warszawski (1999), there are various design rules for enhancing deconstruction, which has to be followed. These approaches help to increase the building flexibility and to separate building components. The most remarkable points are as follows: implementation of materials with high durability (Tingley and Davison, 2012), the potential of reusing materials (Guy and Ciarimboli, 2008), utilizing bolts in joints in lieu of welding (Chini and Balachandran, 2002), avoiding toxic materials (Tingley and Davison, 2012), and using prefabricated materials (Jaillon et al. 2009). Furthermore, Guy et al. (2008) stated that the small number of materials and joint locations have more potential for deconstruction.

Based on California Integrated Waste Management Board (CIWMB, 2000), construction industry consists of approximately 40-50% of greenhouse gas generation in the world, which is the main factor in acidic precipitations. Studies conducted in Green building council of Australia (2006) also show that buildings participate in the emission of CO_2 up to 40%. A cogent choice of materials with less environmental impacts could be a good asset for a perfect building design before starting the construction phase (Scheuer et al., 2003). Carbon emission in the building is normally related to the phases before construction and operation period. Operating carbon will be emitted in the operation levels when energy is consumed by heaters, coolers, chandeliers, and operating people in the site. The amount of the operating carbon varies based on different geographical region and the type of activities in the building. Building embodied carbon (energy) and its associated materials are represented as the amount of consumed energy along with construction processes such as raw material extraction, manufacturing of building components and transportation. Sometimes, emitted carbon during disposal phase is categorized in embodied carbon as well (OEB, 2009).

In this research, the benefits of LCA studies from early design stage are proposed to solve the issues causing C&D waste generation (i.e. poor design management, double material handling, poor participation in C&D waste management and etc.). The integrated BIM-LCA system would assist project team to predict and estimate C&D wastes as well as to analyze the EIs at the conceptual stage of building projects. Impact Estimator for Buildings is used in order to evaluate materials' EIs by measuring consumed energy for transportation from production site to the material distribution site and construction. Moreover, we investigated the amount of pollution emitted to the water, earth, and atmosphere caused by in-situ activities.

3. Methodology and development of the integrated model

The proposed model simplifies the process of buildings waste calculation and evaluates their environmental impacts. The methodology automates the integration process by customizing and using the Application Programming Interface (API) of BIM tool to enable users to connect their design with different modules instantly from BIM tool.

In order to simplify the following sections, the procedure is categorized in five phases. As shown in Figure 1, a comprehensive material's database, which is going to be collaborated with LCA tool, is designed in the first step. The designed BIM-based models (Architectural, Structural and Mechanical) are merged together in BIM environment in the second phase. Programming the plug-in capable of sorting data and quantifying waste in three phases of the building's lifecycle is the third phase. Multifarious causes of waste production are analyzed profoundly and validated by implementing the developed model on a case project in the fourth phase. The environmental impacts diffused from calculated waste are compared to what had been dissipated in conventional method in real constructed building in the last phase. Each phase is elaborated as follows:

Phase 1) Loucopoulos (1992) states that a consistent information system depends on the integration between databases, programming languages, and software engineering, and that its life cycle incorporates the interrelated technologies of conceptual modeling and database design. The design and development of this database is accomplished in two steps starting with the conceptual modeling and ending with the physical implementation. As the term BIM shows, data plays an important role in this project. Thus, BIM-based design needs a comprehensive database, which encompasses all materials' details. Hence, the materials used in each design should be identified physically and practically (Jalaei, 2014). In this regard,

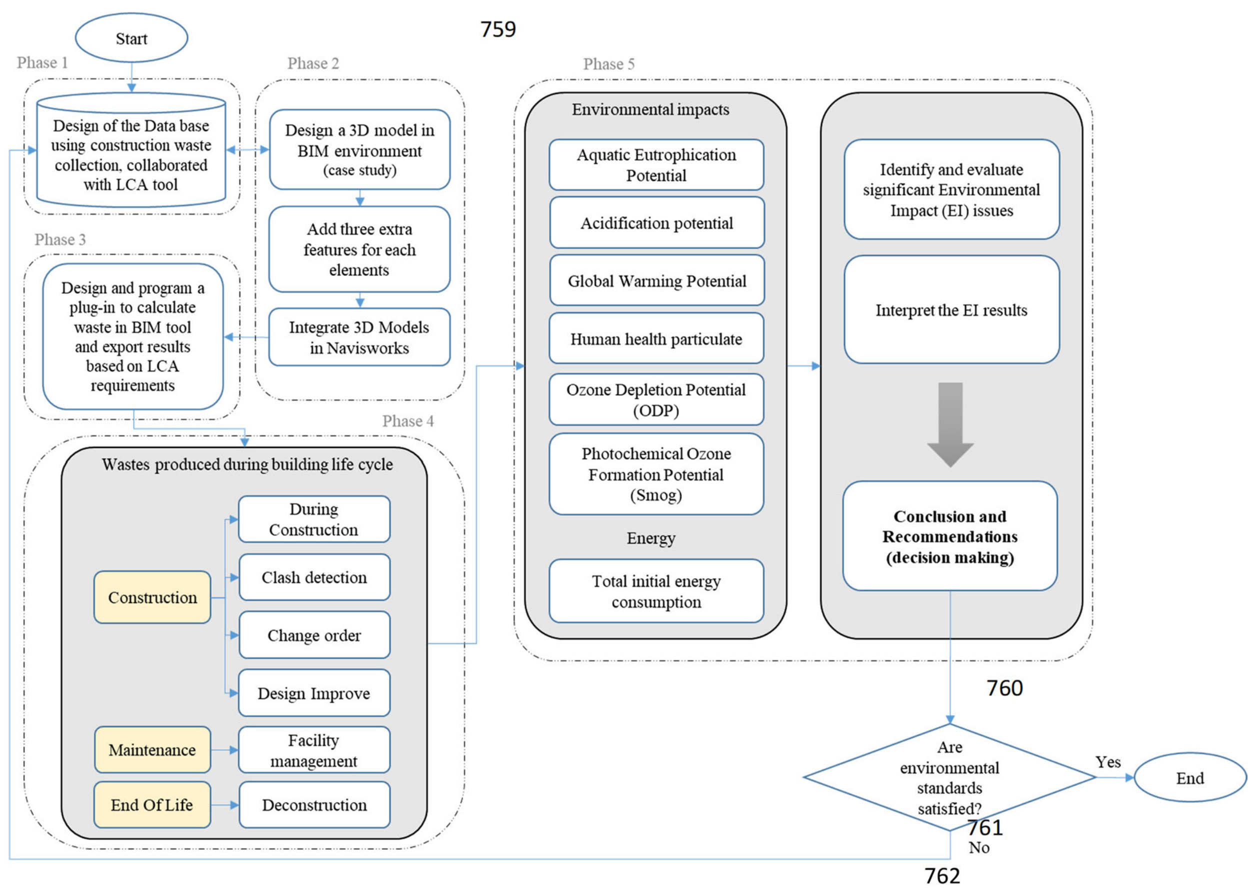

Figure 1. Different phases of the proposed integrated model.

