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Leveraging a Building Information Model to Carry Out Building Energy Performance Analysis

Helsinki Metropolia University of Applied Sciences

Bachelor of Engineering

Sustainable Building Engineering

Bachelor's Thesis

May 2017

Author Title Number of Pages Date	Tibebe Reta Leveraging a building information model to carry out building energy performance analysis 32 pages + 2 appendices May 2017
Degree	Bachelor of Engineering
Degree Programme	Civil Engineering
Specialisation option	Sustainable Building Engineering
Instructor	Sunil Suwal, Senior Lecturer

The goal of this Bachelor's thesis was to understand the process involved in a BIM-based BEPA in an effort to maximize the benefits. To understand the process, the main inputs necessary for the creation of BEM and major tools used for BEPA were explored. Moreover, the creation process of BIM when BEPA is planned to be conducted together with the process and method of extracting a BEM form BIM is explored.

To achieve the desired result first a literature review was conducted, followed by a test which included modelling two different types of residential buildings which were then used to check product model delivery between selected BEPA tools, and to conduct BEPA.

The study found that to maximize the benefits of using BIM-based BEPA, setting the goal of the BEPA, setting up the BIM authoring tool, understanding the limitations of the tool used, checking the BIM for error before exporting, choosing the right tool for BEPA, and simplifying the model were important points that needed to be given attention to.

The thesis can be used for gaining insight on the processes followed and on important considerations to take when implementing BIM based BEPA. Furthermore, it can be used as a starting point for future studies related with BIM based BEPA.

Keywords	BIM, BEPA, BES, BEM, Energy simulation, Building

Contents

List of Acronyms

BIM – Building Information Modelling/Model

BEM – Building Energy Model

BEPA – Building Energy Performance Analysis

BES – Building Energy Simulation

GBS – Green Building Studio

gbXML – Green Building's eXtensible Mark-up Language

HVAC – Heating Ventilating Air-Conditioning

IEA – International Energy Agency

IFC – Industry Foundation Class

SHGC - Solar Heat Gain Coefficient

VRML – Virtual Reality Modelling Language

1 Introduction

The building sector is responsible for approximately 40% of the total energy consumption in the USA, 40% of the total energy consumption of the EU, 20% of the global energy consumption and approximately one-third of energy-related CO_2 emissions [1; 2]. Because of the high energy saving potential of the building sector, there is a constant increase in the demand for complex high-performance buildings. One of the challenges for the architecture, engineering, and construction (AEC) industry to meet this demand is to adopt new integrative design processes and associated design support tools.

Building energy performance analysis (BEPA) gives a clear understanding of the energy consumption of both the whole building and the building elements separately. This can greatly help a designer to make the most effective design decisions to minimize the energy needed by the building. When preparing for BEPA, it is necessary to have information that best approximates the actual building, for instance building geometry, building fabric and building services are needed. Collecting all the necessary information for the use in BEPA can be very tiresome and could get very complicated. But with the help of building information modelling some of it can be minimized or even eliminated. [3.]

Building information modelling (BIM) is an approach to design that uses intelligent 3D models to create, modify, share, and coordinate information throughout the design process, whereas building information model (also BIM) is a representation of the building's physical and functional characteristics using computer generated 3D models. From this BIM, a building energy model (BEM) can be extracted. A BEM is a building model which is used for energy simulation. [3.]

In this thesis, an investigation of the process involved in the creation of BEM, using input data files extracted from BIM, is carried out. Emphasis is given on the type of information extracted from a BIM which can be used as an input for BEPA. Furthermore, additional input information needed by the BEPA tools is explored. To do this, a theoretical presentation of the process is given. In addition, the most important input information to performing a successful BEPA is introduced, followed by a presentation of the concept of BIM-based BEPA. Then the theoretical presentations are tested. The test includes the modelling of two residential buildings of different types using the main BIM authoring tool.

From the model, the BEM is extracted to perform the BEPA. Finally, some conclusions and suggestions are presented.

2 Basic principles of Building Energy Performance Analysis

For decades, building designers have used a number of tools, methods and workflows to analyse and predict energy flows in buildings. Energy simulations are used by building professionals to provide an estimation of energy consumption and to predict the thermal comfort of a given building [4; 5]. A potential challenge when performing a building energy simulation (BES), is the vast amount of inputs and assumptions which are necessary to perform BEPA.

Usually BEMs are developed in an attempt to simulate energy operations of a yet-unbuilt project or an existing building. When a BEM is created, several pieces of input information, from the location of the building and local climate information to more detailed information like building elements, have to be entered [6]. Many unknowns about a building must be assumed. Because of this it is often observed that BEPA tend to be performed at a later stage of the design process when the decisions affecting the energy performance of the building have already been made. Using energy models, different aspects of energy performance can be computed. BEM can be used to predict the total energy use of the building, where the entire building is seen as a single system, or analyse the energy performance of some part of a building, such as a space, a system or an element and the effects it has on the overall system. [5; 6.]

Most of the necessary inputs and assumptions for the creation of BEM are described below, followed by the tools used to perform an energy analysis and, finally, some typical BES output results and their interpretation are presented.

2.1 Building Energy Model Inputs and Assumptions

As with any other simulation, the results of a BES highly depend on the quality of the input data and approximations used to perform the simulation. There are a number of input data which are necessary when creating a BEM. The relevance of the input data differs slightly from one type of energy analysis to the other. Usually, the necessary input data for an energy simulation includes location data, building geometry, internal gains, building envelop, schedules, and energy systems. However, not all input data are readily available, or even possible to get at some stages of the design process. There are many reasons for this. For example, the information in question might not even be known at some stages of the design process just because the decisions affecting it have not been made yet. Another reason could be the degree of difficulty to acquire the information in question. Whatever the reason for the data not being available, the designers have to make an assumption to account for the missing information by using some mathematical formula or previous experience for approximation, and supply with the required data. The next sections of this chapter present a more detailed explanation about these inputs. [6; 5.] Figure1 summarises most of the inputs that are necessary for a BEPA.

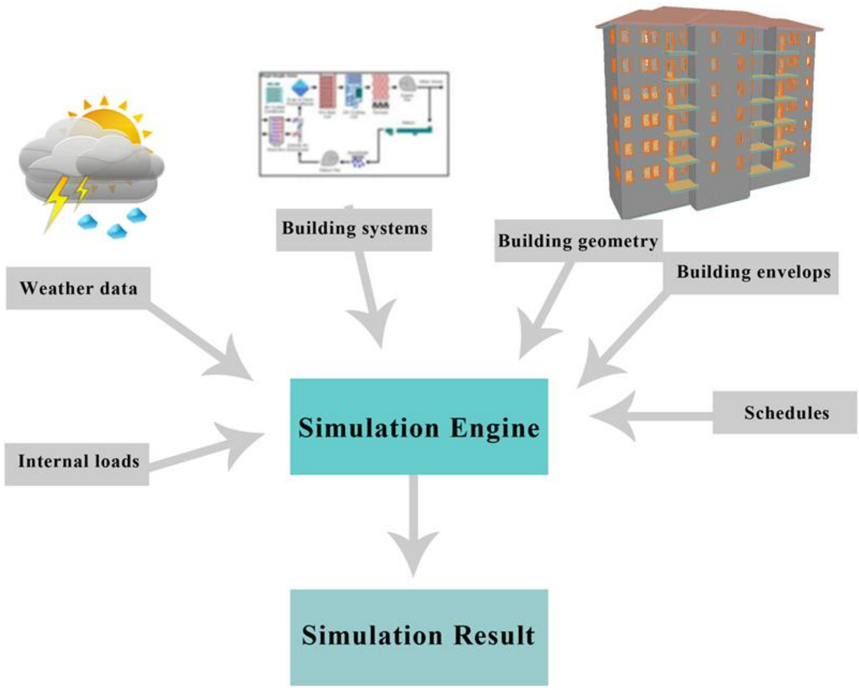


Figure 1. Summary of the input data necessary for BEPA

Location data refers to the exact location of the building expressed in longitude and latitude. The location data is the basis of some input information, like details about the site conditions, climate conditions, interior conditions and temperature set points, shading and other pertinent site features. Location data helps to gather average annual, monthly, and even hourly weather data. Most BEPA tools use location data to select appropriate weather information relevant to the project on hand. There are certain regions in the world which already have a database of their annual weather data that can be accessed by these BEPA tools. This local weather information is used to select interior and exterior temperature set points. For instance, energy goals for thermal simulation are set bon the basis of climate data. It is a priority in a building in a winter dominated climate to keep the interior environment warmer. On the other hand, in a hot climate priority is given for cooling the interior environment. Furthermore, location data can also be the source of other pertinent site data such as possible shadings of the building by vegetation, existing structures, and topography. [6; 5.]

The geometry of a building offers information for some of the basic inputs for an energy simulation model. When talking about building geometry, it is important to have a clear understanding of the basic distinction between the two types of building models, one for architectural representation and the other for energy simulation. While both models try to represent the building geometrically, the one needed for an energy simulation is concerned about grouping the architectural spaces in terms of their thermal properties and thermal comfort criteria. For instance, several architectural spaces might be combined into one thermal space or a single architectural space could be divided into multiple thermal spaces. This is done on the basis of the thermal characters and control patterns of the architectural spaces. Another example of a variation that might occur between the two types of building models are freestanding elements, that is walls or columns. Freestanding elements which are enclosed within a thermal space can be ignored provided that they are small enough so that their thermal mass does not have an effect on the heat transfer process. [6; 5.]

