

A BIM based Energy and Lifecycle Cost Analysis/Optimization Approach

Mohamed Nour, Ossama Hosny and Ahmed Elhakeem

The American University in Cairo

Abstract

This paper reports on ongoing research work within the area of building lifecycle cost analysis including energy optimization. It addresses the interoperability problem between different AEC domain applications within the context of a BIM based lifecycle cost analysis / optimization at the design stage of a building. It discusses the available interoperability options between existing mainstream software applications and identifies areas where there are needs for further interoperability tools that facilitate the production of energy efficient and sustainable designs. A double solution strategy (short and long term) is adapted to achieve the objectives of the lifecycle cost analysis/optimization process for developed prototype building(s). The short term strategy aims at optimizing the design parameters of suggested building(s) prototypes within the collaborative multidisciplinary teamwork environment with architects, structural and HVAC engineers. In the meantime, it points out the interoperability shortcomings and proposes the development of missing interoperability solutions. The long term strategy targets the development of such solutions to be deployed among mainstream software applications with the aim of reaching an automated BIM based round-trip lossless data exchange by bridging the gap between existing interoperability islands.

Keywords: BIM, Lifecycle Cost Analysis, Energy Simulation, Genetic Algorithm

1. Introduction

The research work in this paper is related to a BIM- approach for optimizing the total lifecycle cost of a building. It focuses on the energy component of the building lifecycle cost parameters. It is based on a BIM based data exchange scenario, where the architect sends a request through an open BIM platform (model server) to the lifecycle cost team to analyze/optimize the lifecycle costs attributed to his building design as shown in figure 1. All communication between project disciplines take place through the central model server in the form of IFC files. The architectural team provides the LCC team with a set of predefined alternatives of the building components. These alternatives represent a main selection pool to configure a

building design(s), i.e. a library of objects. These alternatives include different types of walls, windows and slabs that constitute the building's external envelope

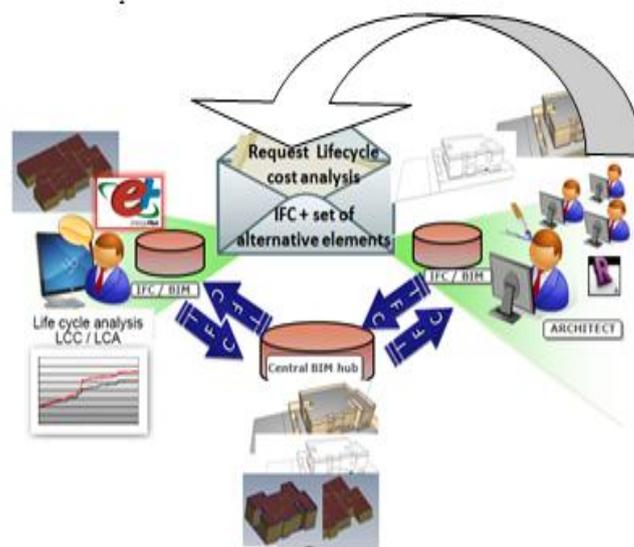


Figure 1: The BIM based data exchange through a central IFC/BIM data hub

In return, the research team has set up a BIM-platform (central data hub) [1] for manipulating the IFC/BIM model in terms of reading, writing and visualization together with an optimization engine that is capable of manipulating energy simulation software input files and parsing its output files. Several architectural designs are evaluated according to building energy consumption cost dimension and results are incorporated to the lifecycle cost model to reach an optimum trade-off between energy and cost resulting in an optimum design.

Lifecycle cost analysis is considered to be a powerful tool that facilitates the proper evaluation and optimization of different building/system designs. Traditionally, evaluation of such systems is carried out on the basis of its investment cost neglecting other costs such as operation, maintenance and repair costs [2] from the National Institute of Standards and technology has presented a description and a methodology for applying lifecycle cost analysis. As building lives are considered virtually long, all their life associated costs are to be considered. These costs are: (1)

Initial costs; (2) Utilities Costs; (3) Operation, maintenance and repair costs; (4) Replacement costs; and (5) Residual Values [2]. Details about the importance of lifecycle cost analysis and the need for optimization and its modeling challenges can be found in [3], [4], [5]. The importance regarding sustainability and energy efficient solutions with relevance to lifecycle cost is discussed by [3], [6].