Athena© is used as supplementary LCA tool, a database should be designed to meet all needs. Each row of this database includes some factors and labels that are assigned as an identifier in order to call the expected amounts. Such factors are used for quantifying the construction waste that will be explicated in the next phases.

Phase 2) focuses on customizing BIM tool to fit the modularity requirements of the model. The first step is to design and implement a 3D module and their associated keynotes for components commonly used in building projects. The module is linked to the database developed in Phase 1. The design should be accomplished in the BIM tool using Design for Deconstruction (DfD) approach, which is proposed in the literature review. The facility (Mechanical), structural, and architectural maps are designed separately by relevant engineers in the BIM tools (i.e. TEKLA© and REVIT©).

As shown in Figure 2, in order to achieve the objectives of the DfD approach, three features are assigned to each element, which have to be entered by the designer. The first quantity is related to the type of material. The designer needs to use the assemblies that their associated material types are available or similar to what existing in the LCA tool database. The next feature is related to material contribution, which determines the type of element usage. The third characteristic is associated with the lifespan of each element. Typically, designers are aware of the quality of the materials required for using in the building project. After locating each design in its original environment separately, they have been layered in the BIM tool (Navisworks©) as a combined model.

Phase 3) includes a design and development of an interface that is used as a BIM plug-in to connect the BIM tool with the LCA tool. A table with 4 columns is required to prepare the input data to be entered in LCA tool. The first column shows material contribution related to the function of each building element. First, all building elements, which have to be measured, are required to be customized under these categories (i.e. walls, roof, floor, beam or column, foundation and project extra materials). Every LCA tool such as Athena© Impact Estimator, which is used in this research, has published a database for all available materials including many types of the most prevalent building materials in the world (Athena, 2014).

The measurement unit of elements is one of the considerable points in the input data for Athena©

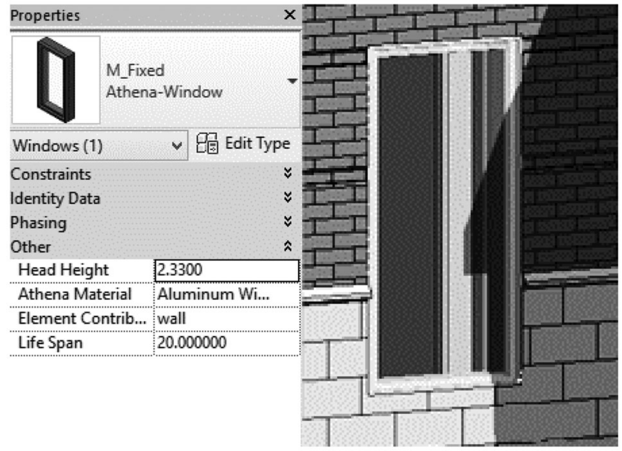

Figure 2. Assigning three new features in the Revit.

tool. Generally, it comprises five units of measurement including Kg, ton, m^2, m^3, block, and liter. Assuming that a liter is equivalent to $3m^2$ in the building's painting, the aforementioned quantities can be calculated. Additionally, the area of the wall is divided into each block's area; thereby computing the number of blocks in walls is taken into consideration. One of the most challenging parts of this phase is to arrange output data from the BIM tool (Navisworks©) and to prepare it to be entered into LCA tool (Athena©).

The main issue regarding the use of Navisworks© and Athena© together is data mining through these tables. In Athena©, depending on the type of material, the type of data could be different. Therefore, the produced waste factor for each element is different based on the type of material. This quantity should be read from Athena©'s database. Additionally, lifespan for each element in the maintenance step is required to be known as well. Also, due to the presence of various teams in the process, numerous mistakes are probable to occur. In this regard, in order to simplify the work and save time and cost and to eliminate errors, a plug-in is developed to be attached as an add-in inside Navisworks© tool, in which all the aforementioned processes could be done automatically.

Figure 3 shows the process of calculations and building data analysis. In the following section, the process of calculating the amount of waste in the various stages of life-cycle is explained.

Merging various models in Navisworks©, the user can figure out the amount of waste in each building' settlement produced at building's life cycle. These data are thoroughly arranged in four columns. It should be noted that the element unit is proportional to the unit that should be entered into Athena©.

