Integration of Building Information Modeling and Economic and Environmental Impact Analysis to Support Sustainable Building Design

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Abstract: Sustainable construction is critical to the architecture-engineering-construction (AEC) industry. The consideration and selection of optimal building components is necessary in order to fulfill multiple objectives of sustainable construction, which are often conflicting. Today, information and communication technologies (ICT) such as building information modeling (BIM) are widely used in the construction industry for decision making during design and construction. However, due to the complexity of building and construction, supporting multiple-objective decision making is not trivial. Currently, BIM has limited capability to support such a process. This paper introduces Simulation of Environmental Impact of Construction (SimulEICon), which is an extension of BIM designed specifically to aid in the decision-making process during the design stage of a construction project. SimulEICon is an add-on to the Autodesk Revit Architecture software, and it uses Microsoft Access for database-related operations. In addition, the genetic algorithm (GA), NSGA-II, is used for optimization in order to find solutions that best conform to project objectives. Moreover, SimulEICon has the capability of finding optimal solutions for all components at a building level or only for specific components and visualizing the solutions in a three- or four-dimensional model to support the decision-making process. Furthermore, the results can be constrained to conform to certain limitations. A case study of a real building, the Future House USA, is used with SimulEICon to demonstrate its use and results. A demonstration of SimulEICon is shown by comparing a set of possible solutions obtained by SimulEICon to those implemented in the building; it is expected that some of the solutions from SimulEICon would match those in the building at a component level, or even at a building level. Moreover, additional solutions to those present in the building show that SimulEICon is capable of presenting a wider range of possible solutions from which the user might choose the most appropriate one for the project goals. **DOI:** **10.1061/(ASCE)ME.1943-5479.0000308.**

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Introduction

Currently, the concept of sustainability is embraced by a wide variety of industries and businesses, such as mining and minerals, tourism, wind energy, and building (Angel and Huber 1996; Azapagic 2004; Hassan 2000; Kane 1996; Russo 2003). It has been over 20 years since environmental issues became critical in those industries. It is also commonly acknowledged today that sustainable construction plays an important role in the architecture-engineering-construction (AEC) industry. Over the years, sustainability has been the focus of much research. Matar et al. (2010) defined sustainable construction as an emergent science that combines sustainable concept and construction projects. Many organizations, such as the U.S. Green Building Council (USGBS) and Building Research Establishment (BRE), developed green building rating systems in order to encourage the construction of environmentally sustainable buildings in the AEC industry and to serve as a guide for construction professionals. Adoption of the sustainable construction concept has been increasing within the AEC industry; however, there are numerous studies that identify and expose several technical and nontechnical obstacles that still hinder widespread adoption (Matar et al. 2010).

Sustainable construction brings more players, new construction methods, and advanced design and analysis into projects; it requires intercollaboration among all the involved parties to effectively communicate and share information, including making decisions on how to meet common goals. Much research dealing with the delivery of sustainable construction projects identifies integrated design as a critical process in the optimization of building systems and fulfillment of project objectives (Pluaski et al. 2006; Raphael 2011). Much research supports the concept that the most beneficial project delivery practice in sustainable construction is integrated project design (IPD), in which all construction professionals working in the project get involved in the early stages of construction. In addition, IPD can be developed to support new trends in sustainable construction (Hellmund et al. 2008).

Sustainable construction projects involve decision making related to construction methods, materials, crews, and planning, such as resource leveling and scheduling (Inyim and Zhu 2013). A particularly critical step in sustainable projects is the selection of the building's components and materials at the design stage (Flager et al. 2009), which involves the assessment of the sustainable, economic, and efficiency-related objectives of a construction project. The difficulty of the selection process is increased by the fact that project objectives are often conflicting. Furthermore, choosing specific construction materials, assemblies, or systems with different

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construction times, costs, and environmental impacts can be done in many ways. Moreover, considering these components at a building level presents the additional problem that the designer must confront the challenge of selecting the optimum combination of building components out of thousands, or even millions, of combinations (depending on project size) to meet the desired objectives. Cantoni et al. (2000) reported how significant the design phase is because there are many available and reliable options related to optimal plant design. In AEC-industry projects, the design process changes when environmentally friendly objectives are considered. This can challenge design professionals trying to find suitable multiobjective design solutions. Bunz, Henze, and Tiller (2006) conducted a survey comparing sustainable design programs and guidelines in North America, Europe, and Asia. They proposed that building designs should consider the entire life cycle of the buildings and that sustainable designs should be implemented in all phases of the life cycle. However, they stressed that most sustainable building programs and guidelines should focus on the design phase. They argued that decisions in the design phase, such as material usage and energy efficiency, are essential. Moreover, Basbagill et al. (2012) emphasizes that decisions made at the initial design stages of a project have a critical effect on its environmental impact.

Given the rapid advance of information and communication technologies (ICT), the construction industry has benefited from the development of efficient and user-friendly building process support systems (Christiansson et al. 2010). In the past several decades, ICT has become an important tool in the achievement of the sustainability concept within the AEC industry. As stated previously, the consideration and selection of optimal building components during the design phase of a building are critical for the fulfillment of the objectives, such as duration, cost, and environmental impact, that are often present in sustainable construction. ICT is a key in facilitating communication between the multiple personnel and teams involved in this process, which allows for making decisions by considering the whole project rather than only individual components, which can cause unexpected consequences (Verbeeck and Hens 2010). Building information modeling (BIM) and ICT allow for modeling, retrieving, and gathering meaningful information about a building; however, currently there is not an integrated solution for BIM that allows the optimization of the selection of components.