2. Building design optimization

2.1. Modeling options and optimization challenges

Trying to optimize a building design from energy/cost point of view -within the context of a specific architectural form- can be seen as a selection problem for the optimum types of its envelop components. These components are mainly the roof, exterior walls and windows where the selection is from a pre-defined list of available alternatives for each envelop component. As a common practice, architects most probably select all windows from the same type and all wall segments from one type too. Such a design approach (modeling option) from optimization point of view results in three variables that need to be determined namely the roof type, the windows type and the exterior walls type. The corresponding optimum design to this modeling option can be reached through exhaustive search by trying all possible combinations, which are limited. With the fact that the windows and wall segments in the building are distributed over various building facades and floors, they are subjected to different degrees of weather severities and solar impacts. Accordingly, the optimum solution might result when using a combination of different types of windows and walls within the building. Wall segments or windows that are less subjected to the sun might need less insulation compared to those that are subjected to more sun. This may result in cost saving which is significant over the building's lifecycle. Considering such modeling option which handles each window or wall segment as a separate entity (i.e., variable) that can be assigned any type will result in a huge number of possible combinations or building designs. Even with few alternatives for each envelop component, this will result in a number of combinations that cannot be examined, raising the need for a true optimization procedure. Figure 2 shows an illustration with only three window alternatives and three wall alternatives using a real two-story building with 24 windows and 94 wall segments. The number of possible designs will be 11,481,993,216 designs. As shown in the figure the number of possible designs equals to the number of wall segments raised to the power of possible wall alternatives multiplied by the number of windows raised to the power of possible window alternatives. Accordingly with any additional alternative the

number of possibilities will increase dramatically many folds showing the need for not only an optimization technique but also to a non-traditional one. GAs is used in this research as one of the evolutionary approaches that proved to be efficient in such type of combinatorial problems.

2.2. Interoperability Challenges

The main objective of the LCC team in this paper is to incorporate the total annual energy cost of the prototype building(s) in the LCC model using the BIM/IFC input and share results for decision making with other project team members. Predicting the annual energy however, is a challenging task that needs energy simulation using weather data, thermal properties of used materials for different building components and information regarding the HVAC and other appliances and their expected schedule of use. It was envisaged that the output from BIM authoring tools such as Revit [7] would be taken as an input to the energy analysis tool used by the Architectural team (Energy Plus) in the form of an IFC STEP-21 file [8]. Despite the existence of an increasing number of Building Information Models that are linked to energy performance simulation models and the existence of models that are linked to BIM authoring tools (CAD) within proprietary environments, there are still limitations to the current BIM tools for energy analysis in terms of interoperability and quality of the results. [9].

By investigating the interoperability status of such a data exchange process, the following shortcomings were found:

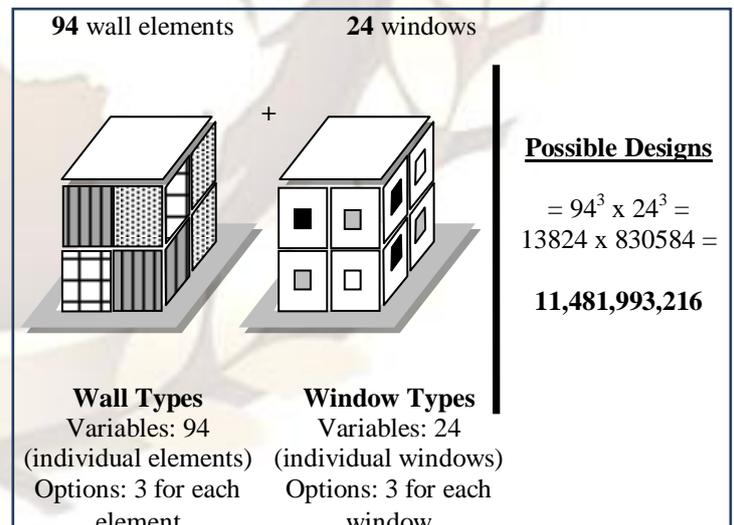


Figure 2: Illustration: need and optimization challenges

1. Often BIM models need to be complemented or even recreated to add information required for energy analysis.
2. Software like AutoDesk Green Building Studio/ Revit or Graphisoft Eco Designer / ArchiCAD

- are proprietary developments that are hardly interoperable outside their own environments.
3. There is no typical and well established analysis method and guidelines for the BIM/IFC based energy performance assessment.
 4. Energy simulation tools like EnergyPlus do not accept IFC files as a direct input.
 5. All workarounds using gbXML[10] as an intermediate exchange format result in a one way communication channel to the Energy simulation tool (EnergyPlus) where results are not integrated or further communicated to other design team members through the BIM model.
 6. The one way communication channel is not suitable for optimization which requires a structured procedure that enables continuous changes (back and forth) in the design variables and the assessment of corresponding LCC including the impact on energy consumption.