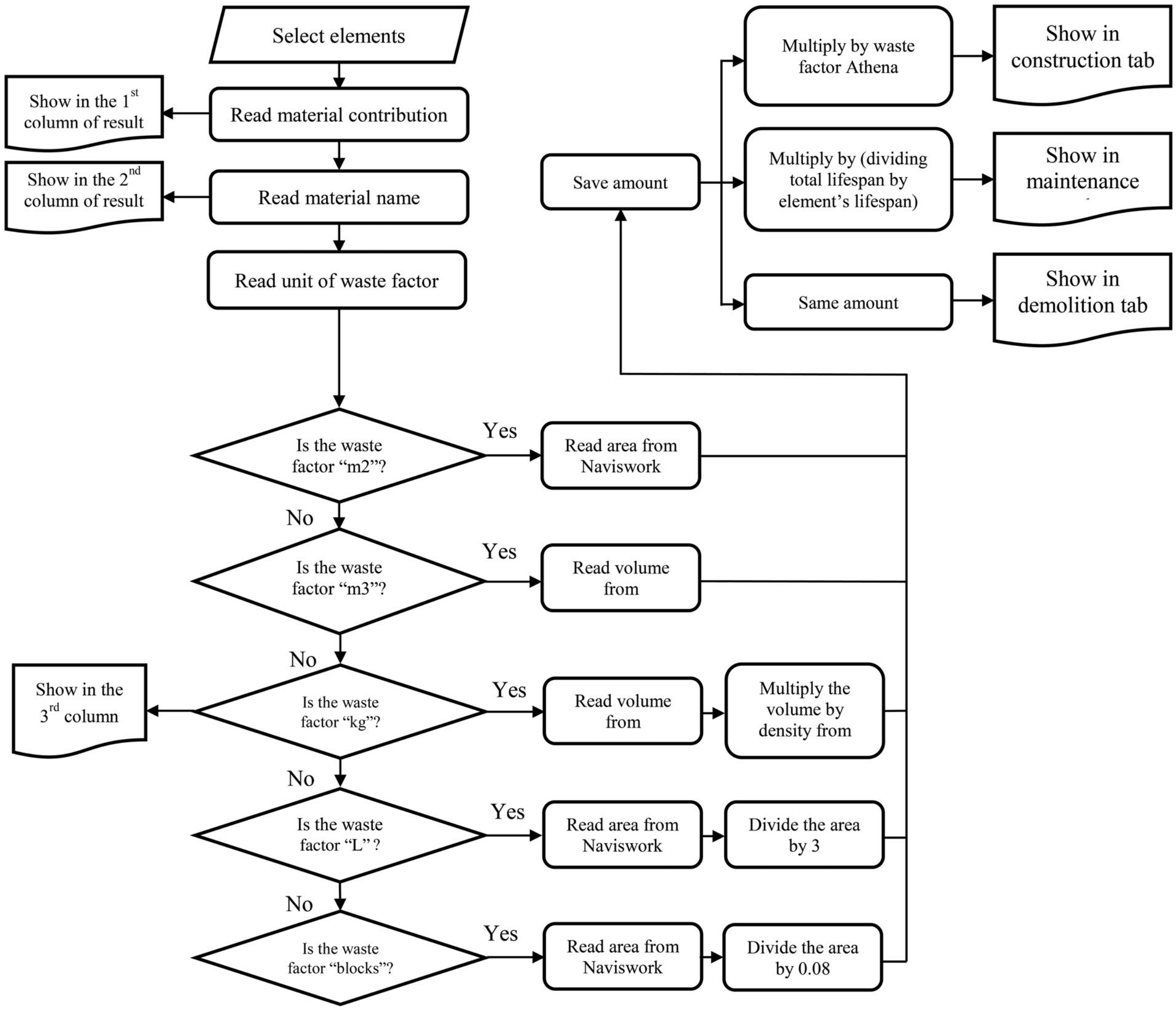

Figure 3. The framework of C&D waste calculation in the developed plugin.

By running the developed plug-in shown in Figure 4, a window asking user for the lifespan of the building shows the program with a window comprising 4 tabs in Figure 5. The first three tabs represent building waste in three phases of building's life cycle. This table exhibits only the elements selected by the user before running the plug-in. To do so, building lifespan is assessed in three phases: construction, maintenance, and demolition or deconstruction. Each phase compares the wastes produced by two methods of design and construction via conventional (non-BIM) and BIM manner. Then, the measured wastes are categorized in different groups in order to be prepared as an input for Athena©, proportional to material type and its measured unit.

Phase 4) focuses on the calculation of the waste production during different stages of the building lifecycle. Various papers investigated the role of BIM in waste reduction and suggested different solutions. However, few researches have been conducted until now on the calculation of this quantity comprehensively. According to Won (2016), building wastes are produced due to various causes, some of which are possibly alleviated by engineers or contractors and some requires innovative methods for distinguishing. In this research, by neglecting some human errors probable happened by labor, the building life cycle was categorized into three phases: a) construction b) maintenance c) demolition (or deconstruction) as illustrated in Figure 1.

Phase 5) consists of running the LCA module and its associated tool (ATHENA Impact Estimator©). This user-friendly tool provides quick results in the form of tables and graphs. The Impact Estimator allows users to change the design, substitute materials, and make side–by–side comparisons. It also lets users compare similar projects with different floor areas on a unit floor area basis. After entering all the necessary information, Impact Estimator provides series of reports in terms of: 1) Global warming potential, 2)

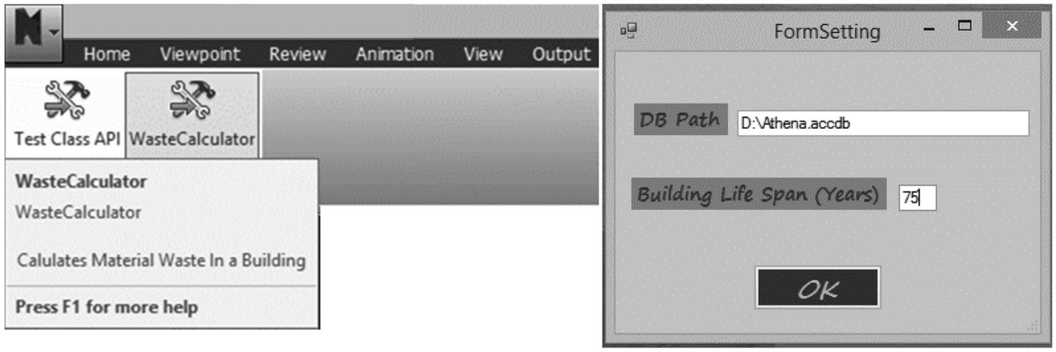

Figure 4. The snapshot of the developed plug-in front-end interface.