This paper is aimed at introducing Simulation of Environmental Impact of Construction (SimulEICon) as an integrated optimization tool with BIM. SimulEICon is designed as an add-on to Autodesk Revit Architecture, and it uses Microsoft Access for database operations. This tool has the capability of finding optimal solutions of building component combinations at the building level, or even at the specific material level, based on several objectives. In addition, the optimization process is achieved by using the genetic algorithm (GA). Currently, SimulEICon allows designers to select different design materials and products for the desired building components. This selection is currently used to generate optimal design options according to three objectives: construction time, initial construction cost, and CO_2 emissions. A demonstration of SimulEICon is performed by using a real building in a case study. Finally, the future development of SimulEICon capabilities is discussed.

Related Study

Information and Communication Technologies—Building Information Modeling

Significant studies have been conducted to support the use of ICT in sustainable construction (Maréchal et al. 2010; Guruz et al. 2012). The AEC industry uses ICT in three major organized ways: (1) information management and service, (2) communications, and (3) processing and computing. BIM is an advanced example of an ICT approach in information management and services because it allows multiple parties to work together and serves multiple objectives at the same time. Oliveira (2009) studied the potential of the BIM system used by different disciplines. From the education perspective, BIM allows for the understanding of design methods and processes. Oliveira (2009) also stated that three-dimensional (3D) simulation, such as that used in BIM, can help in the production stages of a project and result in more logical construction sequences; potential construction conflicts can be identified and addressed in the project schedule. Moreover, using BIM allows for the collaboration of information between project members and leads to faster decisions at the design stage. According to Porwal and Hewage (2013), the benefits of using BIM can be maximized by increasing the integration of project teams and members since the project's initial design stages. Gu and London (2010) stated that BIM integration faces the challenge of integrating the technical and nontechnical aspects of a project. Bryde et al. (2013) presented the notion that the potential benefits of BIM must overcome the challenges of integration and collaboration of multidisciplinary project teams. BIM facilitates the decision-making process and functions as an analytical support tool. Manning (2008) presented BIM implementation in healthcare construction and found that BIM can improve detailed information analysis and collaboration of information between disciplines. This results in improvement of the decision-making process during the project.

Information exchange between different BIM tools can be achieved using the Industry Foundation Classes (IFC) standard language, which is developed by the International Alliance for Interoperability (IAI). IFC is a modeling specification that focuses on the product and process modeling in the AEC industry; it is a common language that is widely used in AEC-related software such as Autodesk Revit Architecture and ArchiCAD. Several problems have been reported about BIM information transfer using IFC (e.g., Fies et al. 2010). Information exchange using the IFC standard is still in development and has not reached complete interoperability between various BIM tools (Porwal and Hewage 2013). Jung and Joo (2011) stated that BIM has widened the use of multidimensional virtualization of construction projects in the AEC industry, but that it still needs further development to improve its efficiency. Despite these shortcomings, BIM has emerged as a critical tool in addressing the challenges associated with sustainable construction (Bynum et al. 2013). The widespread and rapid adoption of BIM technologies in the AEC industry is evidence of this fact. BIM is also used to support sustainable aspects, including life cycle analysis (Häkkinen and Kiviniemi 2008; Wang et al. 2011). It can provide and integration life cycle information such as assembly and material data and building performance. The Royal Institute of British Architects (RIBA) generated a standard construction process used in building construction called the *RIBA work stage*. However, RIBA denied the importance of life cycle assessment (LCA) considerations. Loh et al. (2009) proposed the development of a RIBA work stage to be integrated with LCA as a RIBA subprocess focusing on environmental concepts to be implemented at the earlier stages (namely, the conceptual stage, early design stage, and detail design stage). BIM was used as a modeling tool after the trade-off between layout and materials design decisions was completed. The model in BIM can be changed during the design process based on CO_2 emissions from trade-off design determinations. For data manipulation purposes, users can export the BIM model as a green building XML schema (gbXML) file to provide the amount of CO_2 emissions. The RIBA subprocess addresses the significance of CO_2 impact, which should be considered at the design phase. Furthermore, the combinations of layout and materials can affect the project cost in the long run (Loh et al. 2009). Additional benefits of BIM in the AEC industry have been explored in many studies (e.g., Azhar et al. 2008; Azhar 2011; Eastman et al. 2011).

Multiobjective Genetic Algorithm Optimization

A sustainable building's design phase consists of the creation of a project plan that is capable of fulfilling multiple project objectives; this project planning entails a decision-making process involving multiple construction techniques, crew types, equipment, materials, and other elements. The decision-making process requires choosing appropriate methods to accomplish multiple objectives (Claudio et al. 2009). Those solutions can assist decision makers or designers in grasping the significance of the trade-off between objectives and make rational decisions. In large-scale projects, the number of possible solutions quickly increases to the point where a deterministic assessment of the optimum solution becomes impossible or impractical; in these cases, a stochastic optimization method such as the GA must be utilized. The GA is a stochastic optimization method based on the principles of Charles Darwin's theory of evolution ("survival of the fittest"); it is comprised of four main parameters: number of generations, size of population, crossover rate, and mutation rate (Elbeltagi et al. 2005). Many researchers proposed this method because it can handle large-scale problems often found in construction projects. Wang et al. (2007) mentioned that using GAs is a powerful technique for solving conflicting multiple objectives in pavement design. Jun and El-Rayes (2010) used GAs to solve a problem of multiple labor shifts in construction projects. Multiobjective GAs can overcome the hindrance of traditional resource leveling algorithms (Leu et al. 2000).

