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PRIMARY HVAC SYSTEM OPTIMIZATION FOR BUILDINGS TARGETING ARCHITECTS – PROBA TOOL

Milica Grahovac[1], Peter Tzscheutschler[1], und Thomas Hamacher[1]
[1]Lehrstuhl für Energiewirtschaft und Anwendungstechnik
International Graduate School of Science and Engineering (IGSSE)
Technische Universität München

ABSTRACT

PROBA tool is based on a method which resulted from investigating the relationship between the energy generation and storage systems for thermal conditioning of buildings (primary HVAC systems) and the conceptual building design. The method calculates the optimal primary HVAC system dimensions, the costs, emissions and energy consumption based on scarce data available. The method consists of a time domain simulation, annuity cost calculation and the optimization, which is used to automatically size the HVAC system based on ist simulation performance. PROBA, the primary system optimization for buildings targeting architects, is created by adding a wizard-style graphical user interface between the model and the user. The utilization of the tool is presented using a case study which shows how a change in building geometry can influence the primary HVAC component dimensions, costs, and emissions. Making this tool available to the architects represents an effective way to consider the primary HVAC during the preliminary design, without causing additional cost.

INTRODUCTION

The decisions required during the conceptual building design have an important effect on the building energy performance (BEP). The consequences of these decisions are often overlooked and the extents of their influence on BEP disregarded. Similarly, many heating and cooling generation and storage components (primary HVAC) impose restrictions on building design and, by their nature, cannot be introduced at a later design stage.

A method to quantify this influence has been developed and implemented in a user interface entitled PROBA. The major characteristic of the interface is its suitability for non-expert users. This is achieved by, firstly, reducing amount of input data by implementing preset values and, secondly, providing simple information support. The tool calculates optimal primary HVAC system dimensions, its cost, emissions and energy consumption and enables the use of the developed method by architects during the conceptual design.

The number of available commercial and educational tools is constantly increasing. Several approaches have been identified in the existing primary system design tools. Their complexity ranges from quantitative, such as CIBSE RESET tool (CIBSE, 2006), which is a descriptive Microsoft Excel based tool providing evaluation of renewable energy potential depending on the location, to sophisticated dynamic simulation tools, such as TRNSYS (TRNSYS Documentation, 2009) and EnergyPlus (DOE, 2012).

The majority of HVAC practitioners rely on simple spreadsheet tools based on national norms (e.g. DIN EN DIN V 18599, DIN EN 15316). Some HVAC component manufacturers have taken this approach a level higher and offer complete load, system and economic analysis. Examples are HAP (Carrier Software Systems, 2012) and TRACE 700 (Trane, 2012), which sequentially simulate building loads and the plant in hourly steps. A tool based on the ASHRAE temperature bin method, RETScreen (Natural Resources Canada, 2012), analyses not only heating and cooling systems for buildings, but also district heating and power systems. Optimization and price comparison of hybrid power systems, including renewable sources and power storage using time series data, is possible with the energy modeling software HOMER (Lambert et al., 2006). The lack of working fluid parameters inspired the utilization of such an approach for the early building design. In his thesis Fabrizio (Fabrizio, 2008) developed a multi-energy modeling and optimization framework. However, it includes neither the energy storage and the solar energy converters, nor the control strategies necessary to include such components. A freeware building energy use analysis tool based on DOE-2.2 (Hirsch et al., 2008), eQuest (Hirsch, 2006), offers comprehensive support for BEP design. Chillers and boilers are sized automatically, taking base and peak load into consideration. The program performs cost calculations and displays monthly result analyses. Parametric runs are available for alternative comparisons. Although this sophisticated tool can provide great support and reliable results during design the thermal storage is considered only as a hot water supply component and it does not model solar collectors. The level of detail and input demand, in terms of both data and user expertise, limits the usability of highly sophisticated tools like TRNSYS and EnergyPlus during conceptual design.

The method and the tool presented in this paper have been developed in Matlab environment, (MathWorks, 2012). Such an approach enabled high flexibility and control in terms of both tool development and distribution.

This paper provides, firstly, a short description of the underlying method. A detailed elaboration of the method is available in Grahovac (2012). Secondly, it presents the graphical interface entitled PROBA (Primary HVAC System Optimization for Buildings Targeting Architects). The presentation of the interface continues using a case study, which shows how a change in building geometry can influence the primary HVAC component dimensions, costs, and emissions.

Making this tool available to the architects represents an effective way to consider the primary HVAC during the preliminary design, without causing additional cost. Although such a tool can never replace an HVAC engineer, its use can prevent significant mistakes related to the choice of the primary HVAC configuration during the conceptual building design.