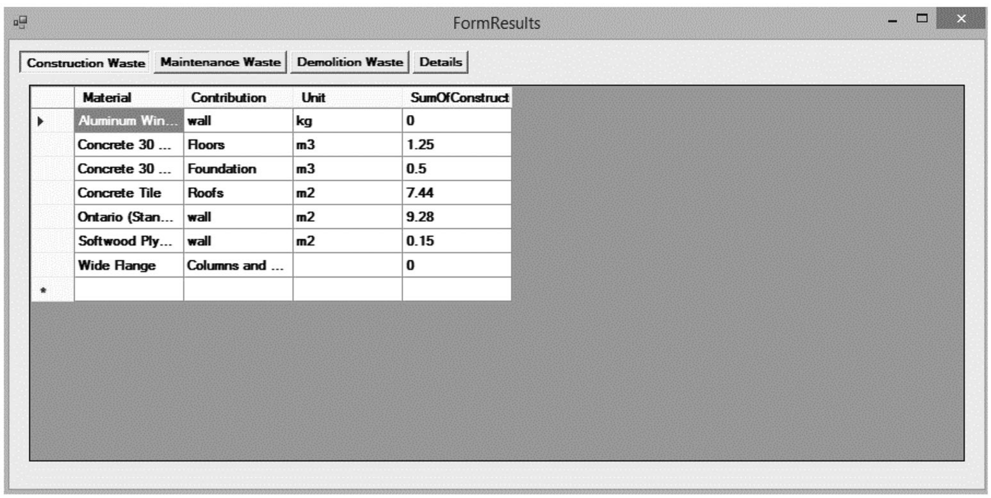

Figure 5. The tab of construction waste.

Acidification, 3) HH Particulate, 4) Eutrophication Potential, 5) Ozone depletion potential and 6) Smog potential, which are the focus of this case example. By identifying and evaluating the significant environmental impacts taken from Athena© and interpreting the results, it could be used as a decision-making tool to recommend optimum types of materials as well as an efficient design.

4. Model implementation and validation

To this end, the developed plug-in is applied in a case example to calculate the amount of waste, which is prevented within the use of BIM. A 12-story commercial building with an area of 11,850 m2 with a clinic occupation in the city of Montreal is studied as a case project in this research. In this project, the design and construction phases have been conducted by the conventional method initially. After redesigning based on BIM accompanied by some rules of DfD approach, some design principles were changed.

4.1. Waste in construction phase

4.1.1. Waste produced during construction

Amounts of materials are likely to be wasted during the construction phase. Numerous tables and waste factors such as Larsen, pp-o and etc. are introduced to calculate such kind of waste. In this research, the coefficients represented by Athena© are utilized, which can have different quantities based on the type of materials and their function. The BIM provides the opportunity to prevent waste production by ordering pre-fabricated components with the aid of 3D visualization before starting the physical process in buildings. In this project, by changing materials and ordering conventional substances, which is determined by architectures through converting them to prefabricated materials, the waste of such materials would be prevented. These changes can be seen in Table 3.

4.1.2. Clash detection

Since facility (Mechanical, Electrical and Pipelines), structural, and architectural designs are drafted and

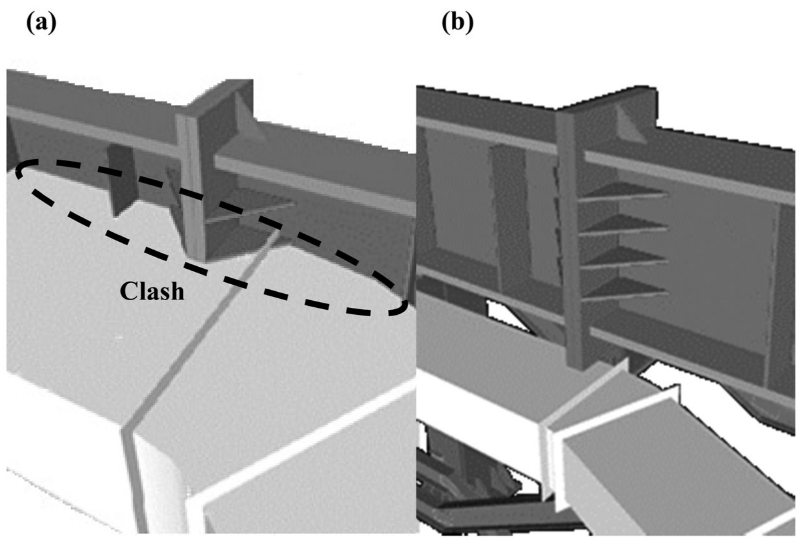

Figure 6. Duct and beam confliction; (a) Before clash removal; (b) After clash removal by changing location and size of duct.

Table 3. C&D waste qualification in construction phase.

Element contribution	Material	Waste factor	Amount	Unit
Wall	Water based latex paint	0.02	4.93	L
Project extra materials	Water based latex paint	0.02	15.87	L
Wall	Water based latex paint	0.02	150.68	L
Roofs	Water based latex paint	0.02	10.78	L
Wall	Natural stone	0.05	8.10	m^2
Wall	Water based latex paint	0.02	0.03	L
Floors	Concrete benchmark (2500 psi)	0.05	5.72	m^3
Floors	Natural stone	0.05	36.06	m^2
Project extra materials	Hollow structural steel	0.01	8235.00	kg
Foundation	Rebar, rod, and light sections	0.01	594.88	kg
Foundation	Concrete Benchmark (3000 psi)	0.05	86.58	m3
Wall	Split-faced concrete block	0.05	14000.20	Blocks
Wall	Glass based shingles (20 yr)	0.05	42.71	m^2
Roofs	Gypsum fiber board (1/2")	0.1	541.32	m^2
Roofs	Stucco over metal mesh	0.1	67.17	m^2
Roofs	Regular gypsum board (1/2")	0.02	57.35	m^2
Roofs	Mineral surface roll	0.05	6.38	m^2
Floor	Galvanized decking	0.01	107793.78	kg
Wall	Softwood plywood	0.05	5.50	m^2
Wall	Clay tile	0.07	141.99	m^2
Wall	Double glazed hard coated air	0.05	67.03	m^2
Wall	Glass based shingles (30 yr)	0.05	38.11	m^2
Wall	Natural stone	0.05	89.74	m^2
Wall	Ontario (standard) brick	0.05	174.17	m^2
Project extra materials	Galvanized sheets	0.01	83.62	kg
Project extra materials	wire rod	0.01	4.85	kg
Project extra materials	Galvanized sheets	0.01	9082.85	kg
Wall	Regular gypsum board (1/2")	0.02	10.80	m^2
Roofs	Organic felt (#15)	0.14	30.66	m^2
Project extra material	Galvanized sheet	0.01	887.67	kg
Project extra material	Steel tubing	0.01	48.90	kg
Columns and beams	Wide flange sections	0.01	14435.72	kg

