QUEEN – A novel design flow and decision support tool for sustainable buildings

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Abstract

The established building design process is a very conservative one. New technologies and energy efficient systems are hardly adopted since there are few reference buildings out there. Risk minimization, cost pressure and the complexity of the design process therefore leads to a poor innovation cycle and old-fashioned, inefficient buildings. We present a design flow that overcomes this hurdle by means of simulation. A decision support tool uses facts and figures from simulation to ease the process of selecting the right system. Furthermore we present the software architecture of the implemented design flow that is already in use by construction industry. The project was initiated and actively supported by STRABAG AG, a construction and consulting company based in Austria operating in international markets.

Introduction

Increasing energy demand

The worldwide increase in demand for energy has put ever-increasing pressure on identifying and implementing ways to save energy. Furthermore, the energy supply is still based mainly on non-renewable energy resources, primarily oil and gas (37 and 24% of total energy consumption in the EU) [1].

Building sector

The building sector significantly contributes to the energy consumption in the European Union, amounting to about 40% of the primary energy consumption. In order to increase the energy efficiency in the building sector, more and more directives – such as the EU building directive [2] - are clearly linked to energy standards.

An aggravating factor in this heterogeneous environment is the fact that the degree of industrialization in the building and construction industry is rather low. Each building is essentially a prototype. This is coupled with traditionally high costs and a complex planning process, which is usually hierarchical according to the different trades acting as a barrier for innovation.

In order to make innovation possible, improved components and operational concepts are necessary to achieve an optimal design of buildings.

The deployment of innovative concepts in building design would provide future sustainable buildings a step towards 20/20/20[1] goals for climate protection. This can be achieved by an integral view of building functionality, performance and characteristics. Energy saving concepts include passive and active measures. In the passive approach, investigation of innovative building envelope characteristics, increasing the use of natural ventilation, and the application of building thermal mass as energy storage are providing promising opportunities for energy efficiency. The active measures involve optimization of HVAC system operation taking into account the combination and performance of renewable technologies.

Problem

Although governments as well as public opinion agree on the importance of energy efficiency in the building sector, a common and broad implementation of sustainable building technologies or renewable energy sources is still to be seen. Instead, often only well-tried standard solutions for buildings and their systems are carried out. There seem to be barriers which make the increased use of such innovative technologies difficult for them. Some of them are listed below:

- To ensure the success of a design process of a building which aims to maximize the energy efficiency for the entire system, the project team has to develop and assess different concepts for the given building project, which then have to be compared. Since this evaluation has to take place at an early stage of the planning process, some fundamental characteristics of the building, e.g. shading types or thermal quality of the building envelope, may not yet be defined, though they have a strong impact on the buildings energetic performance as mentioned in [3]. Thus it is essential to develop a tool which is capable of assessing concepts although not all data needed is available. Since the access to accurate data may be difficult in every phase of the construction project lifecycle [4], by additionally creating a data pool where the different domain knowledge is merged, the missing data for the investigated project can be replaced by easy-to-use standard data sets.

[1] 20/20/20 describes the target of the European Commission to bring out a 20% cut in greenhouse emissions and reduce the energy use by 20% through renewable by 2020

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- The optimization criteria are typically dominated by costs because of the high cost pressure in the building industry. All found solutions will primarily take costs and risks into consideration, energy efficiency might only be a secondary criteria.

- Due to the lack of information especially on the predicted performance of the system in operation, the cost assessment at this stage often considers investment costs only but not operational costs, a strategy which favors low-investment standard solutions while hindering the deployment of innovative (and efficient) system concepts. To optimize Life-Cycle Costs (LCC), it is important to have the operation of the building considered, and not only the investment and building phase.