3.Solution Approach

The solution approach to the problems mentioned in the previous sections was to adapt two strategies. 1) A short term strategy to keep multidisciplinary collaborative work going on with other project teams without time delays due to waiting for software developments to end. This strategy provides short term instant solutions and workarounds to the previously mentioned interoperability problems to maintain the pace of work delivery. 2) A long term strategy based on developing software tools that are capable of being integrated to the mainstream software applications to bridge the gaps between existing islands of automation.

3.1. Short term strategy

The short term strategy depends on making use of what is currently available by mainstream software applications and developing interfaces and software tools that are capable of managing information exchange specific to this research project. A main problem was the integration of the energy simulation tool (EnergyPlus) inside the GA based cost optimization environment. A user interface had to be developed on top of EnergyPlus in order to be integrated to the GA routine of work. Meanwhile, to keep on with the work delivery pace, the BIM/IFC model was converted in a unidirectional way through gbXML to an IDF file as illustrated in figure 3. It was necessary to add all missing HVAC and energy simulation relevant properties of materials and their layering systems to the generated IDF file which are added with the help of the Architectural team. The optimization mechanism can be schematically viewed in figure 4.

3.1.1.Optimization Implementation

The implementation of the optimization process is discussed in this paper through a real case study example. A two-story building was provided by the Architecture team and three alternatives for walls and another three for windows were also determined by the team. The building consists of 24 windows and 94 wall segments. The IDF file corresponding to the initial design was created from the building IFC through gbXML manual transformation as discussed earlier.

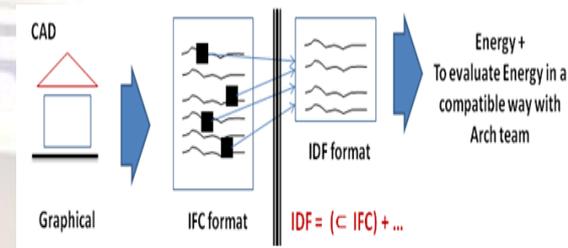


Figure 3: Mapping IFC data to EnergyPlus IDF format

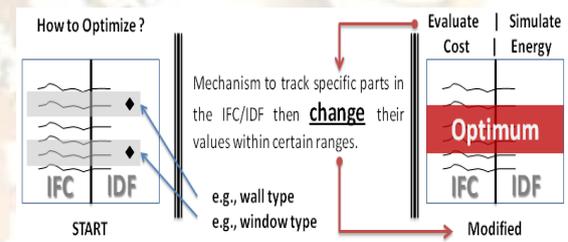


Figure 4: G.A. manipulation of references to construction & fenestration types in IDF files using unprocessed markers

After adding the HVAC data to the IDF file, it becomes a representation for the building design in the format that suits the energy assessment using Energy Plus. From the case dependent IDF file, the LCC team created a generic IDF file by adding all alternatives as a selection library. The LCC team assessed the unit LCC for the different envelop components' alternatives. The quantities of the different components are extracted from the IDF file basic geometrical information. Once a design or an IDF file is adapted during the optimization process, energy simulation will be responsible for providing the annual energy demand in kWh which can easily be converted to equivalent building operating cost.

3.1.2. Mapping the GA procedure in Energy Plus simulation

First, a GA java generic library was developed as the core optimization engine as a package of abstract classes that need to be implemented on specific optimization problems through inheritance. It was tested and verified using known solutions of mathematical equations. The java classes of the GA tool were extended as shown

in the UML diagram in figure 5 to conduct energy simulations of automatically generated IDF files using EnergyPlus at both the initial population creation stage and at the evolution stages.