SimulEICon

SimulEICon is a software application developed to determine relationships among the three objectives and also to aid AEC professionals in selecting components during the early design phase when the objectives are considered. It integrates economic and environmental analysis and BIM as an add-on tool used with Autodesk Revit Architecture. The BIM model can help in visualizing project details and retrieving basic information on characteristics. For instance, based on the 3D model, components used in the project, such as exterior walls, slab-on-grade, and the roof, can be found, including the component types. Currently, SimulEICon is focused on three objectives: construction time, initial construction cost, and CO_2 emissions. All data is currently stored in a Microsoft Access database, including material unit cost, labor unit cost, crew types, equipment unit cost, productivity, and environmental impact. The total initial construction cost and total CO_2 emissions are aggregately calculated to the project level. The Critical Path Method (CPM) approach is used to estimate total construction time, and the GA is applied to the optimization process.

Database Schematic

The presented database schema (Fig. 1) aims to encapsulate the necessary information used during component selection and optimization via the GA. The Assembly entity is analogous to a component from the BIM model. It is made of multiple materials, each of which has a cost and R-value per unit. The environmental impact can be derived for a material based on data contained within a material summary, which has data on fossil fuel consumption, global warming potential, acidification potential, eutrophication potential, and other elements during multiple phases, including manufacturing, construction, and end of life. Global warming potential, calculated using CO_2 emissions, is currently the primary focus of environmental impact data. Crew information is also used to calculate the total Assembly cost. Data on equipment used by crew members is also stored for both cost and environmental impact calculation.

Analysis Process

The Autodesk Revit Architecture add-on uses data values retrieved from a BIM model, along with data stored in an Access database, to help users select components for use in a construction project, create a basic schedule, and finally discover several potential project solutions based on the three primary objectives: time, cost, and environmental impact. Basic information about components such as area and volume can be retrieved from a given BIM model. With this information, calculations about a particular component's cost and environmental impact can be made. When preparing to simulate a project, a user may decide to ignore certain components from the BIM model. This allows for smaller and more focused simulations (e.g., focusing on only the building envelope). Components that are not represented in the BIM model may also be added to the

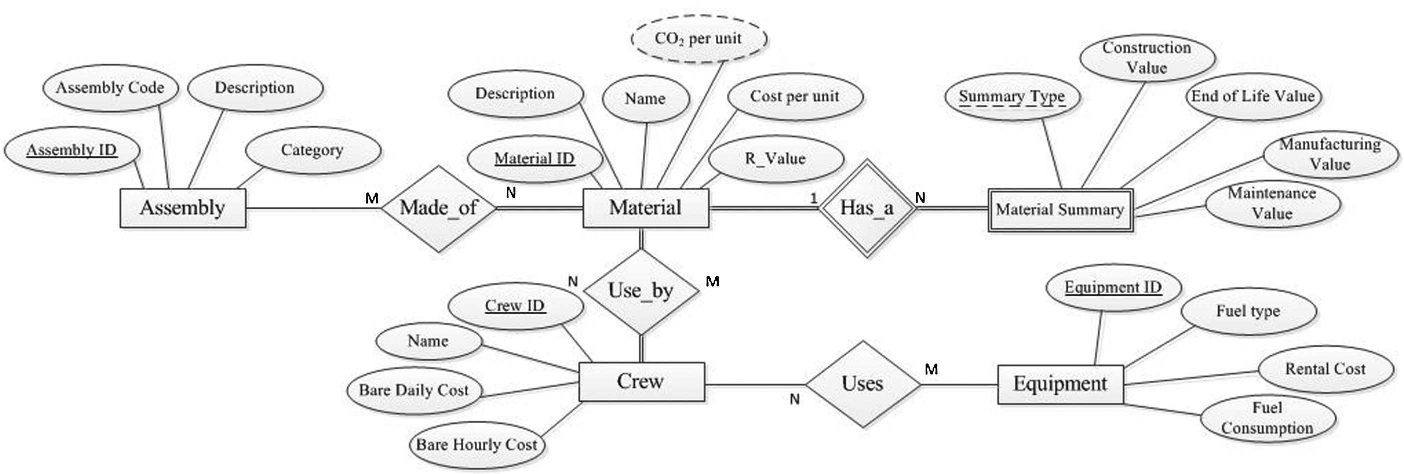

Fig. 1. Data schematic: primary keys (solid underline); partial keys (dotted underline); derived values (dotted ovals); total participation (double connecting lines)

simulation (e.g., site clearing). The options that are available for use during simulation are stored within an Access database. Users may select from these options or define their own, which can be saved to the database.

Once a user has selected components for the simulation, he or she must define a basic schedule. This schedule is used along with the CPM to estimate the duration of each possible project, which is in turn used to find optimal project solutions. Users define the schedule by ordering the selected components in the desired fashion, including in parallel. The schedule can be visualized as a directed graph for ease of understanding. Fig. 2 shows the SimulEICon methodology.

With both the component options and schedule defined by the user, the NSGA-II algorithm can be run. This algorithm attempts to find a set of optimal solutions. Fig. 3 presents a framework of optimization. The three primary objective functions (min {time, cost, and environmental impact}) are used to determine if a solution works. The cost function is the sum of all component costs, while the EI function is the sum of all component environmental impacts. Both are calculated using information stored for each component option and quantities pulled from the BIM model. The time function is the total duration of the project based on the given schedule. Nondominated ranking and crowding distance are used to rank for the selection of the next generation (Deb et al. 2002). Currently, all objectives in SimulEICon are equally weighted. Solutions obtained by SimulEICon tend to exhibit a nondominant behavior, meaning that there is no single solution that excels in all three parameters. Once the simulation is complete, users can visualize results using graphic charts comparing time versus cost, cost versus environmental impact, and environmental impact versus time.