- The definition as well as the assessment of new concepts are done manually and are therefore time consuming. An (IT-supported) automated predefinition of concepts in combination with a pre-selection regarding energy efficiency out of all found concepts would assist the planning team and ease the identification of otherwise hidden energy efficient and yet affordable system solutions. It would facilitate the broad implementation of innovative, energy efficient building and HVAC concepts. The unknown and risky aspects and the time-consuming parts of that process would be solved. Building Information Modeling (BIM) could also be a useful tool to oversee the interdisciplinary planning process. [5]

- The overall goal of optimizing the entire system is often split up into isolated tasks. In every special field (E.g. envelope, controls, HVAC) measures which should lead to an improved behavior of the investigated system are considered. Since the overall performance of the entire system is based on an interaction of all relevant measures, the assessment of the interference of all measures in the different domains is necessary. An isolated view e.g. only on the optimization of the building envelope does not necessarily lead to a global maximum in terms of energy efficiency. There remains a lack of tools which can support an integral planning process [6]

- Although buildings may be adaptive in terms of room layout, control strategies or operation modes, they are in general designed to be in operation for several decades without major changes of their basic characteristics. They are used by occupants who have strict expectations of the indoor climate and functionality of the building. Both of the above mentioned facts prohibit an experimental investigation of a building's performance during operation time. Experiments carried out before a building is put into operation are impossible due to financial reasons. Therefore it is crucial to assess innovative concepts of a building and HVAC system already during the planning process. As mentioned in [7] dynamic thermal simulations are the right choice to investigate the energetic behavior in order to optimize the overall performance.

- Supporting tools are typically used in single phases of the design and construction process and not applicable to the entire project lifecycle, although this is identified as a major requirement [4].

OBJECTIVES

The goal of this project is the development of a tool which facilitates the following functions:

- Thermal dynamic building simulation is a common method to accurately estimate a building's energy use and comfort parameters. It allows the prediction of a buildings' performance during operation and therefore the operational costs. The need for experimental investigation is therefore not necessary any more as the simulations can provide the similar results in a much shorter period of time.
- The usage of standard datasets from international databases allows the calculation of projects at an early design stage when only limited data is available. The method of comparative analysis ensures sound information about the energetic performance of the considered concepts even when non project specific data is used.
- Expert database: This provides the basis for dynamic simulations. The utilization of dynamic simulations in combination with comparative analysis enables the planning team to do comparisons of concepts including the operational performance, which in most cases is a necessity for a positive evaluation of innovative systems, which tend to have higher investment costs than standard solutions.
- A Matrix, containing all possible building envelope and HVAC component combinations, is used to rate the combinations. Innovative building concepts are generated by an algorithm, which processes the whole matrix and ranks the found concepts with regards to their energy efficiency.
- A tool for reviewing the results of the dynamic simulation allows the optimization of the overall system and not just isolated components of the building.
- The overall tool is designed to allow for interoperability with other tools needed during the design process of a building. There exist no constraints to improve the tool or update parts of it.

Software Architecture

Existing tools supporting the planning process of a building mostly use simple approaches to estimate the energy performance of the considered building. Furthermore it is difficult to account for different HVAC systems and their energy efficiency already during the design phase. The developed Tool called 'QUEEN', however, offers the combination of a quick project input and accurate dynamical energy modeling.

A database containing standard datasets from various international sources can be used to specify criteria which are unknown at the current design state. From the input geometry and a selection of HVAC priorities, the tool automatically generates innovative HVAC concepts and ranks them regarding to their energy efficiency. A Matrix is used where efficiency-points are given to combinations of HVAC components which calculate the ranking of the concepts. Selected HVAC variants as well as the basic concept can be simulated for a whole year using thermal building simulation resulting in a set of hourly energy and temperature values.

The results of the simulated concepts can furthermore be viewed in a Charting and Benchmarking Tool which makes them easy to compare.

The developed tool has a client-server architecture, operating on a local user machine and on a web server as can be seen in Fig. 1. The idea for this is that users from different locations could create projects and evaluate the results. Therefore, the basic input such as the geometry is done on a local user PC. A file containing the information is then imported into the database on a web server after authorizing the user. Once the project is created in the database, each user can edit important project specific parameters, simulate, and review the results.