GA functions through three main entities: (1) genes to represent the variables; (2) a chromosome which represents a solution in view of variables values. Hence, a chromosome consists of a number of genes; and (3) an initial population of randomly created solutions (i.e., chromosomes). These three entities are then used in the GA evolution process by calculating the relative fitness of the population and accordingly randomly selecting parents for crossover/mutation. For the case study on hand, each chromosome contained 118 genes representing the elements of the building envelop (24 for windows and 94 for wall segments). The values of these genes are integers between 1 and 3 corresponding to the three possible alternatives of walls and windows.

Within the EnergyPlus simulation, each chromosome is represented as an IDF file and each gene within a chromosome represents an element on the building outer envelope as shown in figure 6 and figure 7. The IDF GA Energy optimization tool depends on putting non processed markers in the IDF file at places where variables (genes) are required to be changed during the optimization process as shown in figure 4. An initial population of 200 chromosomes was generated using the different wall and window types. These chromosomes (designs) were then evaluated.

IDF referencing mechanism

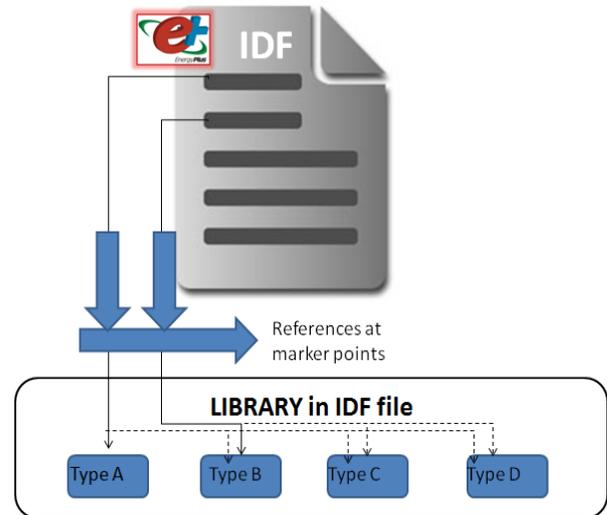


Figure 6: The representation of the set of alternative elements constituting the building envelop through an imbedded IDF library

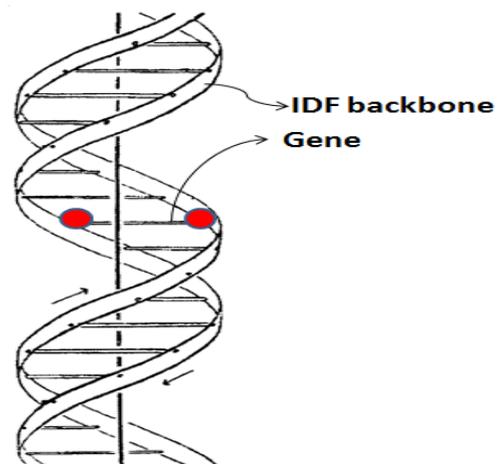


Figure 7: The representation of GA chromosomes by IDF files and genes by building outer envelope elements

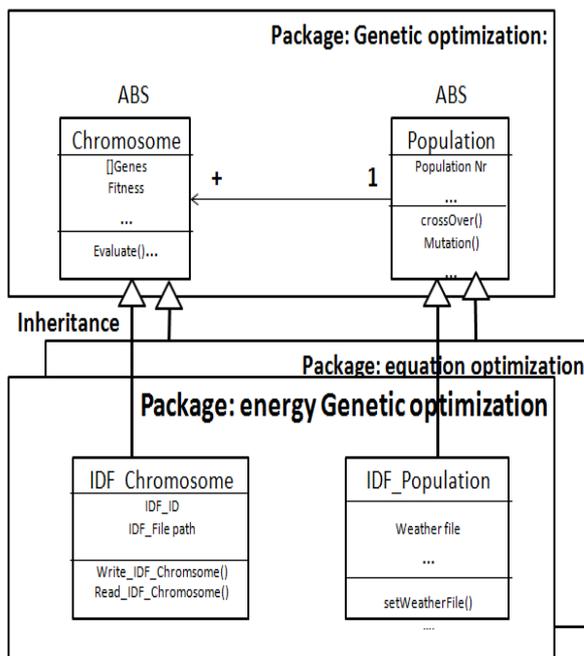


Figure 5: A UML diagram showing the Java based G.A. engine library architecture

The population was further refined using a minimization objective function representing the annual energy consumption of the building design undergoing simulation as well as Lifecycle Cost of the envelop of the building components. The overall fitness of the chromosome was calculated by aggregating all Lifecycle costs together with the average annual energy consumption of the building in monetary units. It is also worth mentioning that all monetary figures are aggregated in their NPVs (Net Present Value). As the lifecycle costs for the building elements are provided in the form of annual price / unit area, it was inevitable to make a quantity take off from the model to be able to get the cost for each building element (Gene). Consequently the

