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Estimation and analysis of building energy demand and supply costs

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Abstract

In modern societies buildings largely contribute to the energy demand and account in some countries for up to 45 % of the primary energy consumption. Detailed consumption data can be used to offer advanced services and provide new business opportunities to all participants in the energy supply chain. In recent years, the intensified research effort by the scientific community and companies from the energy sector has led to an improved estimation of the building energy consumption. This paper proposes a tool that combines on one hand architectural characteristics and, on the other, user interactions with a building to precisely estimate its energy consumption and supply costs. The tool also determines the sensitivity of the energy consumption and the related costs for any variations applied in the building configuration or in the energy tariffs. The identification of critical parameters allows building managers to adopt appropriate measures to improve energy efficiency of the considered building. For the demonstration and validation of the proposed approach the developed tool is then applied to a case of an office building located in Madrid (Spain). It is explained in detail how the estimates of the building energy consumption and the costs were calculated and the sensitivity analysis performed.

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Keywords: building energy consumption; energy demand model; sensitivity analysis; energy efficiency

1. Introduction

Socio-economic development of modern societies and technological progress give rise to a continuously increasing energy demand. Buildings contribute significantly to the total energy demand and account in some countries for up to 45 % of the primary energy consumption [1–3]. Consequently research on building energy consumption has been intensified in recent years by the scientific community and the industrial sector. The growing interest is a result of many factors, including integration of renewable energy sources and storage systems, limitations of the infrastructure for energy production and transport as well as the opportunity to create business models with an added value for customers and companies. Affordable smart meters and the establishment of appropriate legal frameworks pushed smart meter deployment in many countries [4] and allow collecting large data sets on energy consumption in buildings.

Applications and services based on smart meter data provide benefits to end-users, retailers, network operators and utilities. Detailed data on building energy consumption is used in a wide range of applications such as demand

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optimisation, fault detection and network management. Possible positive effects include higher profits, cost reductions, better power quality and improved energy efficiency. However, factors such as legal issues, erroneous measurements or inappropriate sampling prevent general availability of building energy consumption data. Besides, demand data are frequently required before smart meter installation or building commissioning. The lack of suitable data can be avoided by using demand forecasting and estimation and that is why the detailed mathematical modelling of building energy demand plays an essential role.

1.1. Research aim

The objective is the development of a tool to estimate the building energy consumption and the supply costs. The generation of realistic demand profiles for a building needs to combine the architectural properties with the way how people use and interact with it. A high degree of flexibility is required for producing a mathematical model that would allow an estimation of energy consumption of a wide range of different buildings. The artificial data generated by such a tool can be then employed to define an adequate building energy system and to develop additional services.

Buildings are subject to frequent changes in the way how they are used, maintained and refurbished that may affect their energy consumption and supply costs. Variations in the energy demand and costs with respect to changes in the building configuration can be obtained from a sensitivity analysis. The tool will determine the critical building parameters which can be then used to reduce energy consumption and improve energy efficiency.

1.2. Overview

This paper presents a tool to estimate the building energy consumption and the supply costs for an entire year on an hourly basis. The integrated sensitivity analysis determines the elasticity of the energy consumption and costs with respect to the building configuration. The paper is organised as follows: Section 2 reviews different modelling techniques for building energy consumption. Section 3 describes the tool including the estimation of the building consumption, the sensitivity analysis and the implementation. Results obtained with the tool for an office building located in Madrid (Spain) are presented in Section 4. Finally, the most important conclusions are drawn in Section 6.

2. Research background

In recent years, both scientists and companies have intensified their research activities in modelling building energy consumption that resulted in a large variety of prediction models. The interest is a consequence of the growing energy demand in buildings and the rising energy supply costs. Understanding of energy consumption patterns and prediction of future demand creates an opportunity to resolve – at least partially – related energy issues such as security of supply and address some of environmental and economic issues. The following paragraphs explain the frequently used categories to classify modelling approaches for building energy consumption: engineering methods and statistical techniques [5,6].

2.1. Statistical methods

Statistical methods in building energy consumption modelling employ regression techniques, conditional demand analysis or neural networks to correlate energy demand with the influencing variables [6]. These models commonly take into account variables such as ambient temperatures, relative humidity or daytime. The parameter estimation usually requires large amounts of data and runs the risk of spurious correlation or multicollinearity.

Statistical methods are used in [7] to develop an artificial neural network (ANN) that relates weekday and extreme temperatures with the energy consumption of a university building. The monthly energy consumption for a large scale public building was predicted in [8] with a multiple linear regression model. In [9], multiple regression and genetic programming models to forecast the daily electricity consumption in administration buildings were presented. A probabilistic approach was used in [10] to develop a residential energy demand model that takes into account the contributions of a wide range of common household appliances.