METHOD

The major challenge for optimizing the space heating and cooling energy source during conceptual building design is the lack of information about the distribution system (the secondary HVAC) and working fluid parameters, such as flow rates and temperatures. However, there are several common mistakes, which can be avoided if the primary system simulation is performed at the earliest possible design stage. Namely, the primary system is often expected to perfectly match the demand of heating and cooling energy, with a supply profile that synchronizes to the building demand profile. The simplest way to achieve this simultaneity is to utilize boilers for heating and chillers for cooling, while sizing them according to a peak demand. To ensure safe supply, components are often oversized, or redundant components (especially in case of chillers) implemented.

Although, the efficiency of conventional boilers and chillers has significantly increased during recent decades, further savings can be achieved if utilizing intermittent renewable energy sources (RES), thermal storage, and good controls. The reasons such systems have not yet become standard equipment are the higher investment costs and the system design complexity.

Utilizing a conventional steady-state component dimensioning often leads to an unsatisfactory overall system performance efficiency. A step forward, a time domain system simulation, enables the consideration of the part load performance, thermal storage dynamics, fluctuating renewable energy availability and system controls operation. However, the level of detail of a simulation possible with the data available during the early design is low. To address these issues, a model enabling the following has been developed:

- The system design optimization, providing a configuration suitable to satisfy the thermal conditioning demand of provided building alternatives;
- The quantification of the fuel consumption and carbon emissions of the proposed system while conditioning the provided building; and
- The cost assessment, including both the investment and the energy consumption related costs on an annual basis.

The major challenges which mutually influenced the development of this method, suitable for preliminary design utilization, can be categorized as follows:

- Proper assessment of the intermittent renewable energy sources (RES), thermal storage and component part load efficiencies requires a time domain system simulation;
- A large number of primary and secondary HVAC system characteristics and parameters are unknown during the conceptual building design; and
- The targeted users having a low level of expertise in the field of HVAC engineering.

Figure 9 represents the overall process flow within the method.

External Data

The upper part of Figure 9 gives a short overview of the input data. From the user perspective, the complete external data can be classified as following:

- Obligatory user input, i.e. ideal building load, weather data, and available solar collector/PV area (system specific);
- Optional user input (preset technical and cost related data); and
- Fixed parameters: e.g. penalty function parameters, simplified secondary system loss coefficients.

The weather data are required by the models directly depending on ambient conditions. These data consist solely of the solar radiation and ambient dry and wet bulb temperature profiles.

An ideal building load, which must be created externally, is processed within the model to create the primary system set load.

Model and Simulation

To include transient effects of thermal storage, the intermittent nature of RES, boiler or chiller part load efficiency and their optimal staging, component dimensions need to be identified based on simulated system performance, rather than on one stationary peak load condition. Since non-expert users are not expected to know how to configure a primary system and its control, a set of preconfigured systems, further referred to as system models (SMs), is developed. Seven pre-configured primary HVAC systems include components such as boilers, chillers and cooling towers, thermal storage, solar thermal collectors, and photovoltaic modules. One of these SMs, consisting of a biomass boiler, thermal storage and a solar collector is described in Grahovac et al. (2011).

The implemented component models are deterministic and any of the following:

- Empirical, obtained by manufacturer data regression and modified empirical models taken from the literature (used for e.g. boilers, chillers);
- Semi-empirical (used for e.g. solar thermal collectors); and
- Simplified theoretical (used for e.g. thermal storage).

The complexity level of system components is low due to the lack of detailed data in the early design. Rather than defining the components by inlet and outlet mass and heat flows, the energy-balance approach has been adopted.

To perform a system simulation, the idealized control assigns the tasks to each of the components in each timestep. Two kinds of control can be found within the models. The first is the hysteresis control, used to control the boiler based on the storage state of charge, in order to improve the storage utilization and reduce the number of boiler start-ups. The second is the sequential controller in the case of utilizing more than one chiller or condensing boiler, which allows optimal loading and increases the overall efficiency of the system.

Additional measures are applied in order to overcome the problems related to load based modeling of thermal systems. Namely, the simulated heat flow direction is made thermodynamically possible through various temperature limitations imposed to the component performance.

Costs

The performance profiles obtained serve to calculate the energy consumption, carbon emissions and costs. The annuity method based on VDI 6025, VDI 2067 and DIN EN 15459:2008 has been employed to calculate the cost.

Optimization

Optimization is used to automatically size the HVAC systems based on their simulation performance. It identifies the system component dimensions that provide minimal costs, emissions or consumption, while maintaining the quality of the supply and, where specified, achieving the targeted annual solar ratio.

The optimization objective is a simulation based non-linear and non-convex function. Two algorithms, robust enough to identify the global minimum, are implemented:

- Global Bounded Nelder-Mead (GBNM) (Luersen et al., 2004), since it only evaluates the value of the function, and not its derivatives; and
- Exhaustive search, since the components are only manufactured in certain sizes. It is modified to exclude the sets of obviously unfeasible optimization parameters.

The most important constraint imposed on the optimization is the supply task satisfaction. Where user insists on a specific solar ratio, the solar ratio constraint is activated. The quantification throughout the optimization domain is made possible by implementing a problem specific multicriterial penalty functions. Namely, a single scalar penalty value accounts for all the following: the instances of the undersupply, their intensity, duration and frequency. All these features are irrelevant to the user of the user interface, but have allowed further scientific investigation.