Fig. 4 shows SimulEICon's main user interface and also the interface for adding new components. Available commands are located on the right side of the main window, and available possible assemblies and components are shown at the bottom of the main window. Components are associated with data from the model. Since SimulEICon allows users to customize the database by adding new information, this is necessary for the decision-making process since some information can be invisible in a 3D model, such as site cleaning, which can cause a great deal of cost, time, or CO_2 emissions. Moreover, simulated components are based on user preferences. Some small components can be disregarded to simplify simulation, but at the expense of accuracy. Most important, users and design professionals are able to compare between options and view information in each assembly. This interface makes it easier for users to investigate trade-offs at the component level.

SimulEICon Application

Future House Project Description

A case study of a real building, the Future House USA, is used with SimulEICon to demonstrate its use and results. This house was designed and built in Beijing, China; it is a zero-net-energy (ZNE) design that aims to maximize energy efficiency and generate a balance between energy consumption and renewable resources. Based on the design of the project, many possible components can be chosen to achieve an efficient design during the early stages. A total of 16 activities are retrieved from the model and written to

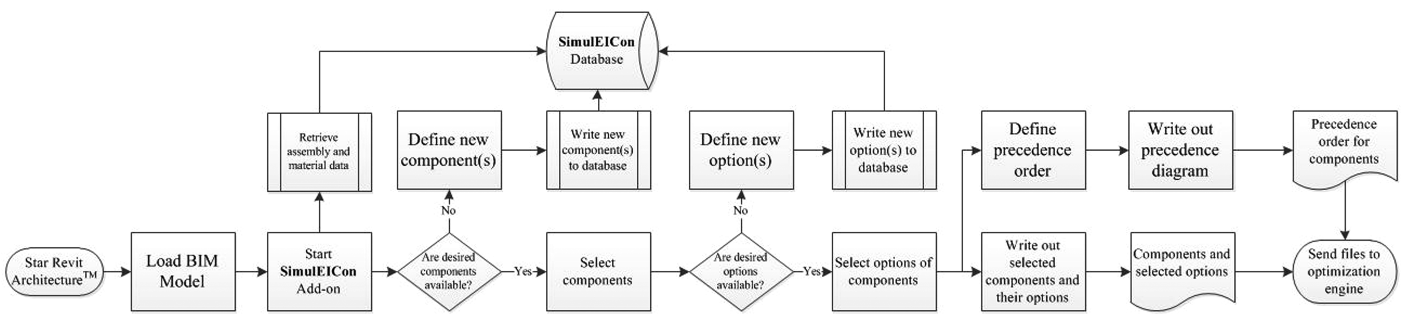

Fig. 2. SimulEICon methodology (Zhu et al. 2012)

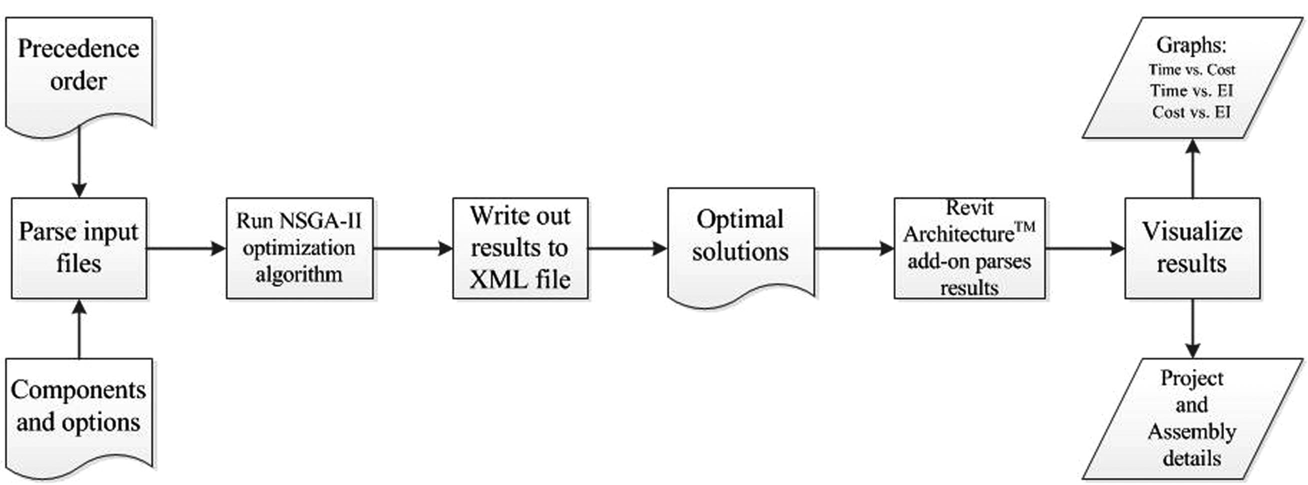

Fig. 3. Framework of optimization (Zhu et al. 2012)