developed by separate groups of the project team, some clashes arise in the final model. Some of these clashes could be resolved by figuring out the design contradictory in various disciplines (i.e. architecture, structure and facility). The remaining clashes could not be perceptible at the design stage and would be remained until the middle towards the end of the construction stage to be determined. These clashes could cause the deterioration of the element as well as rework. Solving such inconveniences is considered as one of the most advantages of BIM in order to save time, cost, and material wastes (Tchobanoglous et al., 1993). After analyzing the building in Autodesk Naviswork©, 227 clashes were identified. By grouping elements, which are involved in several clashes, they were deducted to 153 ones. Then, by solving negligible errors, it became clear that all errors are totally solvable by redesigning 21 elements.

Won (2016) represented diverse categorization of clashes, which are distinguishable by human monitoring without necessity to the BIM. Therefore, after evaluating the process with contractors and engineers, it is concluded that 48% of initial clashes are simply solvable by human vision; and solving the remaining clashes necessitate to be reported to the corresponding designer. It is indistinguishable without utilization of the BIM. Table 4 lists the elements leading to demolish for modification.

4.1.3. Change order

The building wastes are partially produced within the project due to the lack of collaboration between project team and arbitrary changes, which is applied in the project design. The change orders occurred in these types of design clashes lead to waste production of materials at the construction stage, which greatly affects the cost, time and environmental impacts in the project. The BIM can avoid such immediate changes by merging all sources together and visualizing building before physical construction and procurement (Tchobanoglous et al., 1993). According to the documents of a case project, some areas have changed after the construction phase and the contractor had to demolish some constructed elements despite what was represented in the design. Table 5 also illustrates the quantification of waste resulted from the change order.

4.1.4. Design optimization

Sustainable design with the waste reduction is the chief purpose of the DfD approach. As it is represented in the DfD definition, the design can be in a way that deconstruction instead of demolition would be possible at the end of building's life cycle. In this project, the building is a steel frame and all joints are converted from welding to bolts. Therefore, it can be extracted after building's end of life; even some in-cast elements could be replaced with prefabricated materials to eliminate all toxic substances.

4.2. Maintenance's waste

In this research, the amount of wastes produced in the maintenance phase is calculated approximately. The wastes from maintenance have a diverse spectrum. Therefore, based on previous researches, some essential repairs due to external factors are neglected and such maintenance is considered merely by assuming the damage, which is caused by elements' depreciation. These wastes have less lifespan than the entire building (ALCBC, 2003). In this paper, the building's lifespan is presumed as 75 years and the lifespan of 7 to 20 years for other building's elements such as facility system, windows, doors, and other secondary elements.

Table 4. C&D waste quantification through clash detection.

Element contribution	Material	Amount	Unit
Project extra material	Galvanized sheet	25.63	kg
Project extra material	Galvanized sheet	1659.73	kg
Project extra material	Galvanized sheet	8.96	kg
Project extra material	Galvanized sheet	24.63	kg
Project extra material	Galvanized sheet	3.10	kg
Project extra material	Galvanized sheet	15.56	kg
Project extra material	Galvanized sheet	3.037	kg
Project extra material	Galvanized sheet	410.99	kg

4.3. Building's end of life waste

In the building's end of life, there are two possibilities for the components: they can be demolished and disposed in the form of building wastes; the second option is that they can be deconstructed (Akinade et al., 2015). As mentioned in the last section, to apply the right deconstruction policy at the end of the project life, a unified system is always required, which is accessible within the BIM. As an integrated product delivery, the BIM can provide an effective collaboration between stockholders, providing a clear accessibility to a controlled collaboration, sharing information and monitoring all phases of the project (Akinade et al., 2015). After deconstruction of the building, the recycling and reusing processes are accomplished and the retained amount in the final stage could be carried to the landfill as a waste.

The figures of various steps illustrating building construction with and without using BIM are compared to validate the results from the developed model. Based on the list of assembly groups, results are shown in six categories (i.e. foundation, roof, floor, wall, beams & columns and extra materials). Figures 7 and 8 represent six environmental emissions and three types of consumed energy in maintenance and construction phases, respectively.

The potential of becoming acidic is known as acidification for the air or water, which is calculated based on its H + equivalence effect on the material (Athena, 2014). As illustrated in Figure 8, the degree of sulfur dioxide (SO_2) effect decreases up to 49% in the demolition phase by implementing BIM. This quantity reaches 56% in the construction phase. Also, in the

Table 5. C&D waste quantification after change order.

Element contribution	Material	Element type	Amount	Unit
Columns and beams	Wide flange sections	IPE220	1093.16	kg
Floors	Natural stone	Floor/Ceramic	31.85	m^2
Floors	Concrete benchmark (3000 psi)	Floor	3.19	m^3
Floors	Galvanized decking	Floor metal deck	4761.22	kg
Columns and beams	Wide flange sections	PL15 × 400 (1)	828.60	kg
Columns and beams	Wide flange sections	PL15 × 400 (2)	298.72	kg
Columns and beams	Wide flange sections	PL20 × 400	2355.00	kg
Columns and beams	Wide flange sections	PL25 × 1	1786.26	kg
Walls	Concrete block/ Concrete (6")	Basic wall	1160.41	Blocks
Walls	Concrete block/ Concrete (6")	Basic wall	320.26	Blocks
Walls	Concrete block/ Concrete (6")	Basic wall	1416.86	Blocks
Walls	Concrete block/ Concrete (6")	Basic wall	412.06	Blocks
Roofs	Gypsum fiber board (1/2")	Ceiling	31.85	m^2
Walls	Concrete block/ Concrete (6")	Basic wall	1178.03	Blocks
Walls	Ontario (standard) brick	Basic wall	94.24	m^2

maintenance phase, since various building facilities are checked in their life-cycle, 62% of the SO_2 in project extra material wastes is decreased. Moreover, in the construction phase, due to the use of prefabricated materials and the facilities accessible by BIM, the portion of SO_2 is reduced up to 90% in the "floors" assembly as well as 97% in the "Roofs".