Building energy simulation calculations are mainly based on heat transfer from one point to another. One of the main goals of BEPA is to help the building designers meet the thermal comfort criteria for that building, to keep the inside of the building at a constant preferable condition. Hence, the building envelope could be considered as the first line of defence against heat loss from the inside of the building or heat gain from the outside of the building depending on the thermal comfort criteria of the building. Input data related to the building envelope is information about for example the building's opaque surfaces, glazing components, mass of the building, and infiltration rate. The thermal performance of the construction materials has a great impact on the result of the energy simulation. [6; 5.]

Internal heat gain is any heat and moisture increase in a building due to heat emitted by any source in the building. Common contributors to internal gains are heat gained lighting, any house hold appliances which use electricity also known as plug loads, people. Plug loads do not include building energy from major end uses such as HVAC, lighting, and water heating. Sensible and latent loads from people are also seen as internal gains. The main challenge in finding the values for these internal gains is predicting for how long, in a day month or year they should be considered running. That is, how many people are going to occupy the building and for how long, how many electrical appliances are used and for how long are they on. Approximating theses values should be done with great caution, as over or under estimating these values could result in exaggerated or understated simulation results. [6, 5.]

Occupancy schedules provide information about assumptions made regarding the occupant’s behaviour such as when and for how long the building will be occupied. Furthermore, occupational schedules are the basis for operational schedules such as lighting schedule and HVAC schedule. As buildings are not occupied 24 hrs a day, disregarding this data will result in unrealistically high-energy consumption when calculating the energy use. Even though it is very difficult to predict at what time of the day, month, or year the building systems, lights, electrical equipment and other energy consuming devices are operational, an approximation has to be made on the occupational schedules for the energy calculations on the basis of past experience or actual measurements. There are different standards and regional building codes which are used to approximate these schedules according to building type. Most simulation tools use one of the standards or some building survey to approximate the occupational schedules. The schedules chosen allows the approximation of several input data. [6, 5.]

Energy systems are a part of a building used for increasing user experience or indoor quality. They include the heating system, cooling system, ventilation, domestic hot water and many more. For good energy calculations, the systems have to be decided and the correct data must be entered. [6, 5.]

Because of the complex nature of energy simulation, most inputs are simplified on the basis of assumptions so that the simulation is manageable. For example, inputs like internal loads use assumptions as it is difficult to obtain the actual values. Thermodynamic concepts are also based on assumptions. Because of the differences in the assumptions used in various BEPA tools, knowing what assumptions and how the assumptions are made, will help the users when deciding if their choice of tool is appropriate for intended BEPA. [6, 5.]

To summarise, the relevance of the input and assumptions discussed above depends on the type of the analysis that is performed, as well as the design stage at which the analysis is performed.

2.2 BEPA Tools

According to the Building Energy Simulation Tool web directory (BEST-D), there are currently around 150 registered building energy simulation software tools [7]. Generally, the variations in the tools come from their graphical user interface, their interoperability with other tools, the assumptions and approximations employed in their thermodynamic models, and their purpose of use. BEPA tools usually comprise two parts, the simulation engine and the user interface. The user interface receives input files from the user and rearranges them in format that is understood by the simulation engine and supplies the data to the simulation engine. [5.] Figure 2 shows the basic architecture of most BEPA tools.

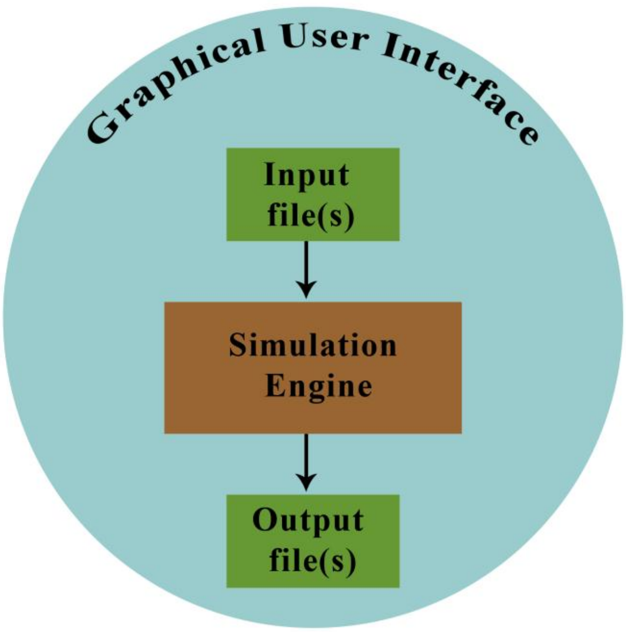


Figure 2. Basic architecture of most BEPA tools

Finally, after the input files have been processed by the engine, the user interface presents the output files to the user, usually in a graphical manner.

2.2.1 Simulation Engines

Thermal simulation engines use thermodynamics equations and routines to predict thermal processes in a building. There are a number of simulation engines available. DOE-2, EnergyPlus, and Blast are among the most commonly used.

DOE-2 is a freeware building energy analysis program that can predict the energy use and cost for all types of buildings. DOE-2 has been used for the last two decades. It was developed by the Lawrence Berkeley National Laboratory. Because of its long presence there are several user interfaces developed for it. The latest DOE-2 version is DOE-2.3 released in 2016. A DOE-2 engine is capable of modelling the building's heat loads such as loads from people, equipment, lighting, solar gain, and HVAC. By simulating the heat loads, DOE-2 is able to predict thermal behaviour of the building. The engine first calculates the heat transfer between adjacent spaces using only external and internal loads, considering thermal mass. Then the result of the calculation is used as an input for HVAC calculation. Based on the defined HVAC system, the engine makes the necessary calculation to satisfy the thermal loads. Here the engine assumes that thermal loads in each space is satisfied at every time interval of the simulation. There is no feedback from the HVAC calculation to the space load calculation. Therefore, if the defined HVAC system fails to satisfy the loads then the temperature of the spaces will change which in turn has an effect on the final calculation. [8.]

EnergyPlus™ is a free, open-source, and console-based simulation engine without a graphical interface. Its development is funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO). EnergyPlus is a whole building simulation program which can model both the energy consumption for heating, cooling, ventilation, lighting, plug and process loads, and water use in buildings. The features of the simulation engine include integrated simultaneous solution, heat balance-based solution, component based HVAC, and user definable time steps. [9.]

2.2.2 User Interface

Due to the complex nature of the thermal process and the vast amount of input data needed, simulation engines tend to get complicated very easily. In energy simulation, user interfaces play an important role in facilitating the data input to and output from process the simulation engines. There are several user interfaces developed for the different thermal simulation engines. This section introduces some of them.

eQUEST (the Quick Energy Simulation Tool) is a, DOE-2 based, interactive freeware for building energy use analysis. eQUEST 3.65 is the most recent release. It is designed to aid users performing complex building simulations without the need for extensive experience in BEPA. eQUEST uses wizards which assist the user when creating a model and collecting all the necessary data for the simulation, graphical result display module, and DOE-2 which is the simulation engine of eQUEST. The three wizards ease the processes of creating and preparing the BEM for the analysis. These wizards are Schematic Wizard used for creating a simple BEM, Design Development Wizard used for creating a complex BEM and Energy Efficiency Measure Wizard used for preparing the BEM for simulation analysis. eQUEST also supports the import of DOE-2 input files created by a third-party software. But when an external input file is imported all the wizards are disabled. Because eQUEST uses DOE-2 as its simulation engine, it has all the capabilities and limitations of the DOE-2 simulation engine discussed above. [10.]

DesignBuilder is whole building energy simulation program, which uses an EnergyPlus hourly building simulation engine. DesignBuilder uses modular solutions, where there is a core 3D modeler that works in conjunction with all other modules. The modules are visualisation for rendered images and site shading analysis, simulation EnergyPlus simulations for energy and comfort analysis, HVAC interface to EnergyPlus HVAC, and daylighting, cost and carbon. DesignBuilder offers up to 10 deferent modules, depending on the package purchased. DesignBuilder’s current release is version 5. [11.]

Autodesk Ecotect Analysis is a sustainable design analysis software which is mainly created to visualise and simulate design performance. Ecotect is capable of performing a wide range of simulation analyses including Whole-building energy analysis, thermal performance, water usage, cost evaluation, daylighting, and shadows and reflection. [12.]

Green Building Studio (GBS) is a web service that allows users to simulate a building’s energy performance and, based on the simulation, GBS estimates the annual energy need and cost of a building at the earliest design phases. The core simulation engine in GBS is DOE-2. To import the geometry of a building model into the services, GBS uses the gbXML file format. Using the imported geometry of the BEM, which includes thermal information such as zones, bounding surfaces with their corresponding openings, exterior shadings, and any additional information added by the user, GBS is able to simulate the energy performance of the building. For a building imported from BIM, users have to enter only the building type and location to have a quick simulation. GBS achieves this by filling out the rest of the input data with default values created on the basis of local building codes and standards. With GBS, users can create several alternatives of the base model to simulate, so that the effects of any changes made can be analysed. For a more advanced simulation, GBS can output files that can be used by advanced BEPA tools like DOE-2 and EnergyPlus. [13.]