Optimization variable bounds are defined automatically based on the load imposed on the SM, as well as the discrete optimization parameter sets used in exhaustive search.

The proposed method has not been verified in practice and thus the results currently have primarily an educational value.

USER INTERFACE

To enable the practical implementation of the presented modeling, simulation and optimization environment by a user who lacks the knowledge in HVAC, a graphical user interface (GUI) entitled PROBA is proposed. It guides the user step by step. In order to assist the user, PROBA automatically disables usage of SMs that cannot supply the inputted load profile in the chosen climate, as well as provide first information on how environmentally friendly the SM is.

Figure 1 presents the steps the user takes to utilize the tool. The three basic steps are:

- Simplified load and weather data input;
- Selection of an SM and proceeding with optimization or simulation; and
- Additional SM related input before running the calculation.

These steps are further explained in this section. The procedure after selecting an SM is explained through a subsequent case study.

1 First Input

To enable SM simulation and optimization, the user is required to provide the ideal building load and the weather data for the location. In general, any externally generated hourly load profile can be

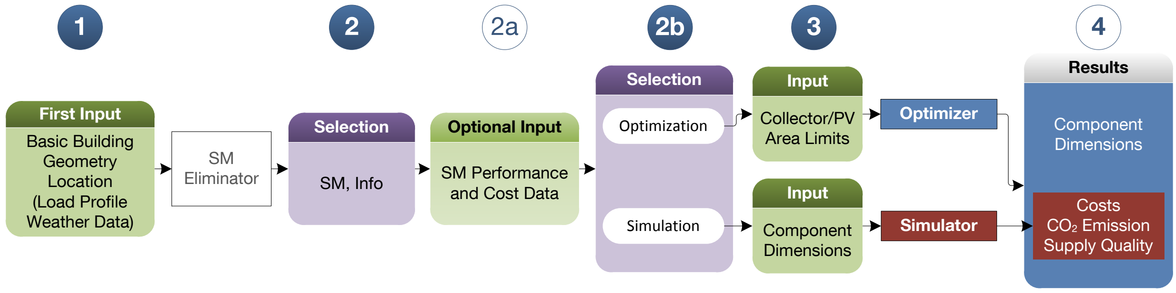


Figure 1 Basic information flow in the PROBA tool. Steps 1, 2, 2b and 3 are obligatory. Step 2a is optional.

provided. Figure 2, left, shows a screenshot of the first user input window. In the current version of the tool there are two possibilities to supply the building load to the simulation:

- If the user has created the ideal building load with a suitable building simulation tool, this file can be loaded using the "Browse" button at the lower part of the window. The required file format is a text file with hourly load data placed in the second column, while the first one indicates the hour.
- Fast and simplified building geometry input is available for the 4 cities (Shanghai, Dubai, Bangalore and Moscow). Locations climatically similar to any of the cities can also use this fast input. Namely, for these locations, a database with single office ideal load profiles has been provided by Liedl (2011).

2 SM Selection

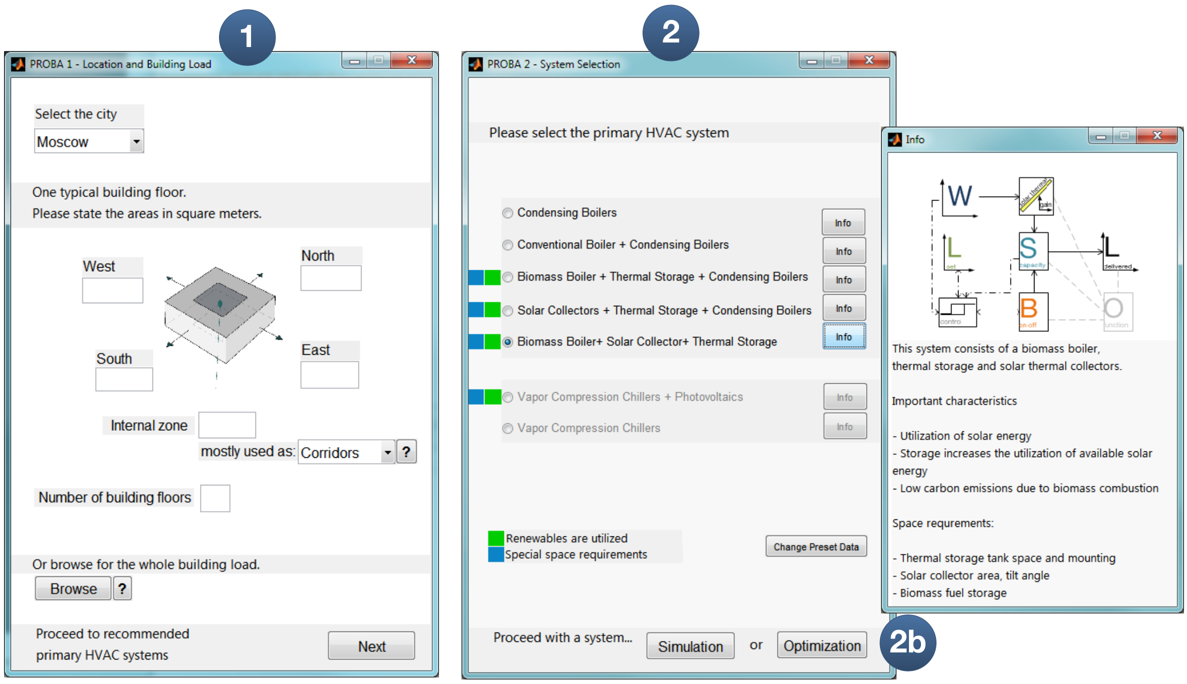
After the user inputs the city and the geometry, or provides an external load data file, the SM Eliminator has a role to eliminate the SMs unsuitable for such a load. Currently, heating systems are eliminated if the location requires only cooling, and vice versa. The user chooses the SM to be optimized. To support this selection, basic information on the system and its limitations are provided, such as place requirement and environmental considerations (displayed in . Figure 2, right, for SM1).