Aquatic Eutrophication Potential is the fertilization of surface water by previously scarce nutrients. The addition of a previously scarce or limited nutrient to the water body leads to the proliferation of aquatic photosynthetic plant life. This may bring assorted repercussions such as production of unpleasant smells and aquatic death. This quantity is derived from the equivalent nitrogen mass in materials (Athena, 2014). The large amount of the produced nitrogen in the building waste is associated with parts of "project extra material" group. In the demolition phase, there are 2508.7 kg of nitrogen, which decreases by material deconstruction up to 12%. This quantity rises up to 51% in the maintenance phase, which indicates that BIM is more influential in this step. Fundamental reconstruction of door and window using BIM belongs to "wall" assembly group that prevents production of nitrogen up to 34% compared to conventional methods of maintenance. However, in general, the great part of this emission is related to mechanical services, which embraces 35% of the N produced in this part of building's life-cycle. As shown in Figure 9, BIM technology can prevent Eutrophication phenomenon in construction level by 44%.

Global Warming Potential (GWP) is evaluated based on the amount of CO_2 measured by kg or ton. The method and knowledge used in measuring GWP are accepted as one of the most desirable methods of Life Cycle Impact Assessment (LCIA) in a way that the effects of other greenhouse gases (heat-trapping capability) are also considered in the form of an equivalent ratio of CO_2. Although the spread of greenhouse gases is considered to be mainly due to energy combustion, a part of it is produced in the time of processing of raw materials (Athena, 2014). The amount of produced carbon after demolition of the building, which is assessed in this paper, is approximately equal to 1.01×107 kg CO_2. The BIM can reduce it up to 56% and make it to reach 4.37×106 with the aid of "deconstruction of materials" capability. Despite the limited decrease in the wall and window's portion in the maintenance phase, BIM could decrease GWP up to 82%. Furthermore, in the "project extra material" group, the amount of CO_2 is diminished up to 63%. In the construction phase, BIM could decrease this quantity up to 50% through reducing the clashes as well as rectifying the change orders before construction. The main part is related to the ducts and facility materials, which is measured to be 75%. BIM has prevented the carbon production due to its life-cycle up to 63%.

Human health particulate comprises various measures, which have profound effects on humans' health. Environmental Protection Agency (EPA) organization has introduced the particulates (resulting from gasoil combustion) as a threatening factor for human's health. It should be noted that the particulates include the most outputs of wooden and concrete products in the building (Athena, 2014). The amount of particle pollution (PM 2.5) in this project in the demolition level is equal to 1.851×104kg, which will be reduced up to 13% when the building is deconstructed at the end of its life. The main portion of this phase is related to the building skeleton, which includes 36.9% of the whole PM 2.5 particles. Moreover, in the maintenance phase, with the BIM-based design, the amount of this impact can be prevented to be produced up to 34%. The most portions belong to "wall" and "project extra material" group with 50% and 40%, respectively. The amount of PM2.5 reduced up to 31% and 42% for each group through BIM. In the