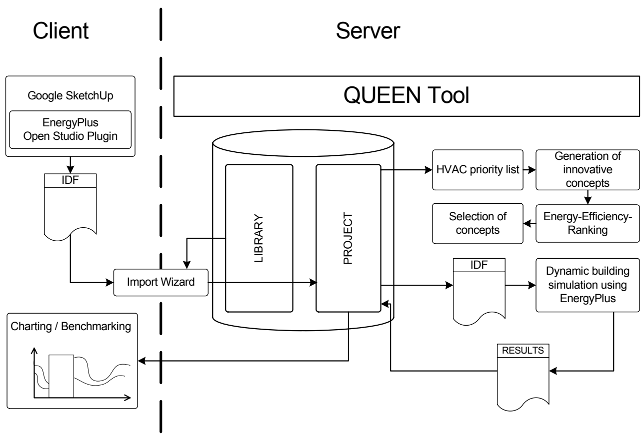

Fig. 1. QUEEN Software Structure
Client: Geometry input, visualization
Server: Data storage, concept generation, dynamic simulation

1. *Geometric Model*

In order to perform an hourly dynamic simulation of a given building, a geometric model needs to be created. This is done using "Google SketchUp" [8], a well known three dimensional graphics program. The U.S. Department of Energy developed a plugin, which acts as an interface to EnergyPlus [9], which is common used and well validated Energy Simulation tool [10, 11]. An example of how the defined geometry looks like can be found in the Examples chapter. The mentioned plugin also allows the user to define thermal zones which divide the building in certain parts according to their thermal behavior. Those zones are connected by opaque or transparent construction elements. In this step only meta-names for constructions are assigned as the actual constructions and material layers are taken from the database later on.

The information of heat being exchanged between the zones is provided by assigning predefined boundary conditions to the surfaces. By saving the *.idf-File (Input Data File) on a local machine, the geometry input is done and can be imported in to the database.

2. *Import in database*

The generated *.idf-File which contains all the geometrical information is imported into the database by starting a "wizard". This wizard acts as the interface to the database located on a central web server. In the first Step, the inputs required by the wizard are the locally saved *.idf-File, a project name and the actual location of the object. There are two more steps to complete the input. In the second step, the meta-construction names which have been defined during the geometry input are mapped with existing constructions from the database. Constructions and building materials have been predefined and imported into the Standard Library in the database from various widely-used sources including ASHRAE (American Society of Heating Refrigerating and Air-Conditioning Engineers), NCM (National Calculation Method) [12] and VDI (Verein Deutscher Ingenieure). Heat gains from occupants, lights and electrical devices can be selected from those datasets as well. To finish the import, set point temperatures for heating and cooling the zones need to be defined and a general predefined HVAC concept needs to be selected.

If all inputs are correct, the project is created in the database. Here the user can modify a number of specifications, as for example changing the construction for some surfaces. Existing projects can also be copied and edited.

3. *Generating innovative Concepts*

As it has been described in the first chapters, a very innovative component of the tool is the automated generation of HVAC concepts with regards to their energy efficiency. Therefore, possible HVAC technology combinations and envelope specifications were separated into groups containing all possible combinations. This results in a matrix with 19 groups containing 83 possible selections. Each group represents a group of features related to a building and it´s HVAC systems, e.g. `Glazing`, `Heat providing system`, `Environmental energy`.

The Matrix also contains a rating for each combination with respect to the energy efficiency of that particular combination. Furthermore, information as to whether it makes sense from a technical point of view, as well as the feasibility with regards to the simulation software is included. Fig.2. shows the first 3 groups of the matrix with points for the rating and crossed out cells for impossible combinations.

To give the user the chance to reduce the possible number of variations, a "Priority List" can be edited. All available groups can be either enabled or disabled for an algorithm which checks the whole matrix for valid combinations. The algorithm used is working according to mathematical graph theory. Fig. 3. shows a graphical representation of what is developed for the finding of variations. Each group contains several nodes, connected to all other nodes. Here, the described matrix determines whether a particular combination is valid (thin solid line) or not (thin, dotted line). Nodes within a group cannot be connected as they are "similar" technical systems of the building. The algorithm goes through all enabled groups of the matrix (full search), trying to find complete tracks which means exactly one node of each group where all nodes are compatible with each other. In the Figure the thick solid path shows a valid, while the thick dashed path shows an invalid combination.