2a Performance and cost data customization

For more demanding users there is a possibility of editing the preset data, as illustrated in Figure 3. However, only a limited set of data is currently accessible. This principle could be extended to component price functions and performance data.

After deciding on the system to evaluate, the process can be continued by running either the optimization or the simulation. To run the simulation, the user needs to provide the component dimensions. To run the optimization, only the models with solar collectors and PV panels require additional input, which consists of the available façade or roof area to mount the stated components.

The description continues from step 3 (Figure 1) through an example of the tool utilization.



PROBA 1 - Location and Building Load

Select the city
Moscow

One typical building floor.
Please state the areas in square meters.

West
North
South
East
Internal zone
mostly used as: Corridors
Number of building floors

Or browse for the whole building load.

Proceed to recommended primary HVAC systems

PROBA 2 - System Selection

Please select the primary HVAC system

○ Condensing Boilers
○ Conventional Boiler + Condensing Boilers
🟦🟩 ○ Biomass Boiler + Thermal Storage + Condensing Boilers
🟦🟩 ○ Solar Collectors + Thermal Storage + Condensing Boilers
🟦🟩 ● Biomass Boiler+ Solar Collector+ Thermal Storage
🟦🟩 ○ Vapor Compression Chillers + Photovoltaics
○ Vapor Compression Chillers

🟩 Renewables are utilized
🟦 Special space requirements

Proceed with a system... Simulation or Optimization

Info

This system consists of a biomass boiler, thermal storage and solar thermal collectors.

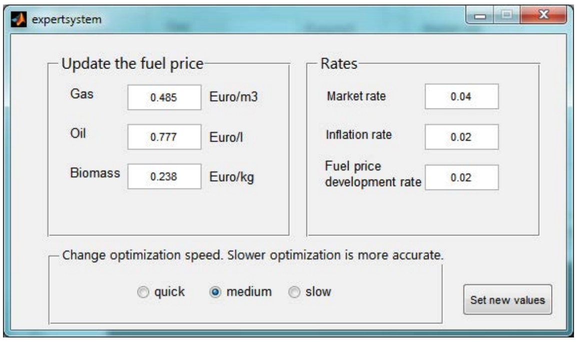
Important characteristics

- Utilization of solar energy
- Storage increases the utilization of available solar energy
- Low carbon emissions due to biomass combustion

Space requrements:

- Thermal storage tank space and mounting
- Solar collector area, tilt angle
- Biomass fuel storage

Figure 2 Left: First data input. Middle: SM selection. Right: SM information window



expertsystem

Update the fuel price

Gas 0.485 Euro/m3

Oil 0.777 Euro/l

Biomass 0.238 Euro/kg

Rates

Market rate 0.04

Inflation rate 0.02

Fuel price development rate 0.02

Change optimization speed. Slower optimization is more accurate.

○ quick ● medium ○ slow

Figure 3 Optional user input – basic cost data customization.

A CASE STUDY

The case study shows how a change in building geometry can influence the primary HVAC component dimensions, costs, and emissions. As an example, a building with 6250 m^2 of office area is planned in Dubai. The designer has a goal to reach a solar ratio of 30%, while minimizing the total cost. First the initial design is presented and its primary HVAC system optimized using PROBA. After the initial design fails to reach the target, an alternative design is proposed and its optimization presented.

The initial building (

Figure 5) has 10 floors, with more office area facing west and east (120 m^2 per building floor) than north and south (80 m^2). The internal zone has an area of 224 m^2 at each floor. The window area ratio is 50 %.

After entering the building geometry into the PROBA 1, illustrated in Figure 4 on the left, the SM selector eliminates all the heating systems, since there is no heating demand in Dubai. Based on a wish to utilize renewables, the user selects SM7 featuring chillers and PVs to optimize it.