overall life cycle cost for the building configuration (Chromosome) is calculated. This quantity take off could not be done from the IFC model due to the lack of identification of objects in the IFC model with their counterpart objects in the IDD/IDF EnergyPlus Model. As a solution, quantities were calculated from the geometrical description of the objects in the IDF file (3D Cartesian points constituting polygons). Furthermore, another problem was the calculation of net areas of walls constituting the outer envelope of the building given that some of such walls included one or more window openings. Each window had to be related to its containing wall in order to be able to calculate the containing wall's net surface area.

At the process of each chromosome creation either by random generation or through crossovers / mutations GA routines, a corresponding new IDF is generated for each chromosome. Each IDF file contains assigned references at markers places to corresponding genes' values determined by the GA. The experimental prototype started with the initial random population of 200 chromosomes that were evaluated by a multi-core batch simulation of EnergyPlus that is controlled through a developed interface linked to the GA tool. Mutations and Crossovers were then conducted at ratios 0.15 : 0.85 respectively. For normal crossover, directed random selection of the population chromosomes was used. At each mutation or crossover process the evaluation of the chromosome is done through the generation of a new IDF file containing the corresponding genes' values followed by an EnergyPlus simulation to integrate the annual average total energy consumption cost of the building with the rest of the life cycle cost parameters.

All GA optimization/ simulation results produced at runtime are kept afterwards in the form of chromosomes represented as IDF files together with all EnergyPlus simulation output files and a list containing the gene sequence of each chromosome as shown in figure 8. Since EnergyPlus simulation runs have proven to be a time consuming process, it was decided that the results of any simulation run are kept for later use when starting a new optimization run to select the best fitting population from all previous runs. If the GA creates a new chromosome with a gene sequence of values that typically coincides with a previously simulated chromosome, then the resulting scores of such a chromosome are taken over without the need to repeat the simulation process. The chromosome fitness (evaluation) is obtained through a developed *.mtr (EnergyPlus meter file) parser that is capable of reading the fitness scores of all chromosomes and arranging them in a list (of chromosomes/ IDF file

names) according to their relative fitness as shown in figure 8. The best chromosome with the best relative fitness score is chosen and considered the best candidate and its gene sequence represents the best reached configuration of the building's outer envelope. This configuration is a subset of the available options provided originally by the designer (architect).

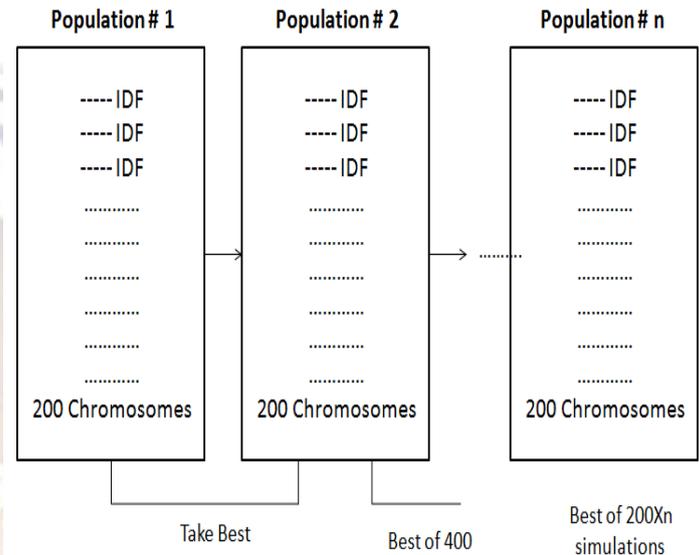


Figure 8: Making use of cumulative G.A. runs

The next main problem was to communicate the simulation results back to the designers through an IFC STEP-21 model. This was achieved by making use of two elements:

- 1- The VRML output file of the EnergyPlus simulation tool.
- 2- An IFC Java3D based visualization tool and IFC toolbox by [11].