After finding all valid combinations, the algorithm calculates the ranking by summing all points from the individual connections. The user can chose from the ranked combinations which of the new concepts shall be applied to the existing project. The ranking of the found variants reflects the energy efficiency of the combination.

Group		**1**					**2**		**3**		**4**		**5**						
Subgroup		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1						1	1	2	1	1	1	1	1	1	1	1	1	1
	2						1	1	4	1	1	1	0	0	0	0	0	0	1
	3						1	1	4	1	1	1	1	1	1	1	1	1	1
	4						1	1	3	1	1	1	1	2	2	1	1	1	1
	5						1	1	1	1	1	1	1	1	1	1	1	1	1
2	6								1	1	1	1	1	1	~~0~~	~~0~~	1	1	1
	7								1	1	1	1	1	1	1	1	1	1	1
3	8										1	1	1	1	1	1	1	~~0~~	1
	9										1	1	1	1	~~0~~	~~0~~	1	1	1

Fig. 2. Groups 1 to 3 of the technology matrix containing information about combination of building envelope / system parameters, energy efficiency rating and overall feasibility

4. *Simulation*

The user has created a project with a specific project-related geometry and has assigned all necessary specifications. The QUEEN Tool has furthermore provided the information which HVAC systems would be more efficient compared to the initial one. A very crucial part in that tool is now that the whole concept of the building can be run through a dynamic thermal building simulation. Dynamic building simulation has evolved to become an extremely useful tool for building designers. A broad range of building concepts can be evaluated in a very short period of time taking heat, light and mass transfer in buildings into account. The driving forces are the climate at a given location, heat gains from internal loads like occupants and the HVAC System conditioning the building.

All selected concepts are simulated on an hourly basis, the main results being temperature distribution in zones, and energy used for conditioning the building. The Files containing the results are imported back into the database and stored within the project.

5. *Results*

The results produced by the Simulation can be viewed by using the implemented Charting and Benchmarking Tool. Individual Output Parameters can be selected and viewed in a charting tool e.g. for comparing indoor climate of two concepts. To compare the energy consumption of the simulated variants, a benchmarking tool can be used which displays a bar chart of the selected concepts. Furthermore a report generated from the Simulation Software EnergyPlus can be used to review input details and additional results.

EXAMPLES

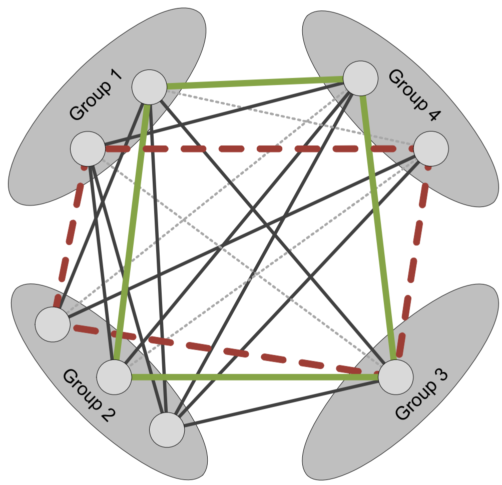

Fig. 3. Graph theory used for generating feasible combinations of parameters for generating additional energy efficient combinations

The following examples shall clarify the approach by means of potential applications. An office building with a floor area of 8400 m² in four levels is used to demonstrate the procedure. The building and the applied thermal zoning (Four peripherical and one core zone) is illustrated in Fig. 4.

Several different concepts are created and compared by varying the building envelope and the applied cooling system.

Using the import wizard the IDF file created by Google SketchUp is imported into the database and basic HVAC and building characteristics are selected. For the presented example cases, constructions of a light thermal classification are chosen for the walls, floor and roof. The internal loads for people and lighting are defined according to NCM profiles for an office.