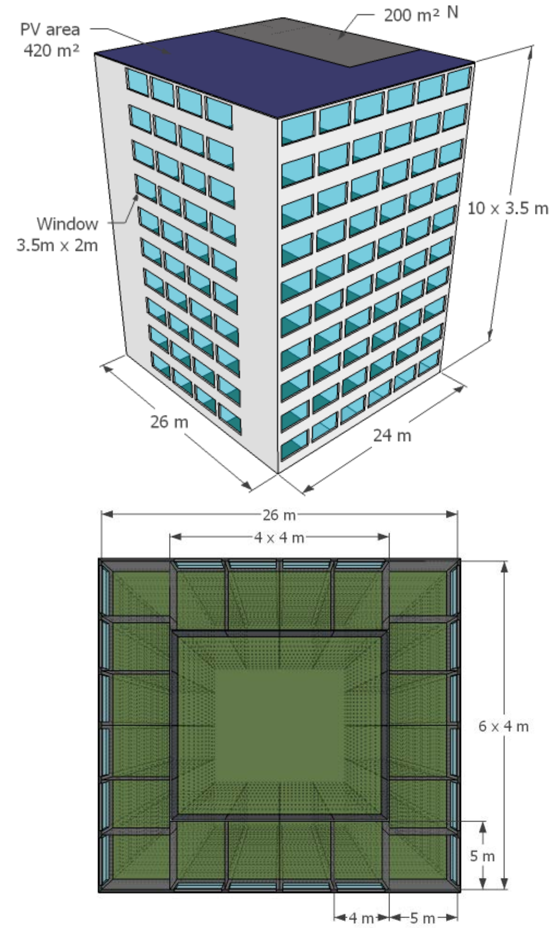
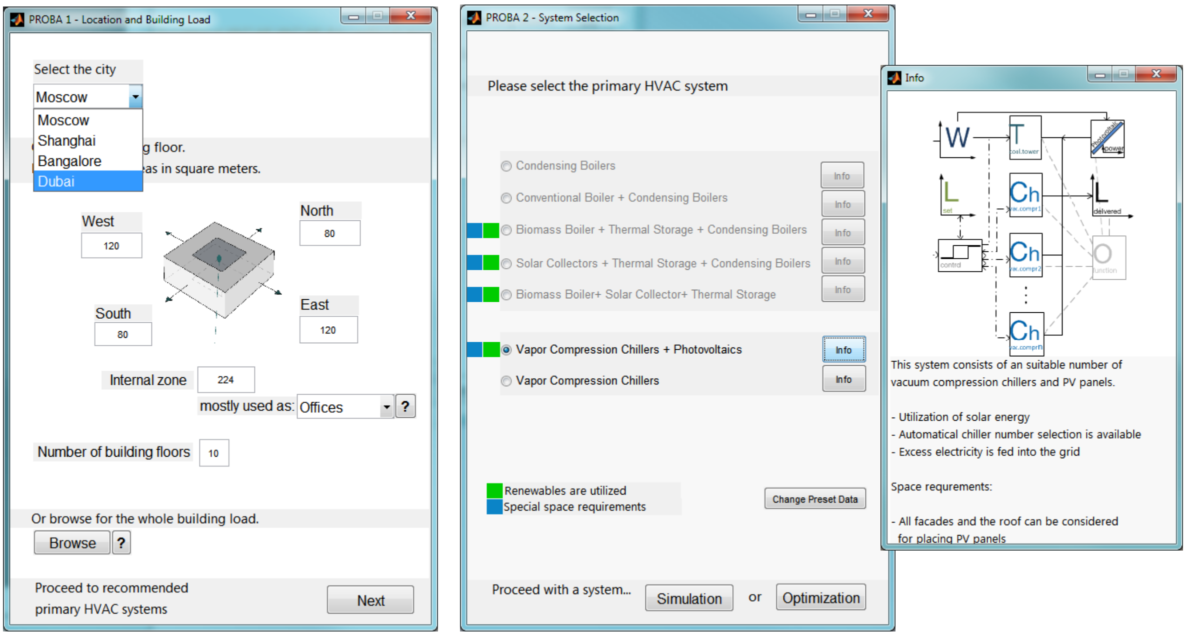


Figure 5 Initial design of a 10 floor building located in Dubai, 6250 m^2 of office area. Window area ratio is 50%.



PROBA 1 - Location and Building Load

Select the city

Moscow

Moscow
Shanghai
Bangalore
Dubai

g floor.

as in square meters.

West 120

North 80

South 80

East 120

Internal zone 224

mostly used as: Offices

Number of building floors 10

Or browse for the whole building load.