The GA controlled EnergyPlus engine undergoes simulation iterations until a stopping condition is reached due to nonexistence of further improvement of chromosomes' fitness as shown in figure 9. The best chromosome represented as an IDF file is then passed over to a Java3D package that is capable of visualizing the IFC model together with the VRML/DXF files (output from EnergyPlus). Both the IFC/CAD model and the IDF VRML model are visualized concurrently next to each other on the same screen as shown in figure 10 to map corresponding elements in both the IDF and IFC models. A workflow approval notation is created within the IFC file as shown in appendix "A" & Figure 11 to indicate the need for change that should be performed in the CAD model by the designers (architects).

3.2. The long term strategy

The long term strategy represents the future development work that aims at developing

interoperability tools that can be deployed among the mainstream software applications to reach an Automated BIM based round-trip data exchange. The long term strategy is carried out separately in order to have enough time and resources for developments to be mature enough to be deployed by people other than its own developers among mainstream software tools. The discovered shortages of interoperability tools using open standards like the IFC are considered to be the main key drivers within the scope of the long term strategy. Among these tools that are being developed are:

1. A Java3D based geometry abstraction tool

There is a lack of a software tool that is able to correctly calculate all necessary 2nd, 3rd, 4th and 5th level space boundaries [12] [13]. The IFC2X3 utility for ArchiCAD 13 was the only capable commercial software tool of carrying out this task. In the meantime, Graphisoft did not support this in its subsequent versions. Hence, there is a need for a tool that can generate higher level space boundaries from the geometry provided in the coordination view of the IFC model to generate the needed IFC space boundaries' objects. These objects are transferred to energy simulation software while keeping references to objects in the IFC model through the management of the objects' GUIDs (Global Unique Identifiers) for later reverse mapping of attributes and properties to the IFC model.

2. An IFC Editor

This tool is envisaged to be a graphical user interface to add all necessary information related to the HVAC domain and energy simulation. This process can also be done through the IFC viewer [1] [11] before the geometry abstraction stage. In the meantime, there is also a need to manage the layers of materials and their properties in the IFC model and instantiate their property sets with relevance to the HVAC and energy domains.

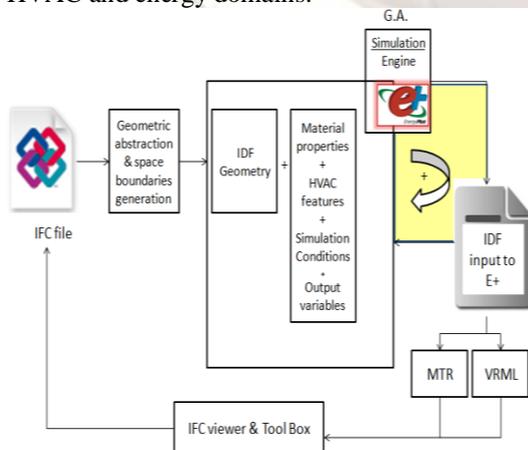


Figure 9: The envisaged BIM based energy analysis and optimization process

3. There is a need to develop an EnergyPlus IDD (Input Data Dictionary) / IDF tool box that is capable of producing new instances of the IDD objects in the IDF file together with relevant properties in addition to any HVAC system definition and EnergyPlus output variables/meters that represent the output from the carried out simulations.

4. There is a need to enable the communication of simulation results within the IFC model. In other words, all changes in the building due to changes of simulation parameters have to be reflected on the BIM model and communicated through the IFC STEP-21 exchange format. However, this matter should be carefully managed and regulated through the "Workflow Approval" system dominating the entire design and decision making team communicating through an open BIM based platform.