Energy Evaluation tool is ArchiCAD's inbuilt BEPA tool. The tool uses StruSoft's VIP-core calculation engine that complies with the standard method of test for the evaluation of building energy analysis computer programs defined in the ANSI/ASHRAE Standard 140-2007. ArchiCAD's Energy Evaluation tool is a free partial implementation of Ecodesigner Star. The users of ArchiCAD have the privilege to use Energy Evaluation tool but for more advanced simulation options they have to purchase an extra license for the Ecodesigner Star. [14.]

The purpose of a BEPA is to gain insights into the thermal processes of a building, either in different stages of the design processes or an existing one, so that the energy efficiency of the whole building or part of the building can be optimized. The use of BEPA might vary depending on the level of information available about the building. For instance, an energy analysis conducted on a concept design could be in order to gain initial insight, to evaluate the multidisciplinary compatibility of the design, and to compare alternative design concepts. An energy analysis could also be conducted at a detailed design stage to analyse the effect of design decisions on the energy consumption of the whole building, to check the compliance with standards, local building codes and certification requirements, and to optimise HVAC design. [5; 6; 15]. Although the use of BEPA is not limited to the design stages of the building, this study is focused on the use of BEPA on buildings at the different design stages.

2.3 BEPA Results and Interpretation

The result of a BEPA depends on a number of factors, such as the quality of the inputs, the assumptions and approximations made, and the type of tool used. Generally, the analysis is a compromise between accuracy and speed. For example, for a simulation conducted to compare architectural design alternatives, the accuracy of a particular simulation result is not of major importance. The consistency of the assumptions that were used to run all the design alternatives is however crucial. This is because the difference in the final simulation results between the design alternatives is only caused by the choice of a particular solution when the rest of the assumptions are similar. But when it comes to predicting the absolute energy values of a building, accuracy becomes crucial. Different tests can be used to compare the energy simulation methods used by the simulation engines. One of this test is the BESTEST (Building Energy Simulation Test). This test is performed to compare energy simulation tools to each other. Another method is to compare the results with actual measurements from a test building. [5; 6; 15.]

3 BIM-based Building Energy Performance Analysis

Traditional physical models and drawings using the conventional CAD software need to be processed before they can be used for evaluating the building performance, which makes the analysis time consuming and too costly [16]. On the other hand, a building information model graphically depicts the building while capturing much of the data needed for the analysis process. Therefore, the integration of BIM with the performance analysis tools can reduce the work required by the analysis processes. BIM-based BEPA can also provide faster feedback on different design solutions so that early design decisions can be made.

When talking about building models, it is important to have a clear understanding of the basic distinction between the two types of building models, one for architectural representation and the other for energy simulation. While both types of building models represent the building geometrically, the one needed for energy simulation either excludes or includes geometric information which affects the heat transfer process. For instance, several architectural spaces might be combined into one thermal spaces or a single architectural space could be divided into multiple thermal space. This is done on the basis of the similarity of the thermal properties and control patterns of the architectural spaces. If they are similar, they are combined, but if one architectural space has different regions with different thermal properties or control patterns then it is divided into multiple thermal spaces. [15.]

In this chapter, first a conceptual understanding of the BIM creation process when BEPA is planned to be conducted is discussed. After that the extraction process of BEM from the BIM is introduced.

3.1 Conceptual Understanding of the BIM Creation Process

For a better understanding of the BIM creation process when BEPA is planned to be performed, this section of the study presents the concepts behind BIM in relation to BEM. In the context of BEM, building geometry is defined using:

- the thermal spaces, a discreet space which represents the volume of air in the building, which is responsible for heat transfer,
- bounding surfaces limiting the spaces,
- adjacency of spaces, the corresponding placement of spaces with respect to each other and the exterior environment,
- openings the placement of doors, windows and other openings on the bounding surfaces,
- shading surfaces elements which are placed outside of the spaces but affect the thermal process as shadings,
- construction material gives information on the type of materials used for the bounding surfaces.

Because of the vast number of tools and methods that can be used to create BIM, there appears to be some challenges in describing BEM when implementing BIM-based BEPA. One of these challenges arise from the use of terminology by different tools and methods, which creates confusion in describing BEM consistently and precisely. To have a consistent use of terminology, this section of the study uses the terminology defined by ArchiCAD, the main BIM-authoring tool used for the study. In the next section the fundamental building blocks of BEM and the importance of correctly defining them in the architectural BIM to produce the desired BEM are described.

Thermal spaces are called Zones in ArchiCAD. To avoid confusion, thermal spaces are referred to as zones in the thesis. Zones represent the volume of architectural spaces. Most of the geometry generated in the BEM are based on zones. The main process of energy simulations is based on heat transfer from one point to another. Zones represent the volume of air in space which thermally interacts with other spaces. Therefore, zones describe the fundamental input parameters of energy simulation. Furthermore, input parameters, like boundary surfaces and openings are based on zones. Consequently, zones need to be defined correctly in order for the simulation to produce more reliable result. [15; 16; 17.]

In ArchiCAD bounding elements are elements such as walls, slabs and roof, which define the limits of zone by surrounding it. In BEM, these bounding elements are represented as 2d surfaces. In some cases, the bounding elements are broken down into multiple surfaces. An example of this is a curved wall, which has to be divided into multiple 2d surfaces to correctly represent it in the BEM. In addition, bounding elements can be broken down in to several surfaces when one bounding element is adjacent to more than one space, if the spaces have different comfort criteria. [15; 16; 17]. Figure 3 below illustrates how a building element is divided into two surfaces.

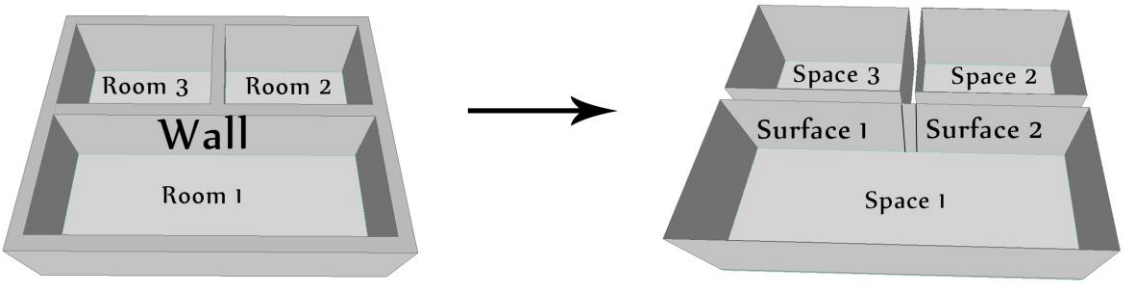


Figure 3. From one bounding element to several bounding surfaces.

ArchiCAD elements such as doors, windows, openings, and skylights are treated as openings in the BEM, and they are represented using 2D surfaces. The same way as the doors and windows need a wall to exist in the BIM, openings need a bounding surface to exist in a BEM. [15; 16; 17.]

Shading surfaces are building elements that are not included in a zone. They are elements which are not considered as bounding elements, openings, or enclosed in a zone provided that they shade the building. For example, a balcony or a roof overhang can be considered a shading element and converted to a shading surface for the BEM. [15; 16]

For the BEM to represent the building model with zones, zones have to be arranged in the same way as the architectural spaces are arranged. For that, adjacencies of zones are used to check all sides of zones and arrange them in the correct manner. Using the adjacency of zones, the BEM is able to determine if a bounding surface is external or internal. If a bounding surface has adjacent spaces on both sides then it is an internal surface, whereas if the bounding surface has only one adjacent space, is considered an external surface, if the bounding surface has no adjacent thermal spaces, it is possible that the bounding surface is a shading surface. [15; 16; 17.]

3.2 Extracting BEM from BIM

Because a BIM created by the BIM-authoring tool has a lot of complex data, it must be simplified or reduced to only include the information needed by the BEPA tool. This could be done either with the BIM authoring tool or with the help of a third-party tool dedicated to extracting the necessary information for a BEPA or with the BEPA tool. Currently there are many data schemas used in the AEC industry for file transfer between the BIM-authoring and BEPA tools. The choice of extraction work flow to adopt for converting BIM to BEM depends on the BIM-authoring and simulation tool used for the analysis. Currently, the Industry Foundation Class (IFC) and Green Building XML (gbXML) are two widely used schemas for the exchange of data between the BIM and BEM. [15, 18, 19.]

Industry Foundation classes (IFC) is file transfer schema defined, published, and promoted by buildingSMART to provide an environment of interoperability among different BIM authoring tools of project stakeholders. IFC allows building simulation tools to receive building geometry and other building data from a BIM if it is created with IFC-compliant CAD software. [20.]

The Green Building XML schema, gbXML, was developed by Green Building Studio to facilitate the transfer of building information stored in BIM between the building design and analysis tools. Currently several industry leading CAD software and BEPA tools use this schema to transfer building information that is required to run a BES. Figures 4 below shows a simplified file organisation in gbXML schema.