Proceed to recommended primary HVAC systems

PROBA 2 - System Selection

Please select the primary HVAC system

○ Condensing Boilers

○ Conventional Boiler + Condensing Boilers

🟦🟩 ○ Biomass Boiler + Thermal Storage + Condensing Boilers

🟦🟩 ○ Solar Collectors + Thermal Storage + Condensing Boilers

🟦🟩 ○ Biomass Boiler+ Solar Collector+ Thermal Storage

🟦🟩 ● Vapor Compression Chillers + Photovoltaics

○ Vapor Compression Chillers

🟩 Renewables are utilized

🟦 Special space requirements

Proceed with a system...

Info

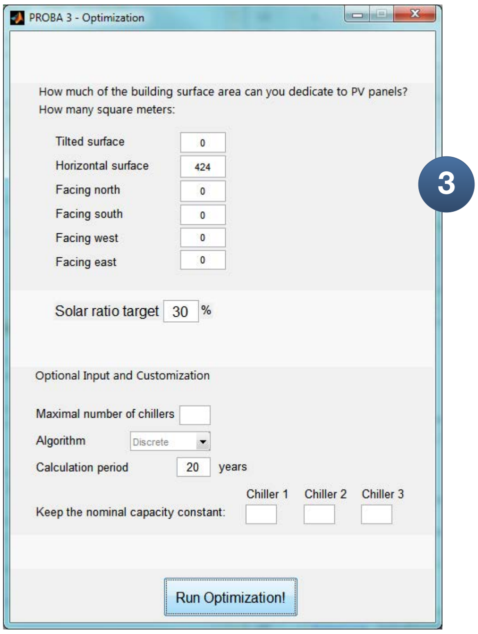
This system consists of an suitable number of vacuum compression chillers and PV panels.

- Utilization of solar energy
- Automatical chiller number selection is available
- Excess electricity is fed into the grid

Space requrements:

- All facades and the roof can be considered for placing PV panels

Figure 4 Left: Selecting Dubai as a location, entering the building geometry. Selecting vapour compression chillers with PVs to condition the building, based on the information provided in "Info".



PROBA 3 - Optimization

How much of the building surface area can you dedicate to PV panels?
How many square meters:

Tilted surface 0
Horizontal surface 424
Facing north 0
Facing south 0
Facing west 0
Facing east 0

Solar ratio target 30 %

Optional Input and Customization

Maximal number of chillers
Algorithm Discrete
Calculation period 20 years
Keep the nominal capacity constant: Chiller 1 Chiller 2 Chiller 3

Figure 6 Final input before optimization: the targeted solar ratio and maximal façade and roof areas available for PV panels.

③ Final Input

The user is required to provide the PV area limits and target solar ratio, see Figure 6. The roof has a horizontal area of 624 m^2, of which 200 m^2 need to be left free for other utilizations, allowing 424 m^2 to be reserved for PV panels.

④ Results and Alternative Design

After the optimization has completed, the window presented on the left side of Figure 8 opens automatically. It offers four sets of results: minimal total cost, running cost, fuel consumption, and emissions. The results for the total cost minimization for the initial design are shown in the middle of Figure 8. The system has achieved a solar ratio of 20% and has thus failed to achieve the target of 30%.

An alternative design needs to be proposed in order to reach the specified target. Corrections are based on information on optimal PV tilt angles, (latitude angles can be used, here we used the optimum from Grahovac (2012)) and guidelines provided in Liedl (2011). The modifications in building design consist of:

- Increasing the roof area for PVs by reducing the number of building floors;
- Tilting the part of the roof at an optimal angle. This in addition makes the south façade smaller than the north, leading to lower heat gains.
- Liedl (2011) states the west façade has the highest gains in Dubai – the building is reoriented to reduce the office area facing west;
- Liedl (2011) provides a diagram with the interaction between the natural lightning, the office length and the window area ratio. The new window area ratio of 30% has been selected, which provides 300 lux.

The proposed alternative design is illustrated in Figure 7. After running the same input procedure as for the initial design, the result shown in the Figure 8 on the right is obtained. Here, the solar ratio target of 30 % has been achieved. Furthermore, the total cost annuity has also decreased, due to the decrease in running costs being greater than the increase in the investment cost. As expected, significant carbon emission savings have been achieved.