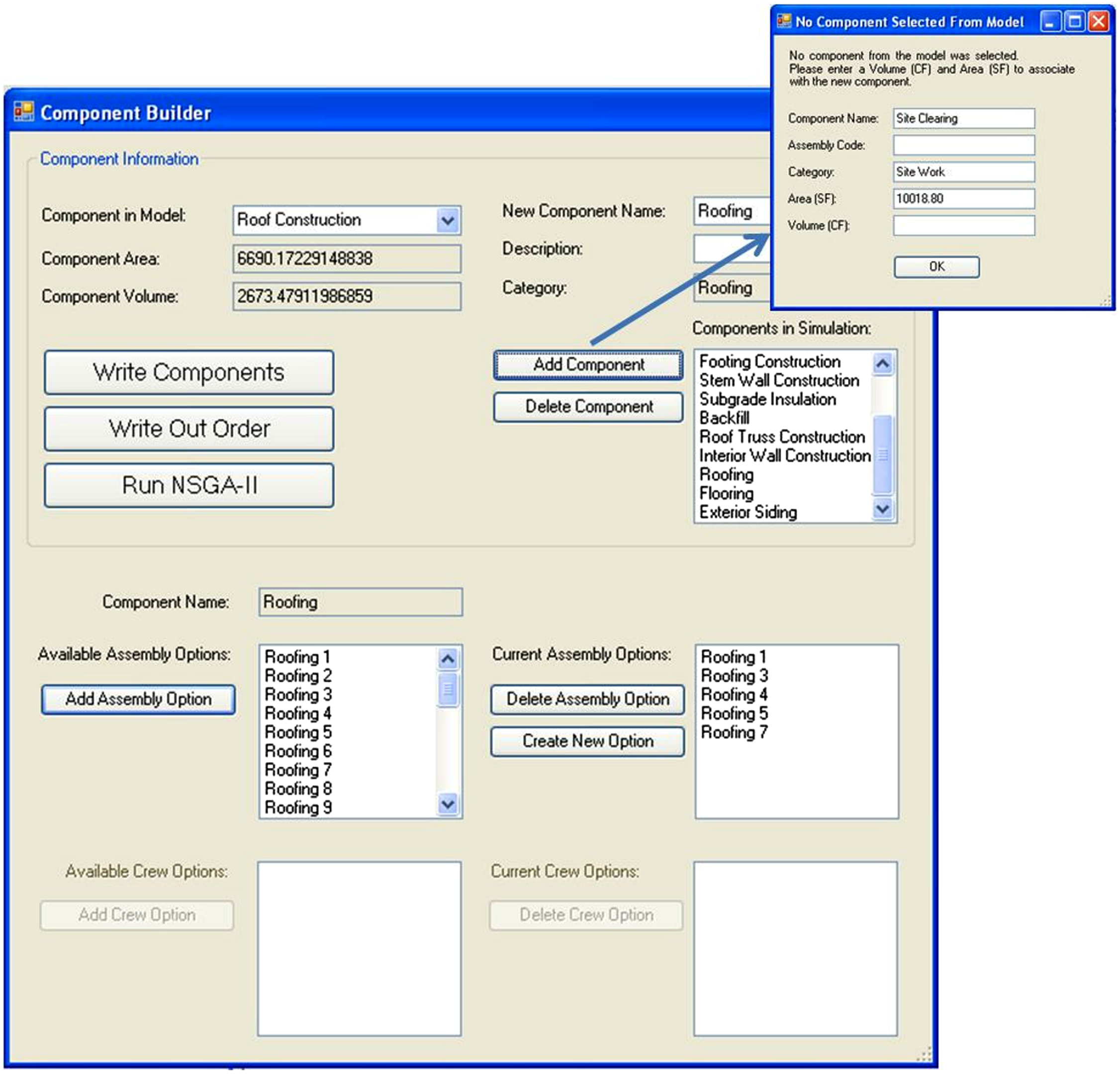

Fig. 4. SimulEICon user interface

the database; there are 185 building components. Environmental impacts (CO_2 emissions in this case) are estimated with the ATHENA Impact Estimator for Building 4.2, an LCA-based software. Cost data is obtained from the Building Construction Cost Data 2007 program. The example building activities and their alternatives are shown in Table 1. With all the available building components, there are over 31 billion possible solutions that professional designers should consider. SimulEICon, hence, aids in the selection of optimal design solutions based on three objectives: minimizing construction time, initial construction cost, and environmental impact (CO_2 emissions in this case).

SimulEICon Results

The Future House USA project was used to demonstrate the use of SimulEICon. The house was modeled in 3D in Autodesk Revit Architecture; since SimulEICon is an add-on to this software, it is started within this environment, and data was retrieved from the model and the database. For the Future House USA model simulation, the population was set to 200 and the number of generations to 500. Three objective functions were considered: construction duration (Time), initial construction cost (Cost) and environmental impact (EI), measured by CO_2 emissions. The results obtained after running SimulEICon are shown as follows: (1) a graph relationship between Time and Cost in Fig. 5; (2) a graph relationship between Time and EI in Fig. 6; and (3) a graph relationship between Cost and EI in Fig. 7.

SimulEICon has another option to visualize results in a text format that shows a list of optimal solutions, as shown in Fig. 8. The list can be sorted based on the user's priority objectives. For instance, the optimal solutions in Fig. 8 are numerically sorted by time. Thus, the first solution has the lowest construction duration obtained by the optimization engine.

A demonstration is performed by comparing a set of possible solutions obtained by SimulEICon with those implemented in the actual project. It was found that at the component level, many of the possible solutions have components similar to those of the case study. For example, the structural insulated panel (SIP) option was chosen in the case project and in several generated solutions. Brown cellulose board was used in the case project for subgrade insulation. This also occurred with various generated solutions because this material produces the lowest CO_2 emissions. Fig. 9 presents two set of optimal solutions from the optimizing simulation, and the highlighted point represents the actual project solution. No exact match between generated results and the case study was found at the building level. This is to be expected, as