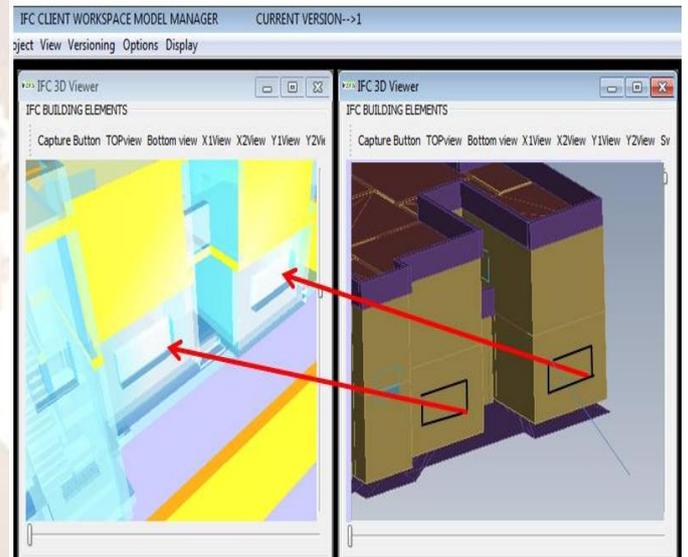


Figure 10: Mapping objects between the IDF/VRML model and IFC

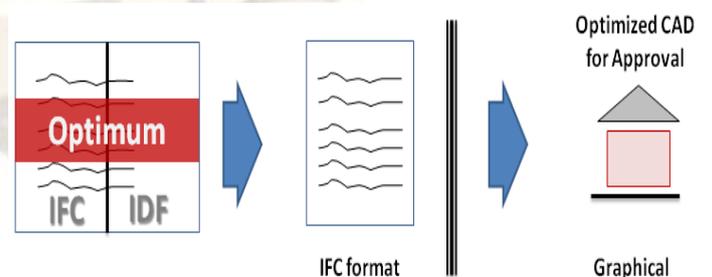


Figure 11: Returning optimization results using the BIM/ IFC Approval entity as a workflow approval procedure

Conclusions

The paper confirmed the effect of buildings' energy performance on their Life Cycle Cost and the need for optimization. This was done using a GA/BIM based solution that has the ability to select suitable building components among the available alternatives to formulate a building configuration with minimum lifecycle costs including energy consumption. Although the envisaged interoperability potential through current ICT technologies seems to be high enough to conduct round-trip data exchange between BIM based software applications, this seems not to be the case within open BIM environments and is still limited to proprietary commercial software environments away from the IFC/BIM model. Moreover, this seems to coincide with the commercial interest of software vendors and their own market share of such software tools that benefit only from the integrity of their own proprietary environments.

With relevance to energy simulation with EnergyPlus, there is still a need for open tools that are both capable of creating higher level space boundaries and in the meantime capable of managing the IFC-GUID (Global Unique IDs) in order to enable the reverse mapping process of energy relevant data back to corresponding IFC model objects and their attributes.

Enabling GA to manipulate energy simulation parameters related to the BIM objects that constitute the external envelop of buildings proves to be a valuable process that needs to be further developed and standardized with the aim of incorporating it into mainstream software applications. Furthermore, there are needs to standardize both the developed tools and the energy simulation process itself as a workflow routine in order to be able to harvest the gains behind adopting the BIM technology.

Acknowledgements

This publication is based in part on work supported by Award No. UK - C0015, made by King Abdullah University of Science and Technology (KAUST).

Appendix A: IFC – STEP-21 Extract of the BIM communication workflow

IFC – STEP-21 Extract of the BIM communication workflow
ISO-10303-21;
HEADER;
FILE_DESCRIPTION (('AUC_Egypt.', 'Build Number of the Ifc 2x interface: 00088 (02-02-2012)'), '2;1');
FILE_NAME ('North.ifc', '2012-03-02T13:53:21', ('Mohamed Nour'), ('American University in