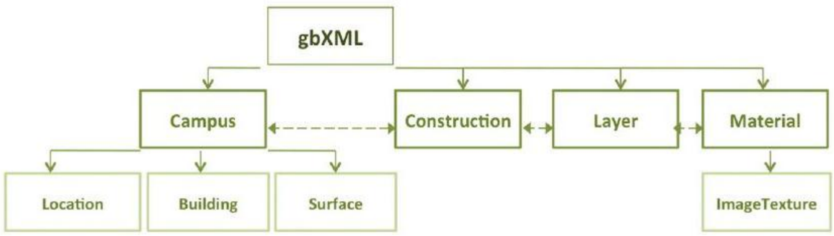
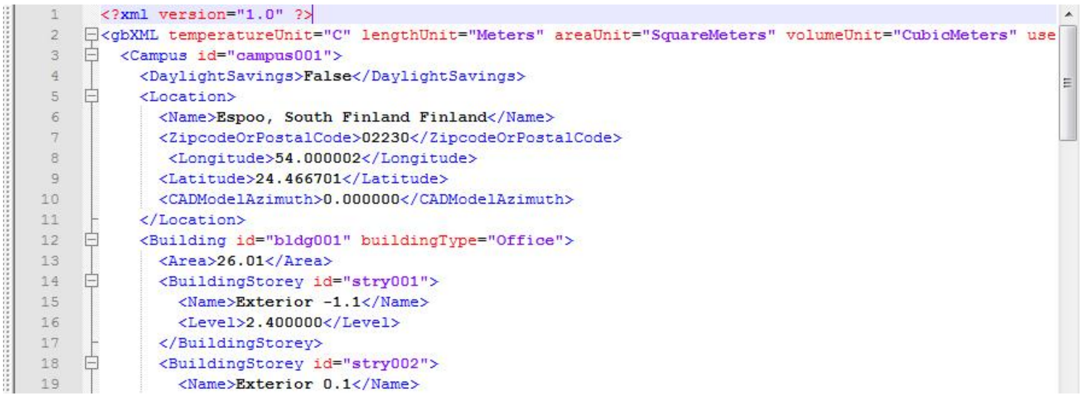


Figure 4. File organisation in gbXML schema

gbXML uses the XML language, which is a type of computer language that allows communication between different computer programs without the intervention of humans.

An XML file can be viewed and edited with a simple text editor. [21.] Figure 5 below shows a sample gbXML file when viewed using a text editor.



```
<?xml version="1.0" ?>
<gbXML temperatureUnit="C" lengthUnit="Meters" areaUnit="SquareMeters" volumeUnit="CubicMeters" use
  <Campus id="campus001">
    <DaylightSavings>False</DaylightSavings>
    <Location>
      <Name>Espoo, South Finland Finland</Name>
      <ZipcodeOrPostalCode>02230</ZipcodeOrPostalCode>
       <Longitude>54.000002</Longitude>
      <Latitude>24.466701</Latitude>
      <CADModelAzimuth>0.000000</CADModelAzimuth>
    </Location>
    <Building id="bldg001" buildingType="Office">
      <Area>26.01</Area>
      <BuildingStorey id="stry001">
        <Name>Exterior -1.1</Name>
        <Level>2.400000</Level>
      </BuildingStorey>
      <BuildingStorey id="stry002">
        <Name>Exterior 0.1</Name>
```

Figure 5. Sample gbXML file when viewed using a text editor

To summarise, BEM can be extracted from BIM using data transferring schemas like IFC and gbXML.

4 Testing BEPA

A test was conducted to better understand the elements, tools, and operations presented in the chapters above. For this purpose, two different building models were created using Graphisoft's ArchiCAD BIM-authoring tool. With the models, the BEPA processes were tested on DesignBuilder, eQUEST, GBS, and ArchiCAD's energy evaluation, introduced above. First, a detailed description of the models tested is given, followed by a presentation of the steps in the main BIM-authoring tool to prepare the model for conversion. Finally, the results of the test are analysed.

Using Graphisoft's ArchiCAD, two hypothetical building models are created for testing purposes. The first one, model 1, is a six story multi-family apartment which is in Espoo, Finland. The second model, model 2, is a single family detached house also located in Espoo, Finland. Model 1 is used for checking product model delivery from one tool to the other when the model is complicated. Model 2 is used for checking product modelling delivery when the model is simple and for testing energy simulation for the calculation of the annual energy consumption.

Figure 5 below shows the architectural rendering of these building.

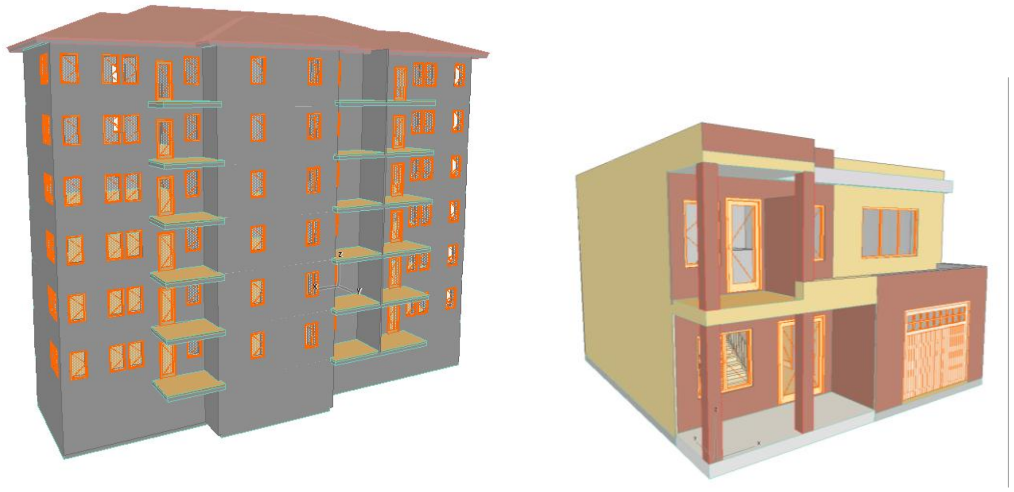


Figure 6. Rendering of model 1(left) and model 2(right).

Both models are used to check the interoperability between the selected design tools, giving emphasis on the extraction process and information losses during the file transfer process.

4.1 Preparing the BIM for Conversion

To start with, since zone volumes are essential for energy simulation, ArchiCAD zones should be correctly defined with the right bounding surface for each zone and right adjacencies (zone placements with respect to each other). If an earlier version of ArchiCAD is used, ArchiCAD 19 or less which does not support native gbXML export, it is a good practice to group all zones as interior and exterior and create a separate layer for each. That is because, in the case of gbXML export using Cadimage, an add-on to ArchiCAD for exporting gbXML files, in addition to the zones which represent the thermal spaces, also known as internal zones in this case, a zone which encloses all the bounding element must also be added. This extra zone is called external zone and does not have any effect on the thermal calculation, but it is only there for Cadimage's use in the extraction proses.

When using Cadimage to export as gbXML there is an option to put zones automatically, where the add-on will figure out all the necessary zones in accordance with the architectural spaces. Figure 7 below shows Cadimage's "place zone" option that will automatically put zones in to the model.

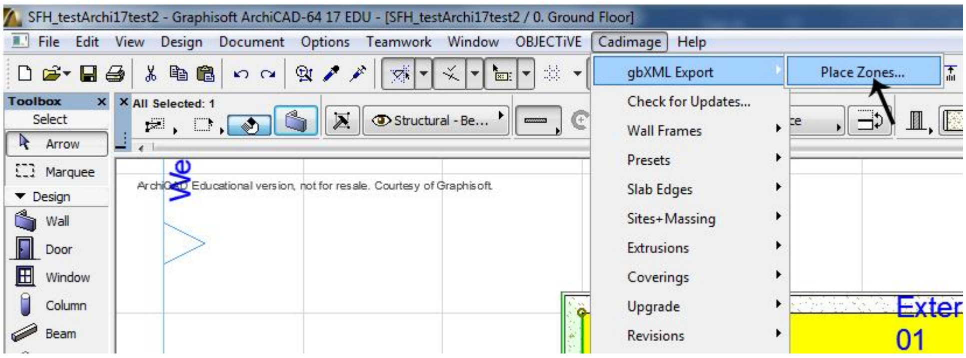


Figure 7. Cadimage's place zone option in ArchiCAD

Furthermore, to make the BIM creation and file transfer process as smooth as possible, ArchiCAD's environment was set up and optimized. Using the layer combination option of ArchiCAD, it was much easier to see and correct errors in the 3D view window. Figure 8 shows ArchiCAD's 3D view with and without optimized layer option for zone.

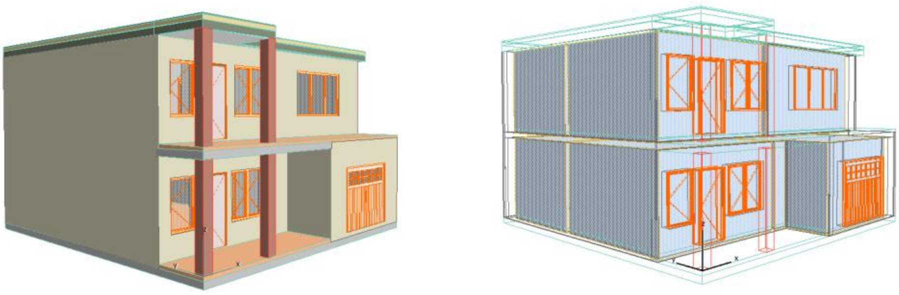


Figure 8. 3D view in ArchiCAD, without and with optimized layer option for zone editing, right and left respectively.