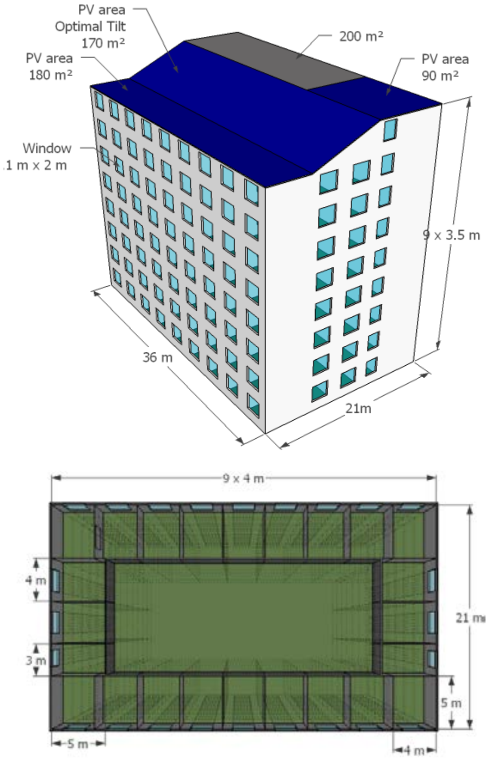
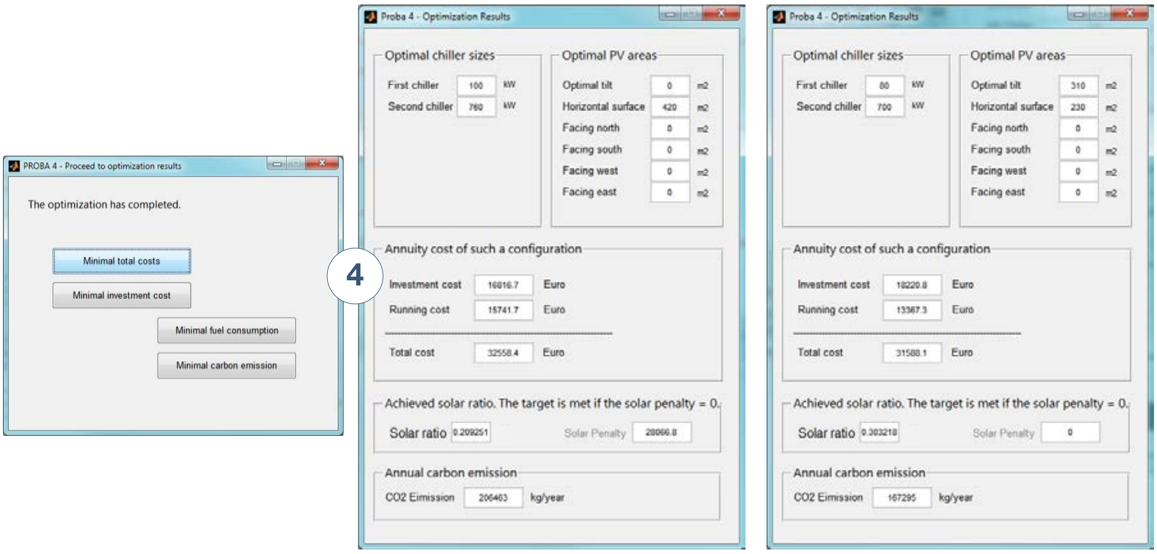


Figure 7 Alternative building design. The building surface area remained approximately the same. The south oriented roof tilt equals the optimal angle.

Please note that the construction related cost have not been taken into account. The example in used solely to illustrate the utilization of PROBA.

CONCLUSION AND OUTLOOK

The goal was to provide a tool, which would help to foresee the influence of the preliminary building design decisions on the optimal primary HVAC configuration. This was achieved through configuring a test version of a tool entitled PROBA. PROBA provides guidance in terms of user input and SM selection before running the optimization or the simulation. The underlying modeling and optimization method enables informing the designer of the suitable primary HVAC configuration, its size, costs, consumption and emissions very early in the building design process. The same information can be provided for each consecutive design variation, thus illuminating and quantifying the consequences that a certain design decision has on the primary



The optimization has completed.

Optimal chiller sizes
First chiller 100 kW
Second chiller 760 kW

Optimal PV areas
Optimal tilt 0 m2
Horizontal surface 420 m2
Facing north 0 m2
Facing south 0 m2
Facing west 0 m2
Facing east 0 m2

Annuity cost of such a configuration
Investment cost 16816.7 Euro
Running cost 15741.7 Euro
Total cost 32558.4 Euro

Achieved solar ratio. The target is met if the solar penalty = 0.
Solar ratio 0.209251 Solar Penalty 28066.8

Annual carbon emission
CO2 Eimission 206463 kg/year

Optimal chiller sizes
First chiller 80 kW
Second chiller 700 kW

Optimal PV areas
Optimal tilt 310 m2
Horizontal surface 230 m2
Facing north 0 m2
Facing south 0 m2
Facing west 0 m2
Facing east 0 m2

Annuity cost of such a configuration
Investment cost 18220.8 Euro
Running cost 13367.3 Euro
Total cost 31588.1 Euro

Achieved solar ratio. The target is met if the solar penalty = 0.
Solar ratio 0.303218 Solar Penalty 0

Annual carbon emission
CO2 Eimission 167295 kg/year

Figure 8 Left: Results for all objective functions are available – total cost minimization is selected and the results for the initial building can be viewed (Middle). Right: The results for the alternative design. With this new design the target has been reached.

HVAC performance, dimensions and configuration. Where the building design remains unchanged, the user can simply compare the resulting costs and emissions for different SM configurations.

In the example presented, a comparison of two coarse building designs was performed. A set of transformation measures helped to reduce the demand and increase the solar gains, enabling the new design to reach the targeted solar ratio, which failed when using the initial building design.