Cairo'), 'PreProc - IFC Toolbox Version 2.x (00/11/07)', 'Windows System', 'Mohamed NOUR.');

```
FILE_SCHEMA (('IFC2X3'));  
ENDSEC;  
DATA;  
#5 = IFCCALENDARDATE (8, 03, 2011);  
#10 = IFCAPPROVAL (' windows material layers in rooms 1,7,15 and 23, have to be changed to type 1001', #5, 'REQUESTED', 'PreliminaryDesign', 'solution should be energy certified', 'SecondApproval', 'AP 123XY');  
#530 = IFCWINDOW ('0sL9z45hDDsxc4rO4qv7C', #1275, '1 Vantail - Droit:0.60 m x 0.95 m - Appui en aluminium:0.60 m x 0.95 m - Appui en aluminium:182803', $, '0.60 m x 0.95 m - Appui en aluminium', #16390, #16395, '182803', 1.0799999999999999, 0.6999999999999999);  
#550 = IFCWINDOW ('0sL9z45hDDsxc4rO4qv7V2', #1275, '1 Vantail - Droit:0.60 m x 0.95 m - Appui en aluminium:0.60 m x 0.95 m - Appui en aluminium:183325', $, '0.60 m x 0.95 m - Appui en aluminium', #20615, #20620, '183325', 1.0799999999999999, 0.6999999999999999);  
#575 = IFCREASSOCIATESAPPROVAL ('c72afa6aA31aaA41eeAa31', #570, $, $, (#16020, ), #10);  
#580 = IFCACTORROLE (.ELECTRICALENGINEER., 'ThermalEngineer', 'MFE Thermal Jobs');  
#590 = IFCAPPROVALACTORRELATIONSHIP (#585, #10, #580);  
#595 = IFCPOSTALADDRESS ($, 'American University Building Main Campus Cairo', $, $, ('Main Building', 'Ground Floor', 'ch. 04'), 'PO BOX 2422', 'CAIRO', 'New Cairo', '78065', 'Egypt');  
#570 = IFCOWNERHISTORY (#600, #605, $, .NOCHANGE., $, $, #605, 1331512806038);  
#585 = IFCPERSON ('Architect', 'KHALED', 'DEEB', ('F.', 'M.'), $, $, $, (#595));  
#610 = IFCORGANIZATION ('AUC', 'Arch', $, (#580), (#595));  
#600 = IFCPERSONANDORGANIZATION (#585, #610, (#580));  
#605 = IFCAPPLICATION (#610, '1.0', 'KAUST Prototype', 'BUILD-ID');  
...  
ENDSEC;  
END-ISO-10303-21;
```

References

- [1] M. NOUR, K. BEUCKE, An open platform for processing IFC model versions, Tsinghua Journal of Science and Technology 13 NoS1 ELSEVIER (2008) 126-131. Retrieved from <http://linkinghub.elsevier.com/retrieve/pii/S100702140870138X>
- [2] F. Sieglinde, Life cycle cost analysis, National Institute of Standards and Technology (2007). Retrieved from <http://ironwarrior.org/ARE/Materials Methods/Life-Cycle Cost Analysis.pdf>
- [3] T. Nielsen, S. Svendsen, Life-cycle cost optimization of buildings with regard to energy use thermal indoor environment and daylight, International Journal of Low Energy and Sustainable Buildings (2002) 1-16.
- [4] H. Winkler, R. Fecher, L. Tyani, K. Matibe, Cost-benefit analysis of energy efficiency in urban low cost housing, Journal of Development Southern Africa (2002) 593-614.
- [5] N. Huberman, D. Pearlmutter, A life-cycle energy analysis of building materials of Negev desert, Journal of Energy and Buildings (2007) 837-849.
- [6] S. Jung, M. Dan, Cost-reliability interaction in life-cycle cost optimization of deteriorating structures, Journal of Structural Engineering, ASCE 130 No. 11 (2007).
- [7] Autodesk Revit Architecture (2012) <http://usa.autodesk.com/adsk/servlet/item?siteID=123112&id=16841348>
- [8] ISO 10303 – 21 STEP 2002 Industrial automation systems and integration, Product data representation and exchange part 21: Implementation methods: Clear text encoding for exchange structure (2002).
- [9] V. Bazjanac, T. Maile, J. O'Donnell, N. Marzovic, October Data Environments and processing in semi-automated simulation with EnergyPlus, Proceedings of the CIB W78-W102 2011: International Conference –Sophia Antipolis, France, (2011) 26-28 October.
- [10] Green Building XML schema gbXML: <http://www.gbxml.org>. [12.03.2012]
- [11] M. Nour, K. Beucke, Manipulating IFC model data in conjunction with CAD, Proceedings of CIB w78-2005 22nd Conference on Information Technology in Construction (2005) 253–260: <http://itc.scix.net/data/works/att/w78-2005-D4-1-Nour.pdf>
- [12] C. Rose, T. Maile, J. O'Donnell, N. Mrazović, V. Bazjanac, The geometry of thermal zone space boundaries for building energy performance simulation, Submitted for publication to Transactions on Modeling and Computer Simulation, a publication of the Association for Computing Machinery (2011).
- [13] V. Bazjanac, Space boundary requirements for modeling of building geometry for energy and other performance simulation, CIB W78, Proc. 27th conference, Applications of IT in the AEC Industry Cairo (2010)