After all the necessary checks and corrections are complete, the BIM is ready for export.

4.2 Results of the Test

First, a test is conducted to investigate the information delivery process from the BIM model to the BEPA tool. The gbXML file format is used to see if a successful file transfer can be achieved using this data schema. Both model 1 and model 2 were tested to see how the tools handle models with different levels of complexity. The results are analysed to understand the significance and barriers of product model sharing among these selected tools. The test goes further to investigate the additional rework needed, if there is one, in the specific application in question. Finally, a simulation is run using model 2 to calculate the annual energy consumption by the building. The following steps and the results of the simulation conducted with BEPA tools are discussed below.

The exported gbXML model contains geometric information such as information about the building's stories, building elements, zones, and openings. It also contains the location information of the building. If the gbXML is exported using ArchiCAD 20, then the thermal properties of the building materials are included. The properties are conductivity, density, R-value, and specific heat.

4.2.1 DesignBuilder

Before importing any BIM file into DesignBuilder, a new project is created. Here, the buildings location information, the simulation engine either EnergyPlus or DBSim used for the project, and a template the project is going to be based on are specified. After that a new building can be added. Through the "Add new building" dialog box we can specify the building's location and the default values to use for some inputs which are necessary for the simulation. At this point the building type that is going to be modelled or imported is selected from a list of options. The options depend mainly on the type of the analysis that is to be performed on the model, and the amount of information available about the model. DesignBuilder also provides a default data template that can be applied to the building or input data templates can also be created and applied. At this stage, there are five categories of input data that has to be entered about the building using templates for each category. The categories are activity, construction, glazing, HVAC, and lighting. It should be noted that there are number of information's that need to be inputted under each category, but once a template is created it can be reused for different projects. After the project creation DesignBuilder is ready to import a gbXML file from the BIM.

Using the building model exported from ArchiCAD in gbXML file format, DesignBuilder is able to understand most of the information about the geometry, construction, and thermal spaces of the model. The software has two options to interpret the model. One is to import the surfaces of the model, and the other is to import the thermal spaces to recreate the BEM in DesignBuilder. Using both options it is possible to exclude or include information from the imported model, depending on the type of analysis needed. After importing the models some shading surfaces were placed incorrectly, some walls and windows were omitted, and there were problems with wall types. Both models needed some tweaking before simulation can be started. Figure 9 shows a 3D view of the tested models imported into DesignBuilder.

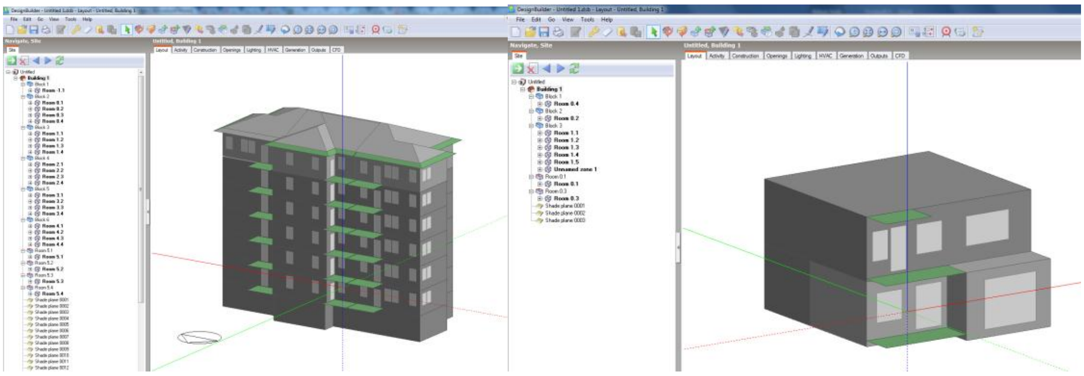


Figure 9. Tested models as imported into DesignBuilder.

DesignBuilder has different categories of input parameters that needs to be filled before a simulation can start. The input parameters can be filled through the input templates provided by the software, but for a more precise simulation the input parameters have to be edited manually. Depending on the selected building elements, DesignBuilder shows the relevant input parameters that can be edited. Figure 10 below shows the categories of input parameters.

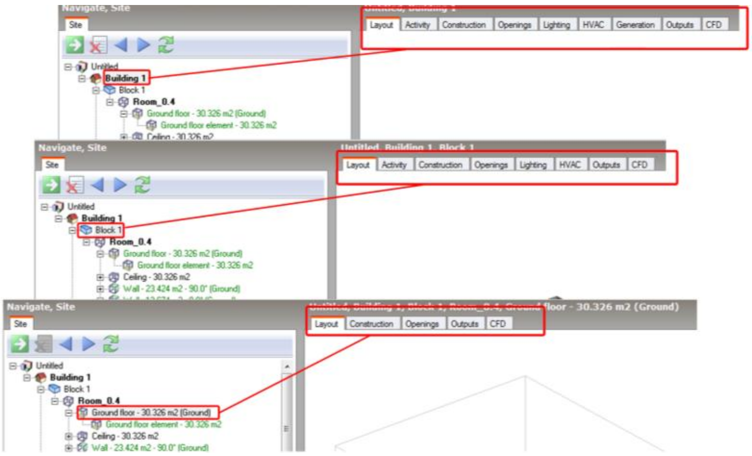


Figure 10. Categories of input parameters.

After all the necessary input parameters have been correctly filled, the final set up, necessary for the simulation, is done, which is to specify the parameters for the method of calculation and the method of output in the simulation. Figure 11 shows the different calculations and simulation capabilities of DesignBuilder.

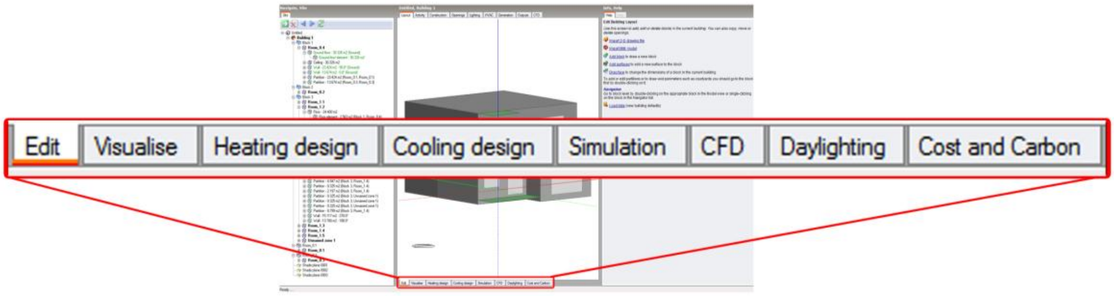
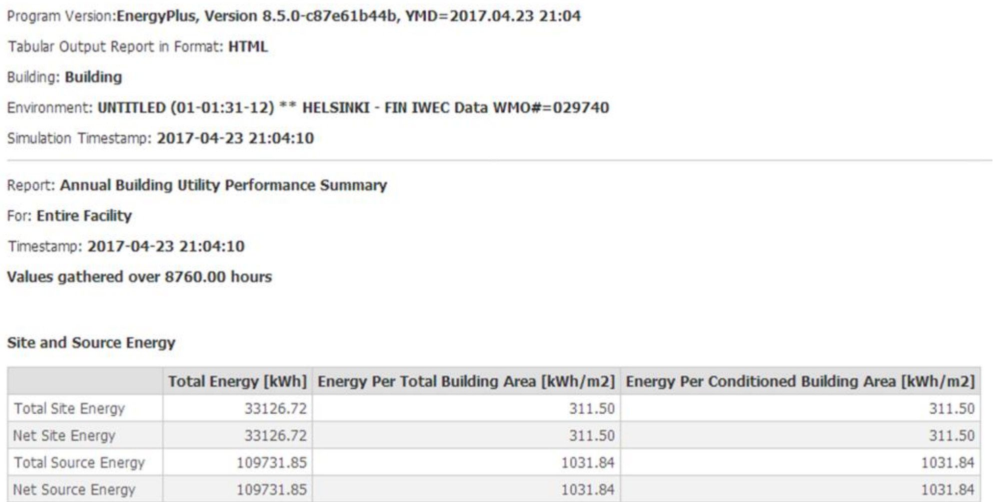


Figure 11. Energy simulation and calculation types availabel in DesignBuilder.

After all the necessary input parameters have been correctly filled in, the simulation can be started. DesignBuilder is capable of for example calculating heating and cooling design, and of simulation using the EnergyPlus simulation engine.

Finally, the annual energy performance of model 1 is simulated using EnergyPlus simulation engine, through DesignBuilder. Figure 12 presents the output from the simulation.



Program Version:**EnergyPlus, Version 8.5.0-c87e61b44b, YMD=2017.04.23 21:04**

Tabular Output Report in Format: **HTML**

Building: **Building**

Environment: **UNTITLED (01-01:31-12) ** HELSINKI - FIN IWEC Data WMO#=029740**

Simulation Timestamp: **2017-04-23 21:04:10**

Report: **Annual Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2017-04-23 21:04:10**

Values gathered over 8760.00 hours

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	33126.72	311.50	311.50
Net Site Energy	33126.72	311.50	311.50
Total Source Energy	109731.85	1031.84	1031.84
Net Source Energy	109731.85	1031.84	1031.84

Figure 12. DesignBuilder Simulation output using EnergyPlus simulation engine.