Table 1. Example of the Project's Components and the Components' Alternatives

Components	Alternative number	Alternative descriptions
Footing construction	1	3,000 psi; average fly ash; reinforcing in place; pumped
	2	3,000 psi; 25% fly ash; reinforcing in place; pumped
	3	3,000 psi; 35% fly ash; reinforcing in place; pumped
	4	3,000 psi; average fly ash; reinforcing in place; direct chute
Exterior wall construction	1	SIP, 5.5 in. thickness
	2	Wood stud kiln dried 16 on center (o.c.); 2 × 4, expanded polystyrene board; ½-in. regular drywall; 3/8-in. plywood
	3	Wood stud kiln dried 24 o.c. ; 2 × 4, expanded polystyrene board; ½ in. regular
	4	Wood stud kiln dried 16 o.c. ; 2 × 4; expanded polystyrene board; ½-in. flame resistant drywall; 3/8-in. plywood
	5	Wood stud kiln dried 16 o.c. ; 2 × 4; expanded polystyrene board; ½-in. water resistant drywall; 3/8-in. plywood
	6	Wood stud kiln dried 16 o.c. ; 2 × 4, blown cellulose board; ½-in. regular drywall; 3/8-in. plywood
	7	Steel stud (20 GA) 16 o.c.; 1 5/8 × 3 5/8; expanded polystyrene board; ½-in. regular drywall; 3/8-in. plywood
Exterior siding	1	Concrete brick
	2	Metric modular brick
	3	Stucco

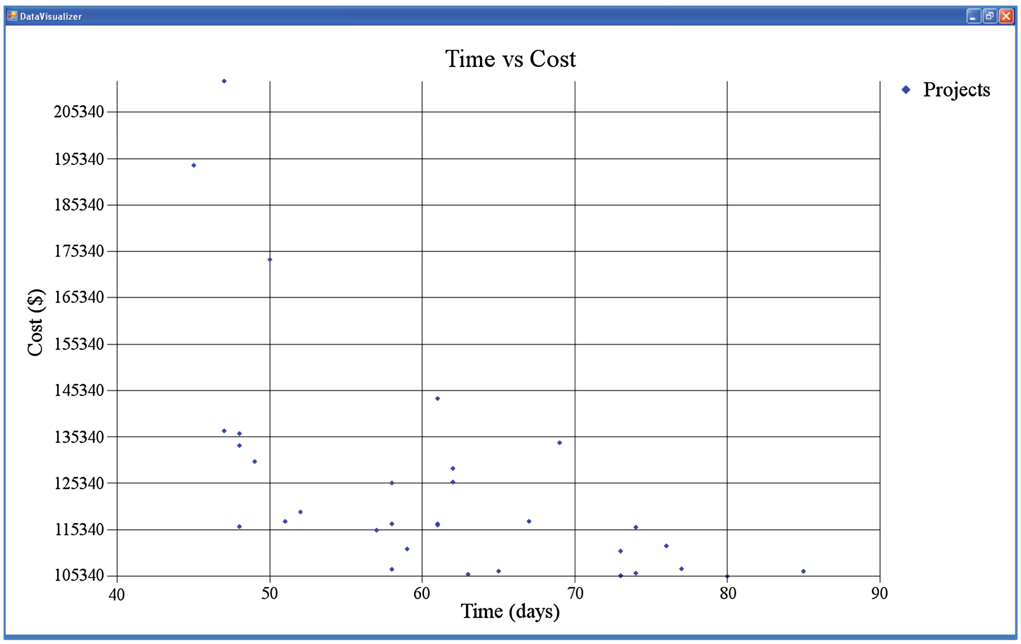

Fig. 5. Optimal solutions shown in a two-dimensional (2D) graph between Time and Cost

the number of possible solutions was very large. Increasing the population and generations of the model could yield an exact match, but at the expense of a longer computation time period. Compared to the range of possible solutions, the case study exhibits low project duration, while values of cost and EI range in the highly medium values.

Validation of both SimulEICon and similar approaches is difficult (Sargent 2005). Most validation approaches require experts or professionals to assess the validity of the simulation results, and there is no exact test to determine the validity of the model. This problem is compounded by the fact that SimulEICon yields a wide array of different possible solutions that change with each simulation due to the effects of uncertainty and the GA optimization process. Thus, instead of striving for a full-scale validation, this paper uses a case to demonstrate the capabilities of SimulEICon with respect to BIM and ICT. Future efforts are needed to develop a more robust strategy to validate the results generated by SimulEICon.

SimulEICon yields a wide variety of possible optimal solutions; these solutions are nondominant, and they do not converge to a single point. This means that usually, there is not a single solution with the lowest values in all three objective parameters, as shown in Fig. 9. Most solutions exhibit values in the medium range for all parameters, with some exhibiting a trade-off behavior where a low value in one parameter translates into a relatively high value in another. The results also exhibit the traditional relationship between cost and time, where reducing one increases the other.

Parties involved in the AEC industry have different expectations and interests in a construction project. For example, in a given project, the owner might be primarily concerned about the total cost of the project, the contractor in reducing the project duration to avoid liquidated damages or earn early completion bonuses, and the architect in achieving a certain green building certification. All these interests and requirements lead to decisions that must be made during the design phase of the project. SimulEICon allows construction professionals and decision makers to evaluate multiple