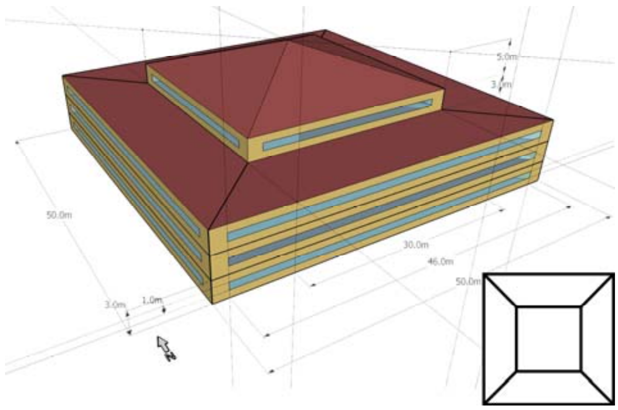

Fig. 4. 3-D model of an office building

In a first example two projects for different locations are created: Athens, Greece and Helsinki, Finland. The building is equipped with a Fan Coil system, being supplied by district heating and cooling. Since the tool offers the possibility to change the quality of the building envelope, the impact of different shading systems on the thermal and energetic behavior will be assessed: no shading devices, external and internal blinds. After enabling the group `Mechanical shading devices` and running the search routine for innovative concepts, the QUEEN tool provides the following ranking results: no and external blinds (178 points), internal blinds (175 points). According to these results unshaded and exterior shaded windows should show a similar energetic performance. The suggestions of the ranking list are therefore compared with the results gained by means of dynamic simulations. The simulation results for Athens and Helsinki are shown in Fig. 5 and 6. The comparison of the results for the unshaded, interior and exterior shading concepts shows an increasing heating demand, caused by the reduced solar gains during winter time. Due to lower irradiation in the summer period, cooling demand is decreasing for both locations. The overall change in the sums of the total absolute heating and cooling demand, represented by the numbers above the bars,

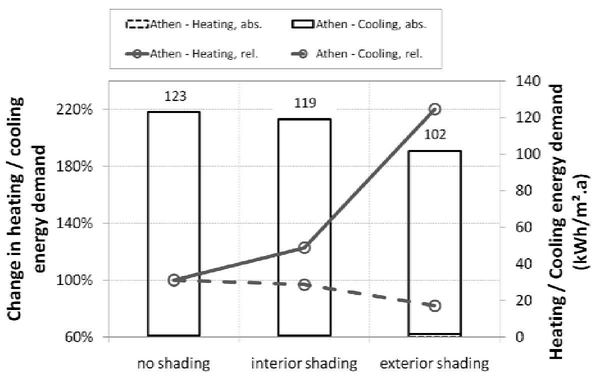

Fig. 5. Results for different shading systems in Athens

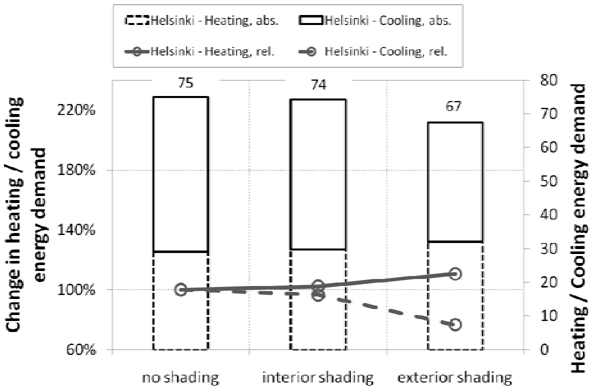

Fig. 6. Results for different shading systems in Helsinki

is -17% for Athens and -11% for Helsinki. The simulations show valid results, however in the matrix only one ranking in terms of energy efficiency can be set for a single shading system. Therefore the best ranked concept must not be the most efficient as it also depends on the location of the building to be simulated.

In a second example, the groups “Glazing” and “Free Cooling” are enabled in the priority list. The result of the generation of innovative concepts is a ranking and short description of each concept, displayed in table 1.