The simulation output from EnergyPlus simulation engine can be saved as HTML file which can be viewed using a web browser.

4.2.2 eQUEST

There is no setup required prior to importing the input data of the building. The workflow of eQUEST involves the uses of two methods to enter input data, which is either using a wizard which simplifies the data inputting processes significantly or through the use of an external input data file. Unfortunately, when importing external input data files into eQUEST, the software will disable the functionalities of the wizards.

Although there is no direct 3D BIM import capability, using a third-party software, capable of exporting DOE-2 input file formats, eQUEST is able to import the BEM. Therefore, the BEM exported from the ArchiCAD's BIM in a gbXML file format has to go through GBS to be converted into a DOE-2 input file using inp file format. Using the DOE-2 input file exported from GBS, eQUEST is able to import the models 1 and 2. As seen in figure 8 below, visual inspection of the tested models reveals a relatively accurate translation of the model geometry from the BEM, with only some minor errors. Some of the materials assigned to the boundary surfaces were incorrect. Figure 13 below shows the 3D view of the models when imported in eQUEST.

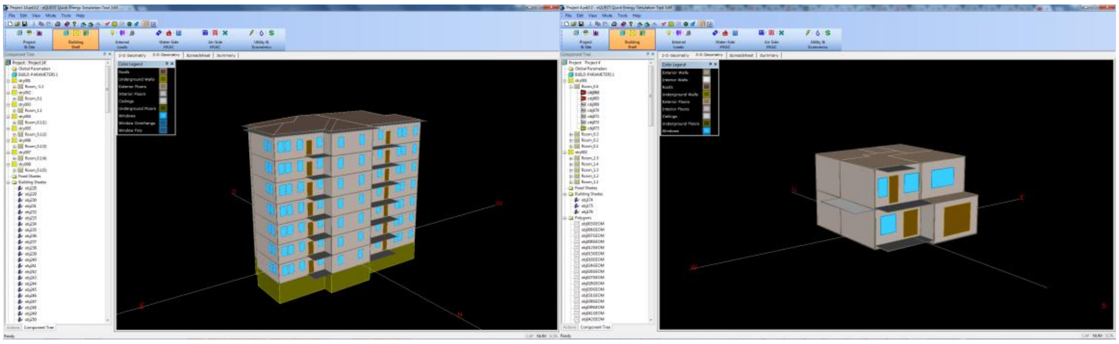


Figure 13. Tested models as imported in to eQUEST.

Because the original gbXML file was converted using GBS, the DOE-2 input file was populated with default input values from standards and regional building codes within GBS. This is very helpful if a quick simulation is required based on the standards and regional building codes. But for a more precise simulation, going through all the input parameters manually, as opposed to using the wizard since it is disabled after the import of external input files, is necessary. eQUEST requires advance level understanding of the simulation processes in order to go through all the necessary input parameters. eQUEST also provides a list of standards and codes that can be used to check the building's compliance with them. Weather data has to be entered in a separate file format that eQUEST can understand, bin file format. The necessary input parameters are categorised into six different categories that are project and site, building shell, internal loads, water-side HVAC, air-side HVAC, and utility and economics. Figure 14 bellow shows the different sets of inputs needed.

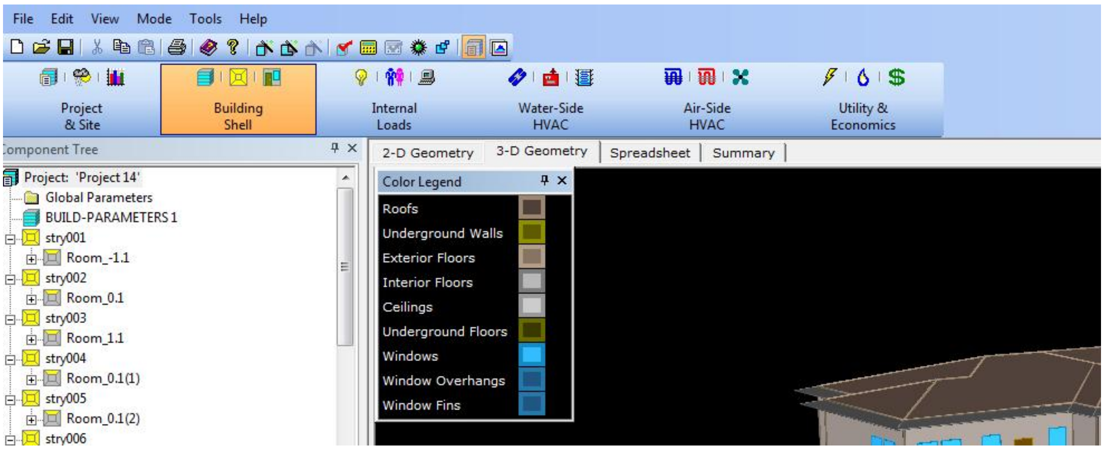


Figure 14. Category of input parameters required by eQUEST

The last category of input options before running the simulation are mainly about the simulation itself. They cover the simulation period starting and ending day of the simulation, and the output method yearly, monthly, or hourly. Finally, the simulation can be started. Figure 15 shows the baseline design simulation result for test model 1.

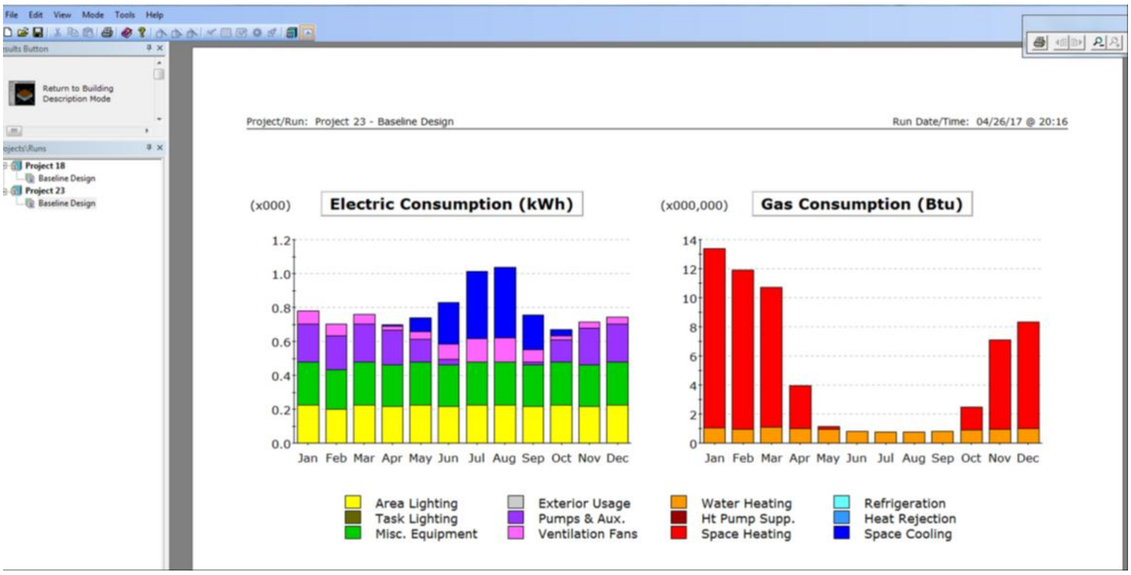


Figure 15. eQUEST’s simulation output result for annual energy consumption.

The simulation results can be viewed either inside eQUEST, with a graphical presentation, or the full output from DOE-2 can also be viewed in a text format.

4.2.3 Green Building Studio

To start a new project in Green Building Studio, first some mandatory input information for the project have to be entered. This information is the project name, building type, project type, location information, and schedules which can be left to be filled by default values by GBS. Based on these information, GBS automatically fills in the rest of the necessary inputs using standards and regional building codes. This process makes it very easy to have a quick simulation run when the model is imported.

After the project is created, a gbXML file is imported. Then the 3D geometry correctness of the building can be checked using a VRML viewer. GBS does not have any options to edit the 3D geometry. It was not possible to import he extracted BEM from ArchiCAD into GBS using Cadimage's gbXML file export option. But using Ecotect as a middleware, the exported gbXML models were imported into GBS.

After the gbXML file is loaded, GBS starts the simulation run. If there are any data missing which are necessary for the simulation, GBS automatically fills them in with default values from standards and other sources. GBS also allows for the user to create and use templates with pre-set input values. GBS is able to deliver the result of the simulation very quickly. For advanced simulation options GBS can export an input file for import to DOE-2 and EnergyPlus simulation software. Figure 16 below shows a 3D visualisation of the imported gbXML file using a VRML viewer.