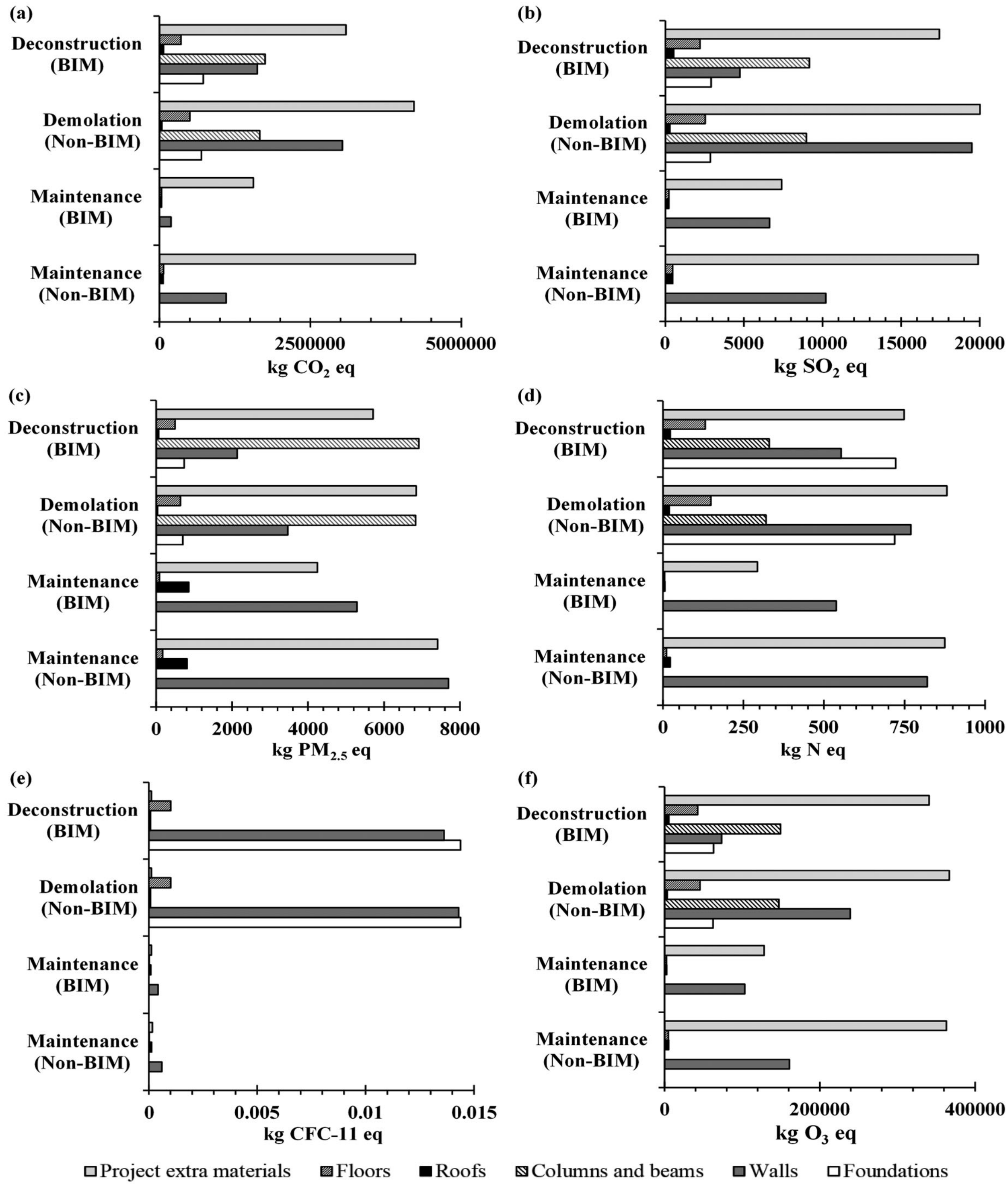

Figure 7. The comparison of environmental impact of C&D waste in case of BIM and Non-BIM modeling in demolition and maintenance phases: (a) Global warming potential; (b) Acidification; (c) HH Particulate; (d) Eutrophication Potential; (e) Ozone depletion potential; (f) Smog potential.

construction phase, 4.32×102 kg PM 2.5 is produced, which is decreased up to 2.21×102kg in the BIM-based model.

Ozone Depletion Potential (ODP) accounts for impacts related to the reduction of the protective ozone layer within the stratosphere caused by emissions of the ozone-depleting substances [CFCs, HFCs, and halons] (Athena, 2014). In this part, the amount of the produced CFC is equal to 0.00299 kg at the demolition stage, and 49.1% of it is related to the foundation. As it is clear, the considerable volume of this impact reaches the building from the foundation. Moreover, in the maintenance phase, BIM prevents CFC production up to 30%. In the construction stage, 0.00048 kg of CFC is produced, which can be prevented to be reduced up to 28.8% by decreasing waste

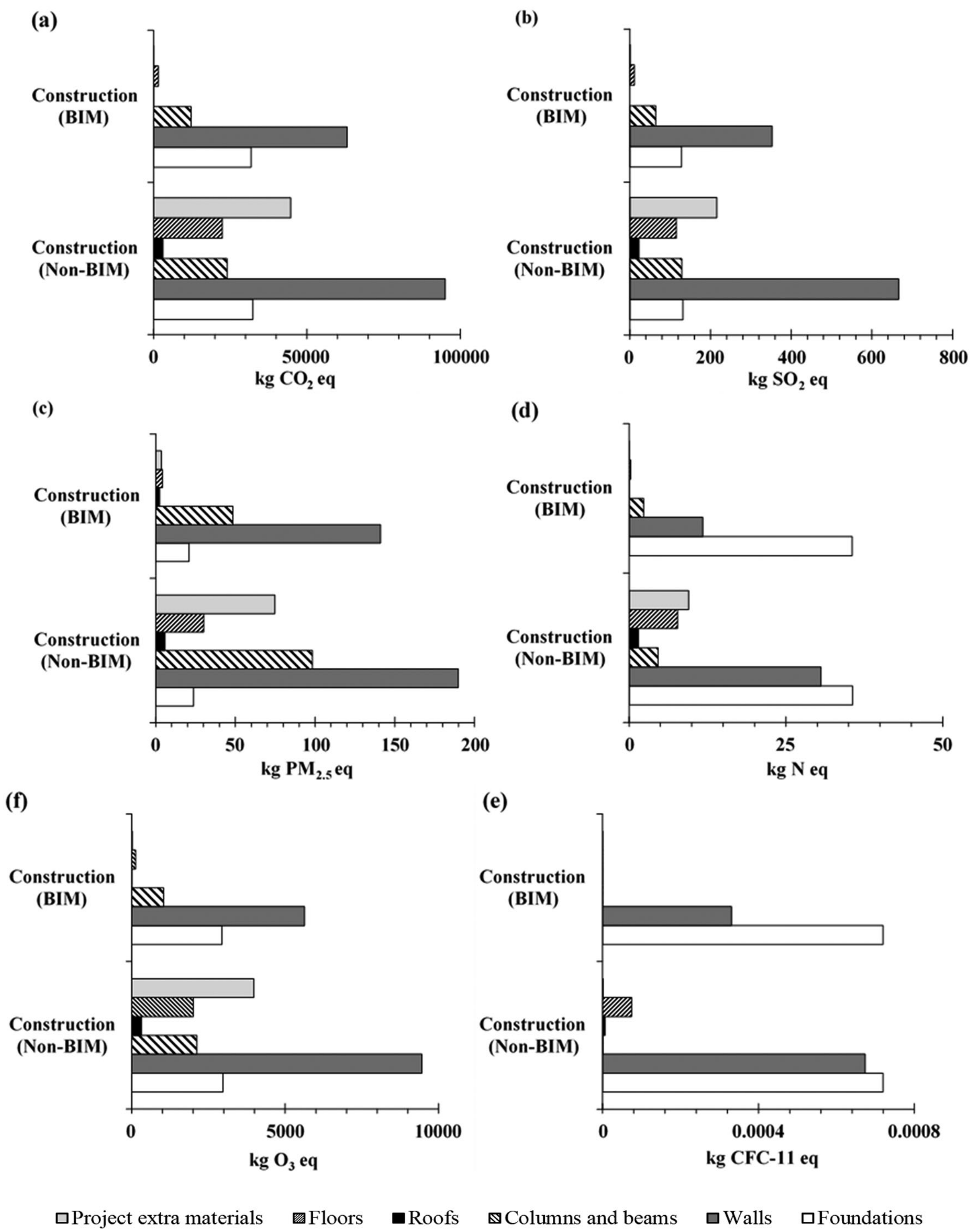

Figure 8. The comparison of environmental impact of C&D waste in case of BIM and Non-BIM modeling in construction phase: (a) Global warming potential; (b) Acidification; (c) HH Particulate; (d) Eutrophication Potential; (e) Ozone depletion potential; (f) Smog potential.

of this phase through BIM. Additionally, "foundation" and "wall" assembly groups have the most contribution to the production of this impact, which is 48.7 and 45.6, respectively.