TABLE I
RANKING OF INNOVATIVE CONCEPTS

Points	Description
185	Thermal classification: light; District heating/cooling, Fan Coil, Free Cooling Glazing: U<0.9 W/m².K, g<0.4
184	Thermal classification: light; District heating/cooling, Fan Coil, Glazing: U<0.9 W/m².K, g<0.4
179	Thermal classification: light; District heating/cooling, Fan Coil, Free Cooling Glazing: U>1.3 W/m².K, g=any value
178	Thermal classification: light; District heating/cooling, Fan Coil, Glazing: U>1.3 W/m².K, g=any value

The simulation results for the annual cooling demand of the created example concepts are displayed in Fig. 7. The gained ranking and the simulation results fit well, except the order of the second and the third concept. Within the simulated time period of one year concept 3 equipped with improved glazing needs less cooling energy demand compared to concept 2. The results of the concept ranking routine form a sound basis for the preselection of innovative concepts, although the final assessment of the energetic performance has to be carried out by means of dynamic thermal simulation.

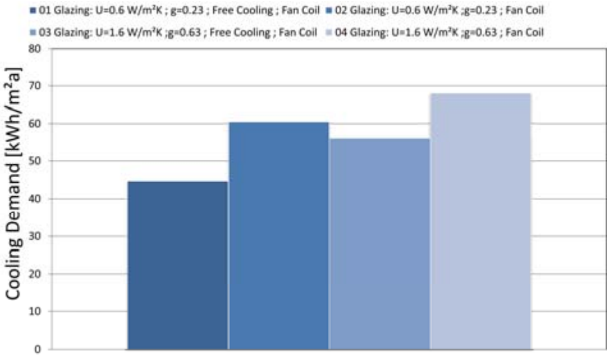

Fig. 7. Cooling demand for office building in Vienna

DISCUSSION / CONCLUSION

The targets discussed in the objective section were achieved to a large extend even though some limitations were implicated.

A huge database was arranged in order to enable dynamic simulation of innovative building and HVAC concepts which again are recommended for comparison reasons. One point to distinguish is the possibility that the user can expand and adapt the database, e.g. for including new construction materials, according to his demand.

As far as the interoperability of the tool is concerned there are two things to mention: the usage of the wide spread Google SketchUp for defining the 3-D building model as well as the export of results in text format enable further development of interfaces to other tools.

During the first appliance test phase it has been shown that the definition of the 3-D building model is time-consuming, especially the allocation of the required details for large in-depth building models.

The implementation of the automated definition and pre-evaluation of the innovative concepts encountered one of the biggest challenges during the development phase, since the implemented routine may deliver unsatisfactory results. The problem occurs, if the combined information of more than two properties has to be considered, since the 2 dimensional matrix isn´t capable of representing such connections.

OUTLOOK

The presented system handles a complex process. It is the complexity that leads to the situation that existing innovative technologies are not adopted in the market. The limitations described in the discussion lead to a number of necessary improvements.

One important aspect is the visualization of a multi-parameter multi-objective problem. The input parameters are plenty, will be more in future and in some cases of continuous nature. This leads to a non-countable space of input sets. Even if discretisation and heuristics lead to a finite number of possible input sets, the number will still be high. Visualizing an n-dimensional matrix is not easy if n is of 3 or 4 digits. For this, pre-processing, clustering and other smart ways of reducing the complexity is necessary.

The second half of the problem is probably easier. Most of the utility functions (costs, CO2, other emissions) can be mapped onto a universal metric: costs. Even regulatory aspects and comfort might fall into that category. In any case, a pareto-optimal evaluation of the alternatives is possible,

The key aspects of the described tool, however, are

- Extendability,
- Streamlined workflow, and
- Easy user interfaces,

which always give room for improvements.

The multi-objective and multi-parameter nature of the design flow might also be approached with evolutionary algorithms, which would increase the automatic aspect of the tool.

During the design and planning process decision makers have to cope with uncertainties in the input parameters of the evaluation process, which may have a strong impact on the gained results. As shown in [13] a stochastic approach considering the bandwidths of uncertainty of the inputs combined with Monte Carlo simulations improves the significance of simulation results. It has to be investigated how far comparative analysis without utilizing statistical models are affected by input uncertainties.

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