In the case of a simple system, the tool utilization is comparable to receiving preliminary recommendations from an HVAC engineer, as if he/she would be available to the architect all the time. Further benefits are gained with the increased utilization of complex hybrid systems, due to the difficulty in experience-based initial dimensioning. However, the results obtained are to be considered with care, as recommendation and orientation values, since the method has not been verified in practice.

Further improvements are needed in the area of the thermal distribution losses, and SMs should be configured automatically based on the optimization goal, building size and climate. A series of test and improvements, both in terms of software development and in terms of applicability, are required to upgrade PROBA into a reliable tool.

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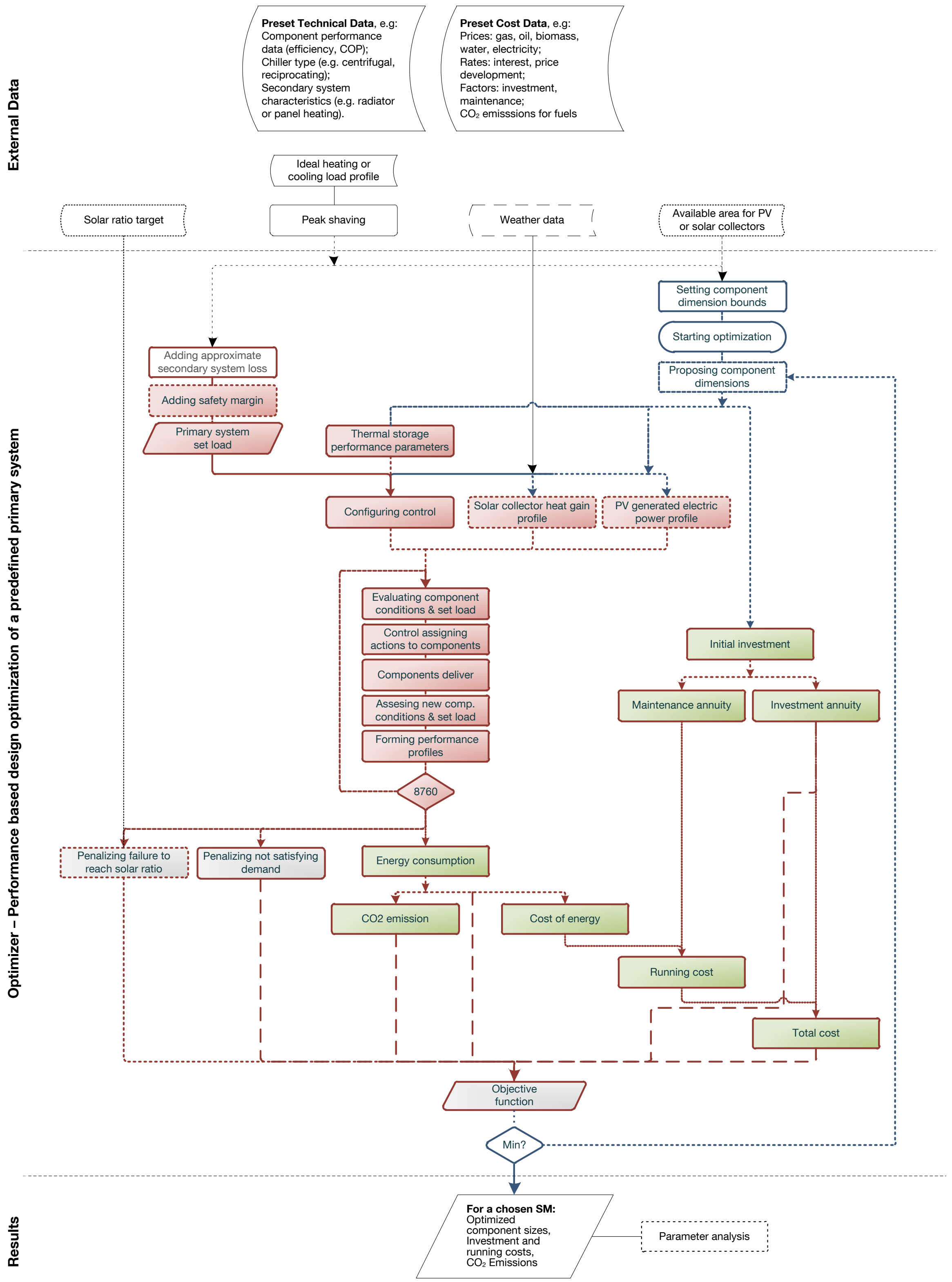

Figure 9 Overall process flow: external data flow into the optimizer which runs the simulator to yield the result. Blue connection lines belong to the optimizer, red to the simulator, which consists of pink SM performance processes, green cost and emission calculation processes and grey objective definition processes. Dotted lines represent SM specific inputs and processes. Each of the dashed lines connects a value that added to the penalties defines one objective function.