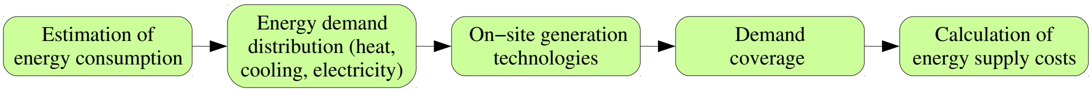

Fig. 1. General structure for the estimation of the building energy consumption and the corresponding energy supply costs.

2.2. Engineering methods

Engineering methods use physical principles to estimate the energy consumption on building level or for sub-level components [6]. The scope of models based on engineering techniques range from simple designs to highly complex structures considering concepts such as heat and mass transfer, thermodynamics and fluid mechanics. These models can be created without historical data but require parameters that are often unavailable or difficult to obtain.

An example for engineering techniques is the energy demand model of a university building divided in 215 thermal zones considering architectural data and thermal properties of materials [11]. A one-storey office building modelled as a thermal network is used in [12] to optimize the building energy consumption. The computational fluid dynamics and airflow modelling are combined in [13] to simulate the air infiltration rate in an office building.

3. Building energy assessment tool

The building energy assessment tool has two main functions: estimation of the energy consumption and supply costs and analysis of the sensitivity with respect to changes in the building configuration. The following paragraphs explain in detail the functionality of the developed tool.

3.1. Estimation of energy consumption and supply costs

The estimation of the building energy consumption and the corresponding costs for the energy supply is carried out in successive steps (see Fig. 1). The tool employs the building configuration to estimate the energy demand for a complete year on an hourly basis. The estimated demand is then divided in its heating, cooling and electricity components. Afterwards, the demands are distributed on the considered generation technologies (e.g. heat pump, chiller, etc.) and corresponding energy sources (e.g. electricity, gas, etc.). Finally, the total costs for the energy supply are calculated on basis of the demands covered by the energy sources.

3.1.1. Building model

The building model used in the tool considers both the building architecture and the presence of people. The flexible configuration allows modelling a wide range of different building types. The building configuration takes into account the following aspects related to the energy consumption and supply costs:

- **Architecture:** general architectural characteristics of the considered building. Parameters include dimensions of the building, surface covered by windows, thermal transmittance of walls and windows, g-value of the windows as well as number of floors (including subterranean floors).
- **Building usage:** definition of the different building areas (e.g. office, canteen, etc.). The required parameters for each area contain surface, desired luminosity, luminous efficacy, desired relative humidity, air changes per hour, permitted minimum and maximum temperatures and available natural light.
- **Location:** definition of geographic position and environmental conditions. Parameters comprise latitude, longitude, altitude, standard meridian, clear sky ratio, cold water temperature (supplied by public utility) as well as relative humidity and minimum and maximum temperatures for the coldest and warmest month of the year.
- **Facilities & services:** configuration of devices (generation and consumption) installed in the building. Includes parameters for lifts and other energy-demanding equipment (distinguishes between workdays and holidays), heat pump, boiler, electric space heating, chiller, solar collectors and CHP (combined heat and power).
- **People:** configuration of energy consumption related to the presence of people (e.g. office staff, cleaners, etc.). For each group of people the parameters include number of persons, hot water consumption per person and day, average electric demand per person, ratio of absenteeism as well as working time on workdays and holidays.

- **Economic data:** defines economic tariffs for different energy sources, includes a possibility to consider time-of-use (TOU) pricing schemes for electric energy supply.

3.1.2. Estimation of energy consumption

The building energy consumption is estimated with the given configuration (see Section 3.1.1) for an equilibrated energy balance, i.e. the developed model is based on a static approach assuming a steady-state condition of the building. The estimation includes both energy demands based on the architectural configuration of the building as well as consumption related to the people in the building. Currently, the model considers the following factors:

- **Environmental interaction:** heat transfer (both losses and gains) between building and environment, includes transmission and solar radiation
- **Workplace conditioning:** energy demand to ensure appropriate conditions for working, comprises ventilation and illumination
- **Personnel consumption:** energy consumption directly related to the presence of people in the building, considers hot water supply, electric devices in workplace (e.g. computers, machines, etc.) and elevators
- **Other energy demands:** energy consumption by equipment not included in the aforementioned groups, includes continuously running devices (e.g. emergency lights, locking systems, etc.) and other equipment not used permanently (e.g. laboratory devices, kitchen appliances, etc.)
- **Non-dispatchable generation:** reduction of necessary external energy supply by non-dispatchable generation systems such as solar collectors or photovoltaic (PV) panels[1].