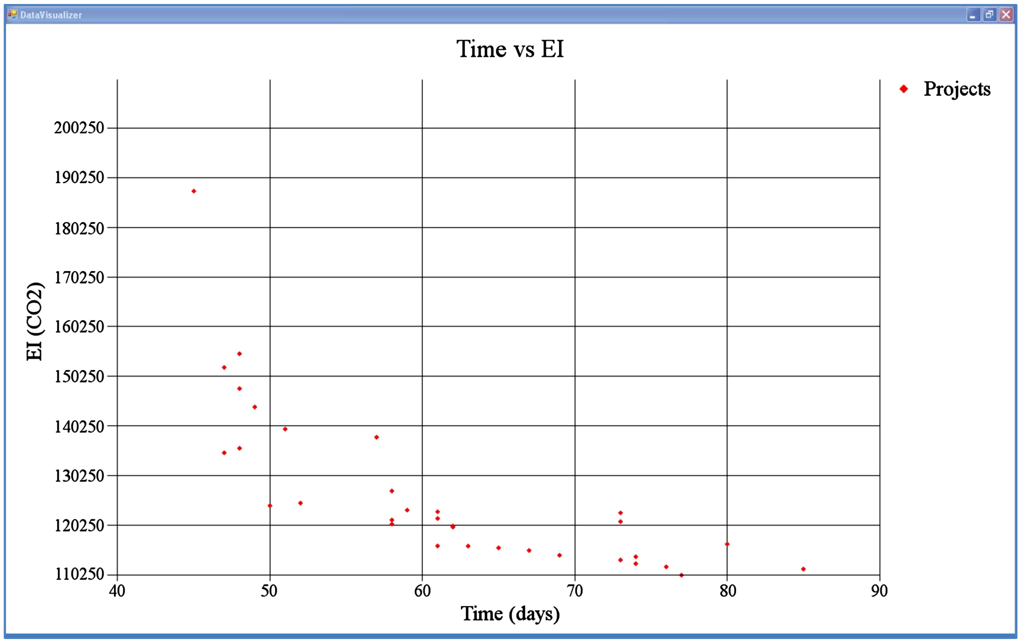

Fig. 6. Optimal solutions shown in a 2D graph between Time and EI

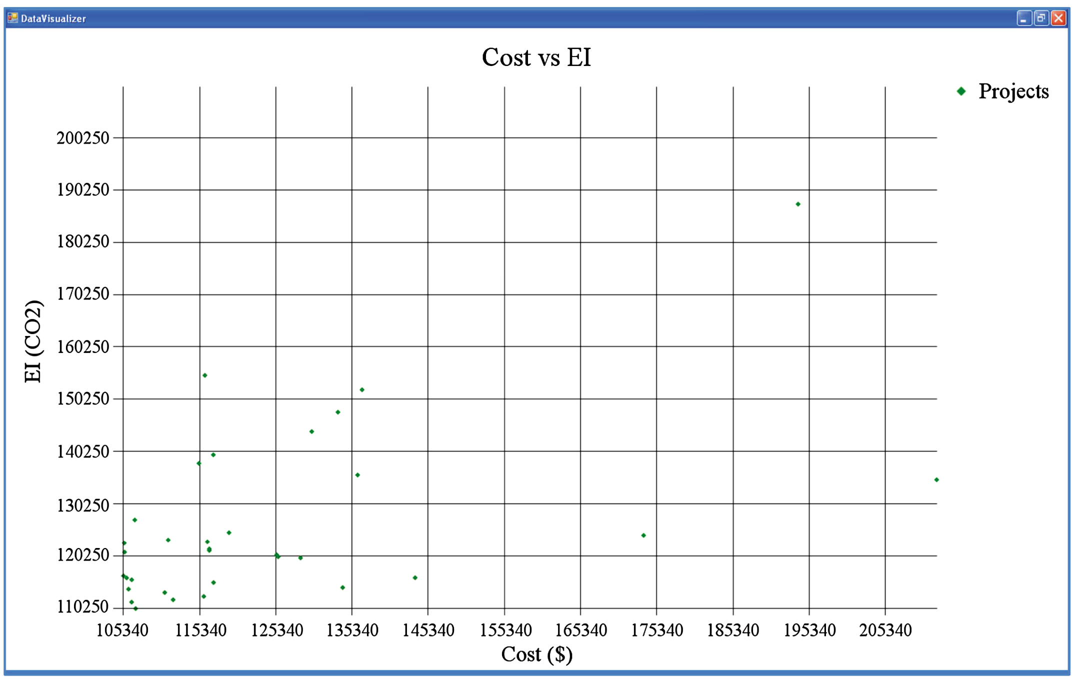

Fig. 7. Optimal solutions shown in a 2D graph between Cost and EI

optimum solutions and choose the one that is best suited to meet the project's particular objectives. The tool captures certain databases to carry out the decision-making process. It is recognized that those databases can affect the optimal outcomes. The optimization results also highlight that there are many possible optimal or near-optimal solutions based on multiple factors such as component availability, market price, and so on. Given the fact that without optimization processes, a simple building with 10 components and only three alternatives for each component can create over 59,000 possible solutions, it becomes evident that an analytic tool such as SimulEICon is needed.

SimulEICon can limit the search spaces of users and provides a robust optimization tool for the decision-making process during the design phase, when the variety of alternatives and possible solutions can be overwhelming. For instance, if a project has clients who are interested in only a specific range of investments, some optimal results can be filtered out. On the other hand, if CO_2 emissions are restricted to a certain amount, designers can put constraints to the model. From the case study, after 500 generations, the first frontier created by nondominated sorting contains those solutions that are not dominated. This means that there is no other solution that has all three parameters superior to others.