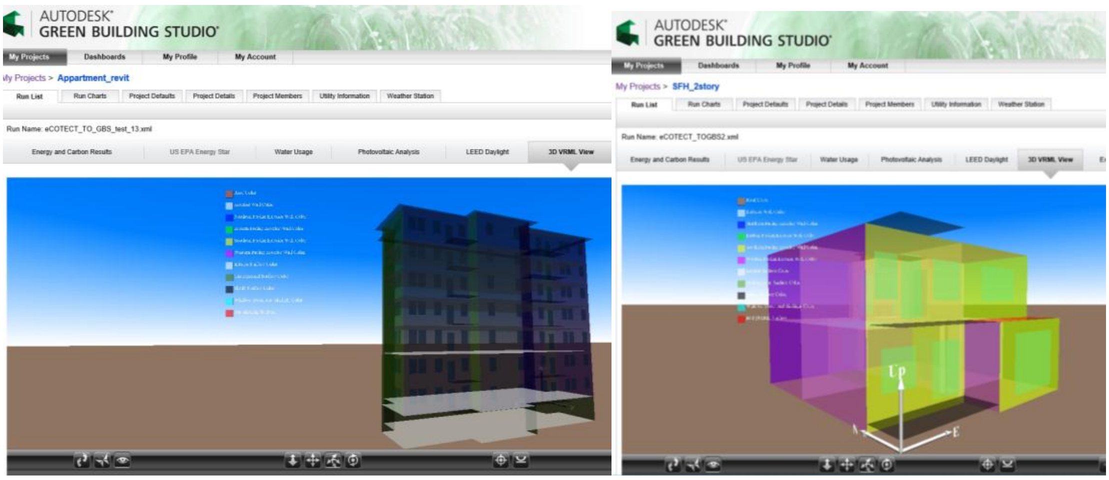


Figure 16. GBS imported model 3D view using a VRML viewer.

For advanced simulation options GBS provides a limited number of modifiable input data sets. In GBS some options cannot be edited once a model is submitted for simulation.

For example, utility information, building type, and the corresponding schedules used cannot be edited or changed once a run is initiated. But other input parameters, like the projects default which contains information about spaces, zones, surfaces, openings, and HVAC & DHW can be edited. In GBS it is possible to create different design alternatives which can be compared to improve the building's energy performance.

After all the preparation is complete, the model is imported to GBS. As soon as the model is imported GBS automatically runs the simulation and shows the building's annual energy consumption, carbon footprint and energy cost. The results from the simulation are presented in appendix 2.

4.2.4 ArchiCAD's Energy Evaluation

ArchiCAD's built in energy evaluation tool needs some calibration before starting an energy simulation. Because the energy evaluation tool is embedded in ArchiCAD, the extraction process from BIM to BEM is done automatically and the BEM can be reviewed instantly. Once all necessary preparation is completed, the energy evaluation processes can start. The first step in the process is to review the energy model and check that all the architectural spaces are assigned a corresponding zone. After that, thermal blocks are created and assigned a certain operation profiles. For each thermal block, a predefined building system, such as heating, cooling and ventilation, is selected. The building systems can be modified. After all necessary thermal blocks are created zones are added to the corresponding thermal block. Finally, the simulation can be started. ArchiCAD's energy evaluation tool can be upgraded to EcoDesigner Star with the purchase of an extra licenses. EcoDesigner Star has some extra features for advanced simulation options. The results from the simulation are presented in appendix 1.

4.2.5 Summary of the Results

In this section, a summary of the results from the tests is presented. Figure 19 below shows the summary of interoperability between the tested tools.

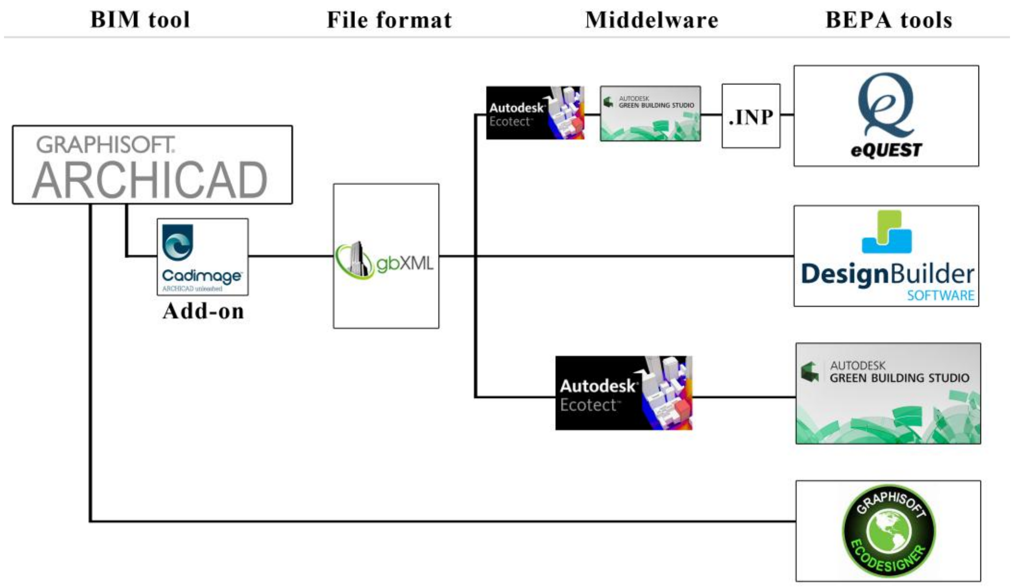


Figure 17. Summary of interoperability of the tested tools

The BEM exported from ArchiCAD with the help of Cadimage could be imported directly into DesignBuilder. But in order to import it into GBS, it had to be re-exported using a middleware, Autodesk Ecotect. In the case of eQUEST, two middlewares, Ecotect and GBS, had to be used to generate the necessary input file.

Table 1 below summarises the result of a comparison between the different BEPA tools that were tested.

Table 1. Summary comparison between the tested BEPA tools

Functionality/ Tools		**Design-Builder**	**eQUEST**	**GBS**	**EcoDesigner**
Engine		EnergyPlus	DOE-2	DOE-2	VIPcore
Weather data input file format		.epw	.BIN	Download from GBS	Download from Strusoft
Geometric data input file format		gbXML	.inp	gbXML*	Not needed
Ability to modify the BEM using 3D CAD tools inside the BEPA tools		Yes	No	No	Yes
Data exchange with ArchiCAD’s gbXML	Location	Yes	Yes	Yes	Yes
	Building	Yes	Yes	Yes	Yes
	Surfaces	Yes	Yes	Yes	Yes
	Openings	Yes	Yes	Yes	Yes
	Construction	Yes	Yes	No	Yes
	layer	Yes	Yes	No	Yes
	Material	Partial	Partial	No	Yes
Re-input needed		some correction on geometry Construction Layer Material	some correction on geometry Construction Layer Material	some correction on geometry Construction Layer Material	
Difficulty of use		medium	complicated	simple	simple
Other input data entering method		Country or region specific templates. or manual input	manual input	Country or region specific templates. or manual input	manual input

* This gbXML file was re-exported using Ecotect.

The results show that out of all the information included in a BEM exported from ArchiCAD, information regarding the materials could not be translated by all of the tools tested. Out of all the tested tools, eQUEST and DesignBuilder are more suited for advanced users, whereas GBS and Energy Evaluation are slightly easier to use and more suited for users with basic knowledge on energy simulation.

4.3 Analysis of the Results

As mentioned in chapter 3, a BEPA is objective. The intended use of the BEM dictates what specific information it should contain, and its level of detail. With that in mind, the test showed some significance and barriers of product model delivery when implementing BIM-based BEPA with the selected tools. In this section, the results are interpreted.

As mentioned chapter 3 one of the main benefits of using BIM as a basis for BEPA is to save a significant amount of time, which otherwise would have been spent recreating the building model for energy simulation purposes. The results from the study have proved that it is possible to reduce the amount of time spent on creating a BEM through the implementation of a BIM-based BEPA. This is achieved by extracting information from the BIM and using it as a starting point for creating the BEM, which otherwise would have been created from scratch.

One of the major problems observed in the test is errors with the product model delivery. Problems occur while transferring the file from the BIM to BEM mainly because of the difference in organising the BEM data, in the BEPA tools, and BIM. For instance, a gbXML file exported from ArchiCAD, using Cadimage as a translator, fails to import in GBS, but the same file was successfully imported in Ecotect. When the same gbXML file was re-exported using Ecotect, it was possible to import it to GBS. The gbXML format files created with the three different programs show that there is a slight difference in how they are formatted, even though they all represent the same building energy model. These differences create the errors mentioned. Another problem is the need for extensive knowledge of the BEPA tool in question, to identify and rectify errors during the translation. The constant switching from one software to another, or manually going through and changing the input parameters before getting the correct geometry for simulation are drawbacks.

Taking a closer look at the organization of the data exported from the ArchiCAD's BIM into a gbXML file using Cadimage, it can be observed that it contains information like project data, geometry information such as size, shape, boundary, and adjacency of each spaces, material and construction information, and other information from the document. In most BEPA tools that were tested, using the exported gbXML file it was possible to transfer geometric information more precisely. But for the other information types, re-inputting the data or mapping the bounding surfaces with their corresponding material type was unavoidable.

Although BIM-based BEPA has proven to be helpful by transferring geometric information about thermal spaces, there are still vast amounts of information that need to be entered in to the BEPA tool. Some tools try to approximate or guess this missing information using standards and country codes. For instance, GBS can start the simulation with just location information, building type, and the 3D model in gbXML file format. Because GBS is mainly intended to be used for comparing design alternatives, the accuracy of a single simulation is not that important but rather the relative difference between the simulations of the different design alternatives. But as accuracy becomes important, the number of inputs that must be entered increases. Most of the tested BEPA tools have an option to create templates that can be applied whenever a new project is created. But for a more precise simulation it is necessary to go through the input parameters and change them to the desired value. Due to the difference in the level of detail in the sets of input data the BEPA tools are capable of defining, and other factors that are beyond the scope of this study, the tested BEPA tools produced different results in the final simulation output for the annual energy consumption of the test building.