For the Photochemical Ozone Formation Potential (Smog), in a particular climate circumstance, the air pollutants emitted from the industry or the transportation are trapped at the low level of atmosphere. In this level, photochemical ozone layer is produced in the presence of sunlight; this is an indicator of Photochemical Ozone Creation Potential (POCP). While ozone layer is not emitted directly, it is a product of interactions of Volatile Organic Compounds (VOC) and Nitrogen Oxides (NOx) emissions

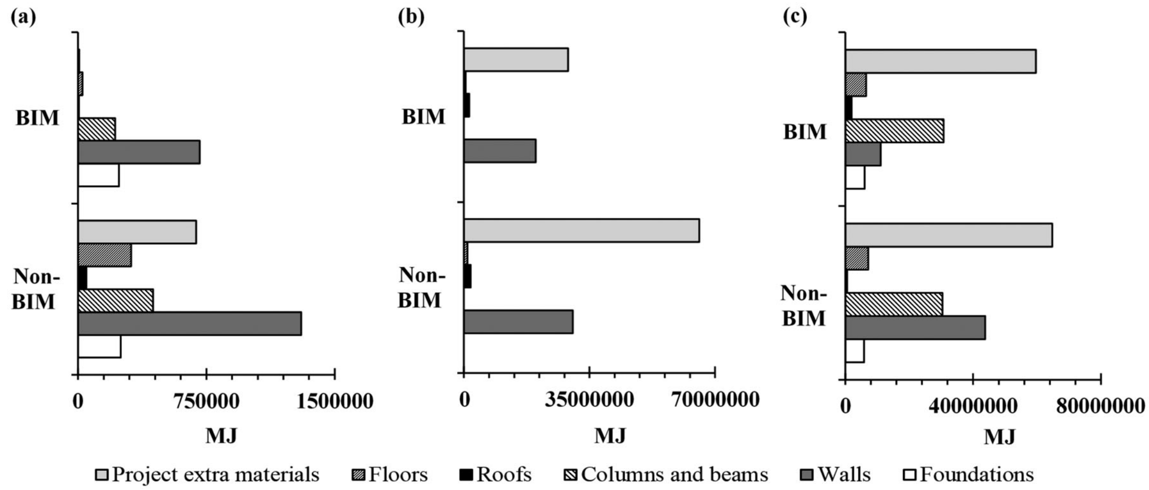

Figure 9. Comparison of total initial energy consumption in case of BIM and Non-BIM modeling in different phases: (a) construction; (b) maintenance; (c) deconstruction.

(Athena, 2014). Smog index is defined based on the mass of equivalent O3. In this project, the amount of this impact is calculated as 8.65×105 kg in the demolition phase. By using BIM, it can get 6.75×105, which indicates 21% decrease. Major impact of BIM is evidence in "wall" group that has 69% decrease. In the maintenance stage, BIM has more interaction to the extent that has reduced production of O3 up to 55.6%. The most portion of this impact is for "project extra material". In such group, smog is reduced up to 64% through BIM. In the construction phase, 2.08×104 kg of O3 is produced which has been reduced 53% by BIM. The "wall" assembly group has the most contribution to the production of such mass of O3, which is 45% of the whole in this phase. BIM has reduced it up to 40%.

In order to evaluate the total initial energy consumption, embodied initial energy comprises all energies that are consumed directly or indirectly in transportation and transformation of raw materials to applicable materials in the building, which is calculated with MJ unit (Athena, 2014). Total initial energy consumption in the life-cycle of waste due to the demolition of this project is equal to 1.53×108 MJ that can be reduced up to 23%. The most considerable impact of BIM has been on "wall" assembly group, which has led to prevent the loss of energy up to 74%. Additionally, with the BIM-based design, the total energy loss in the waste of maintenance phase is reduced up to 48%. In the construction phase, the waste of "wall" assembly group contributes to the total energy consumption up to 42%, with the amount of 1.3× 106 MJ. The total energy in the construction phase with the conventional design is 3.04×106 MJ, which is reduced up to 60% within BIM.

5. Summary and conclusions

This study investigated the workability and usefulness of Building Information Modeling (BIM) technology in the construction waste management. Although several theoretical studies and frameworks have been proposed in this field, one of the most innovative point and novelty of this research is to quantify the previous theoretical concepts practically suggested as the methods of reducing waste during building's lifespan. This is done by applying some rules of DfD approach and comparing it with the amount of waste, which is produced in the conventional building.

In this paper, several causes of waste generation in three phases of building's life cycle were analyzed profoundly and the way that BIM affects these factors was examined and quantified. A 12-story building was used as a case project. Applying BIM-based design to this building, calculating the amount of waste generation, and comparing it with the available documents of waste generated through the conventional method provide opportunities to show the impacts of using BIM in reducing the C&D wastes. By completing the aforementioned steps, all tables are categorized for assessing life cycle of waste and its environmental impact by Athena©tool. To simplify the process, waste calculator plug-in has been developed and installed as an add-in into the BIM tool. This plug-in allows users to get the categorized list of waste quantification with interoperability potential through the Athena©.

As an overview, total energy combustion of wastes in wall group is decreased up to 42.4%. This parameter gets 82.9% for "Floors" category and is equal to 67.6% for "Project Extra Material". In total initial energy combustion, 66.1% of MJ is prevented by reducing waste generation.

As is illustrated, BIM has the wide range of impacts on common pollutant in the atmosphere during the 75 years of building's lifespan. BIM could reduce 35% of ozone production, 42.5% of CFC mass, 27% of Nitrogen gas and 23% of PM2.5 particulates. BIM plays the most significant role in CO_2 reduction, which is considered as a benchmark in global warming standards. The percent reduction is calculated as 62.6% that is approximately more than half of this gas. Some results do not determine the quality and perfection of the structure. It is just an environmental scheme between two methods of structure in waste management scope. The results show that BIM could improve waste reduction in whole building's life. Furthermore, it is clear that BIM has the potential to progress from environmental perspectives similar to its development in the other fields of building technology hitherto. As this research is a progressing study in this area, it can be developed in a way to simulate the process of waste generation by some simulation tools such as Symphony and Arena especially in deconstruction phase for the further studies. Additionally, it can evolve in the life cycle cost of the recycling process.

Disclosure statement

No potential conflict of interest was reported by the authors.

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