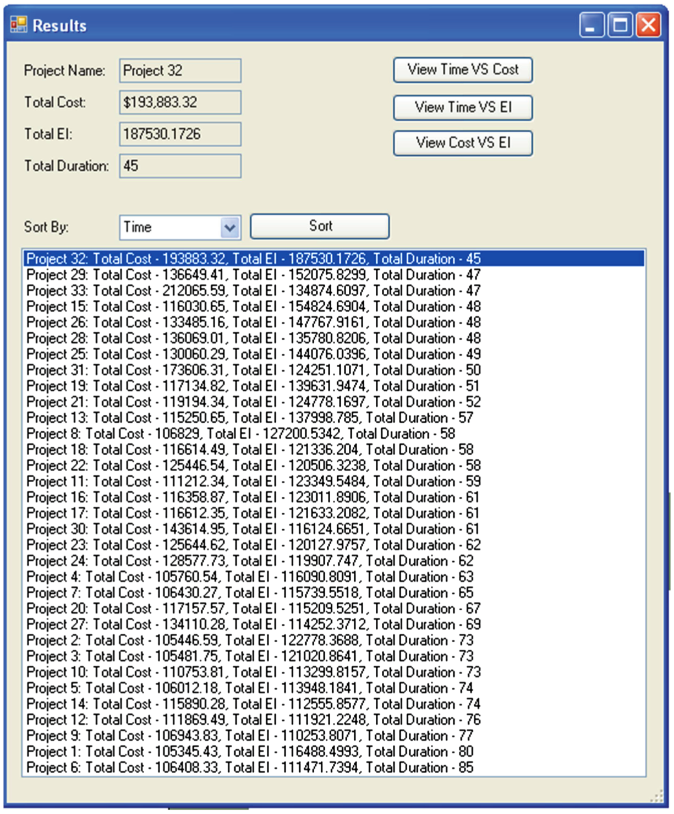

Fig. 8. A list of optimal solution sorted by time

The results from 200 populations amounted to approximately 35 optimal and near-optimal solutions. Each solution has a superior value in at least one objective. This cannot be interpreted that there is no better solution. Optimization can vary between runs because the NSGA-II approach mimics natural selection. Mutation and crossover chances make it somewhat randomized, but the solutions lean toward better or even near-optimal solutions. There is no exact best solution. Thus, it is important for AEC professionals to understand the behavior of all multiple objectives. In addition, since it allows users to simplify desired components, the selection of alternatives is also significant. It is not possible to evaluate what solutions are better than others. However, a comparison of the results can be easily analyzed with this tool. AEC professionals can prioritize the results based on certain criteria. This can limit the number of choices during the decision-making process to only the desired optimal solutions. In summary, SimulEICon can provide benefits to the AEC industry, in that it can address the impact of multiobjectives at the building level. The trade-off behavior between parameters can be displayed in many ways. It helps to discuss the optimal solutions with professionals in the project. Finally, further development of this application could include additional simulations and consideration of more building parameters during the optimization process.

Conclusion

This paper presents SimulEICon, an economic and environmental impact analysis ICT utility that uses a multiobjective GA, and it is simultaneously integrated with BIM. This tool is designed as an add-on application to Autodesk Revit Architecture. It combines BIM with optimization techniques. NSGA-II, a widely used GA, is used to find optimal results according to multiple project objectives. In this paper, three objectives are considered: time, cost, and environmental impact (expressed in terms of CO_2 emissions). SimulEICon has the ability to find the optimal alternatives for all the components in a building. Moreover, the optimization process can be tailored to only specific components. Generated results can be visualized in graphs or in lists that can be sorted by objective parameters. A case study was presented for demonstration purposes, and it was found that several of the solutions generated by SimulEICon had components matching those in the case study. The wide range of results generated by SimulEICon contributes to the selection of building solutions that successfully meet the project

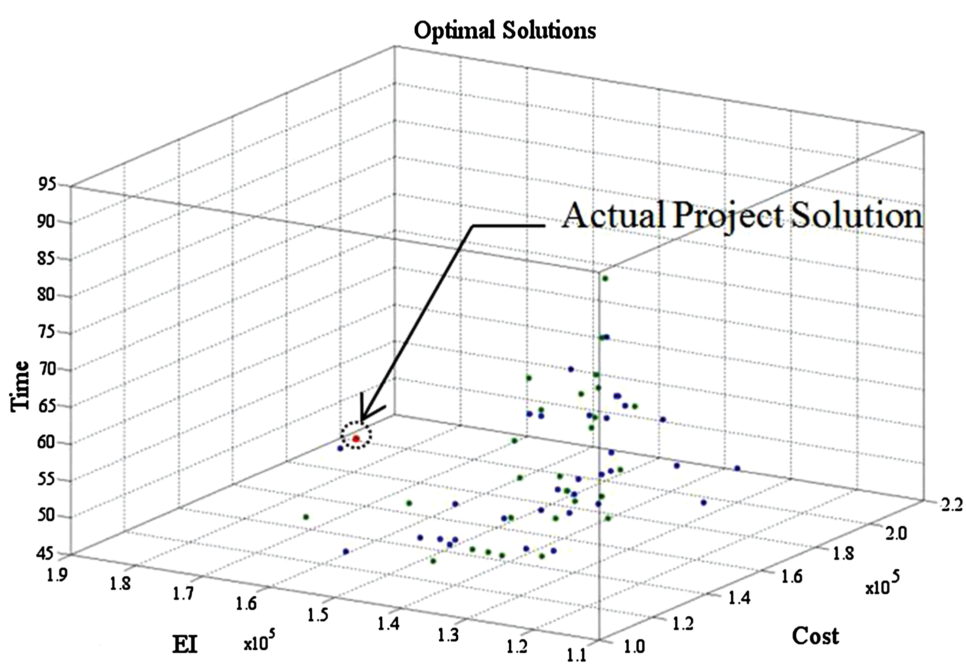

Fig. 9. Optimal solutions and actual project implementation in a 3D graph

objectives. Moreover, the inclusion of environmental impacts into the optimization process facilitates the integration of sustainable construction concepts with traditional construction practices. A current limitation of SimulEICon is that it considers only three project objectives, whereas other design objectives also should be considered during the decision-making process. Further work on integrating more project objectives, such as energy consumption during the occupation phase, is recommended. SimulEICon benefits the AEC industry by extending the capabilities of BIM during the design phase of construction projects and allowing construction professionals to consider a wide range of combinations of building components and materials before selecting the alternative that is best suited for the project.

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