5 Findings of the Study

After exploring and testing the required steps and processes involved in the BIM-based BEPA, the findings of the study are presented in this section. The findings are presented it two sections, the first section deals with the important points that should be given attention to while performing an energy analysis using BIM as a basis and the second section deals with additional input information that is needed for a successful BEPA.

5.1 Important Point to Consider Before Implementing BIM-based BEPA

Based on the results, the following points were found to be important and need to be given attention to, to maximize the benefits of using BIM in the case where BEPA is planned to be performed.

Set the goal of the BEPA: Before starting the BIM creation processes, it is a good practise to have clear goals for the type of analysis needed. This highly depends on the information that is available about the building in question. For example, for a building in its early design stage, the goal of the analysis is usually to have a better understanding of the effects of a particular design decision; what type of form, orientation, and envelope to choose. On the other hand, for a building in its design development stage, the goal of the analysis could be to achieve the thermal comfort criteria or predict the annual energy usage. Therefore, knowing the goal of the BEPA helps focusing on the information that is important for that particular simulation, when creating the BIM.

Choosing the right tool for BEPA: Because of the vast number of tools available in the market, which differ in their application area, degree of difficulty of use, level of accuracy, and the speed they perform a simulation, it is very important to choose the right tool suitable for the type of analysis performed.

Understanding the limitation of the tool used: The goal of the energy simulation tools is to mimic the thermal processes that exist in real life and apply them to a model which represents an unbuilt or existing building. Because of the complexity of these thermal processes, BEPA tools use assumptions or approximations to simplify the processes. These approximations and assumptions put a limitation to the type of analysis and level of accuracy that can be achieved using a certain tool. Therefore, it is necessary to understand the limitations of the tools that is going to be used, to make sure the tool is right for the intended type of analysis.

Setting up the BIM authoring tool: To make the BIM creation and file transfer process as smooth as possible, setting up and optimising the main BIM authoring tool is crucial. Grouping elements according to their types, defining construction materials and layer composite, correctly assigning zones to all the architectural spaces with the right area and volume are some of the things that seem simple but are important to have a seamless transfer of data from the BIM to BEM.

Checking the BIM for error before exporting: It is a good practise to check the BIM for errors before exporting it to any BEPA tool, as it will save a great deal of time and frustration from trying to correct errors in the BEPA tools. For one thing, it is very difficult to spot errors in the BEPA tools as errors made in BIM when translated could distort the BEM in unpredictable ways that are hard to trace to the cause. And even if the error is spotted, to correct it one must either back and forth between the BIM and the BEM, or manually change the values in the BEPA tool, which is time consuming.

Simplify the model: Model elements which are unnecessary for the specific simulation only hinder the processes. It is important to include model elements which are needed for the analysis, as model elements are processed in the BEPA tool, but the ones that are not important only make the processing time longer. Therefore, it is a good practice to exclude model elements which are insignificant for the analysis in question, before exporting to BEM.

The study has shown that implementing BIM-based BEPA saves significant amounts of time spent on recreating the BEM for the analysis. But the transfer of data from the BIM model to BEM is limited to the geometric information. This limitation exists because either the BIM authoring tool is not capable of producing the necessary data that can be used as an input by the BEPA tool, or even if the BIM-authoring tool is capable of producing this information, the interoperability between the tools limits the use of this information by the BEPA tools. For example, ArchiCAD is able to produce some additional information like the thermal property of building materials, aside from the building's geometry, and gbXML is capable of transporting that information. However, Cadimage, the tool used to extract the BEM, is unable to represent information other than geometry. Therefore, all the information produced by ArchiCAD could not be exported to the BEM.

Regardless of the type of tools used, it is unlikely that the need for additional inputs can be avoided. Some BEPA tools use standards and regional codes to approximate and guess the long list of input parameters needed, but this can only help if the intended simulation is to have a quick overview of the buildings thermal performance or to check the conformity of the building against the standards and regional codes.

6 Conclusion

This thesis explored the basic principles of BEPA by looking at the necessary processes and inputs needed to simulate the thermal processes in a building and analyse the result. The study also explored some selected BEPA tools which support BIM-based BEPA. Finally, in an attempt to further understand the BIM-based BEPA, a test was conducted using a BIM created for this purpose. The test included the creation of the BIM and the extraction of the relevant information that can be used for creating and simulating a BEM in the BEPA tools.

The result of the study shows that, to maximize the benefits of using BIM for BEPA, the following points should be emphasised.

- The goal of the BEPA
- Setting up the BIM authoring tool to have a seamless translation of data
- Understanding the limitations of the tool used
- Checking the BIM for errors before exporting
- Choosing the right tool for BEPA
- Simplifying the model

Moreover, the study found out that even though implementing a BIM-based BEPA saves a significant amount of time when creating the BEM, there still remains a great deal of work involved in the creation of BEM. However, the level of detail of the necessary input data needed varies depending on the BEPA tools used. From the test, it can be seen that DesignBuilder and eQUEST needed far more detailed inputs than GBS and ArchiCAD's Energy Evaluation. Some BEPA tools use predefined sets of input data that can be applied to a building model depending on the intended use of the building.

Problems related with interoperability were constantly faced during the testing process. The main reason for problems that occurred during information transfer from the BIM to the BEM were found to be either misreading of the extracted information by the receiving BEPA tool or loss of information during the transfer process. Furthermore, the tool that was used to extract a gbXML file also had an impact on the transfer process. For instance, a gbXML file exported from ArchiCAD failed to import into GBS, whereas when the same file was re-exported using Ecotect it was possible to import it using GBS.

Finally, the author suggests further study on the relationship between the different input parameters that are available for customization within the BEPA tools and their effect on the final simulation outputs. The suggested study will strengthen the work presented on this thesis.

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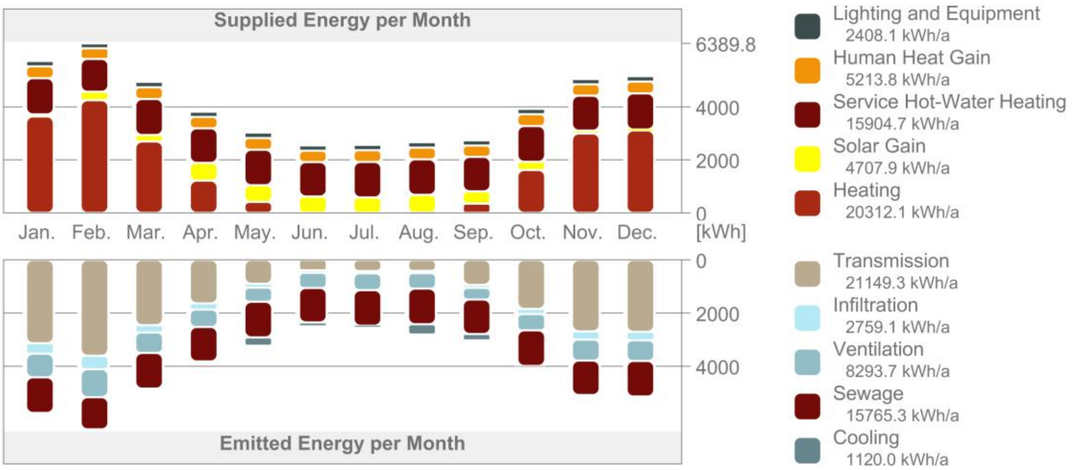
Simulation Output from ArchiCAD's Energy Evaluation.

Project Energy Balance



Key Values

General Project Data		
Project Name:	SFH_testArchi17test2	
City Location:		
Climate Data Source:	Strusoft server	
Evaluation Date:	4/26/2017 8:36:10 PM	
Building Geometry Data		
Gross Floor Area:	**172.60**	m²
Treated Floor Area:	**148.80**	m²
External Envelope Area:	**278.13**	m²
Ventilated Volume:	**415.21**	m³
Glazing Ratio:	**3**	%
Building Shell Performance Data		
Infiltration at 50Pa:	**3.09**	ACH
Outer Heat Capacity:	**39.36**	J/m²K

Heat Transfer Coefficients	U value	[W/m²K]
Building Shell Average:	**0.78**	
Floors:	**1.02 - 1.02**	
External:	**0.34 - 1.02**	
Underground:	**--**	
Openings:	**2.11 - 3.33**	
Specific Annual Demands		
Net Heating Energy:	**135.31**	kWh/m²a
Net Cooling Energy:	**7.53**	kWh/m²a
Total Net Energy:	**142.84**	kWh/m²a
Energy Consumption:	**314.67**	kWh/m²a
Fuel Consumption:	**314.67**	kWh/m²a
Primary Energy:	**401.27**	kWh/m²a
Fuel Cost:	**--**	GBP/m²a
CO_2 Emission:	**9.35**	kg/m²a

Energy Consumption by Sources

Energy					CO_2 Emission
Source Type	Source Name	Quantity	Primary	Cost	
		kWh/a	kWh/a	GBP/a	kg/a
Secondary	Electricity	6442	19327	--	1391
	District Heating	35899	35899	--	0
	District Cooling	4480	4480	--	0
	Total:	**46821**	**59706**	Not Applicable	**1391***

Simulation Output from GBS.