The estimation procedure computes the different components that affect the building energy consumption for an entire year on an hourly basis. The obtained results for the heat transfer, energy demand and generation are given by the following variables (all $\mathbb{R}^{8760}$): transmission $\dot{Q}_{trans}$, ventilation $\dot{Q}_{ventil}$, solar radiation $\dot{Q}_{rad}$, illumination P_{illum}, elevators P_{lift}, hot water $\dot{Q}_{water}$, people P_{people}, other equipment P_{equip} and solar collectors $\dot{Q}_{coll}$. Generally, heat losses and energy demands are given as positive values (e.g. $\dot{Q}_{trans} > 0$ and $P_{lift} > 0$) whereas heat gains and energy generation are represented by negative values (e.g. $\dot{Q}_{rad} < 0$ or $\dot{Q}_{coll} < 0$).

3.1.3. Energy demand distribution

Building energy demand can be represented as three independent components: heating, cooling and electricity. Given their nature the contributions of the non-dispatchable generation and the heat transfers affecting the building energy consumption (see Section 3.1.2) should be represented in the same way. The total heat flow between the building and the environment is given as the sum of transmission, ventilation and radiation:

$$\dot{Q}_{flow} = \dot{Q}_{trans} + \dot{Q}_{ventil} + \dot{Q}_{rad} \tag{1}$$

The total heat flow has to be compensated by heating ($\dot{Q}_{flow} > 0$) or dissipated by cooling ($\dot{Q}_{flow} < 0$). The heating corresponds to the positive heat flow and the energy required for hot water supply after using the solar collectors:

$$\dot{Q}_{heat} = \max(\dot{Q}_{flow}, 0) + \max(\dot{Q}_{water} + \dot{Q}_{coll}, 0) \tag{2}$$

In contrast, the energy to be dissipated by the building air conditioning system is the negative part of the heat flow:

$$\dot{Q}_{cool} = \max(-\dot{Q}_{flow}, 0) \tag{3}$$

Note that $\dot{Q}_{cool}$ has been defined as a positive term as it leads in later stages to an energy demand. Finally, the required electric power is given as the sum of all previously estimated electric demands:

$$P_{power} = P_{illum} + P_{lift} + P_{people} + P_{equip} \tag{4}$$

[1] In the current version of the model only solar collectors for hot water supply have been considered.

3.1.4. On-site generation technologies

Heating and cooling demands (see Section 3.1.3) have to be satisfied by the facilities or technologies available in the studied building. The nominal or maximum power of the technologies can be adjusted in the building configuration. Any additional technologies currently not included in the tool can be easily integrated in the developed structure.

In the current version, the tool employs CHP, heat pumps, boilers and electric space heating in a predefined order to satisfy heat demand $\dot{Q}_{heat}$. The heat supplied by CHP is given by:

$$\dot{Q}_{heat}^{CHP} = \dot{Q}_{heat} - \max(\dot{Q}_{heat} - f^{CHP} P_{nom}^{CHP}, 0) \tag{5}$$

where P_{nom}^{CHP} denotes the nominal output power (heat+electricity) of the CHP system and f^{CHP} is the ratio of the heat production with respect to the nominal power. In the case of the heat pump, the produced heat is defined as:

$$\dot{Q}_{heat}^{h-pump} = \dot{Q}_{heat} - \dot{Q}_{heat}^{CHP} - \max(\dot{Q}_{heat} - \dot{Q}_{heat}^{CHP} - \phi^{h-pump} P_{nom}^{h-pump}, 0) \tag{6}$$

being P_{nom}^{h-pump} the nominal electric power of the heat pump and ϕ^{h-pump} denotes the coefficient of performance (COP). The heat produced by the boiler can be expressed as:

$$\dot{Q}_{heat}^{boiler} = \dot{Q}_{heat} - \dot{Q}_{heat}^{CHP} - \dot{Q}_{heat}^{h-pump} - \max(\dot{Q}_{heat} - \dot{Q}_{heat}^{CHP} - \dot{Q}_{heat}^{h-pump} - P_{nom}^{boiler}, 0) \tag{7}$$

with boiler nominal power P_{nom}^{boiler}. In the case of the electric space heating the produced heat is defined by:

$$\dot{Q}_{heat}^{space-h} = \dot{Q}_{heat} - \dot{Q}_{heat}^{CHP} - \dot{Q}_{heat}^{h-pump} - \dot{Q}_{heat}^{boiler} - \max(\dot{Q}_{heat} - \dot{Q}_{heat}^{CHP} - \dot{Q}_{heat}^{h-pump} - \dot{Q}_{heat}^{boiler} - P_{nom}^{space-h}, 0) \tag{8}$$

where $P_{nom}^{space-h}$ represents the nominal output power of the electric space heating[2].

Any excess heat has to be removed from the building to avoid undesired working conditions. Currently, the tool considers a chiller to produce necessary heat transfer $\dot{Q}_{cool}$ for cooling:

$$\dot{Q}_{cool}^{chill} = \dot{Q}_{cool} - \max(\dot{Q}_{cool} - \phi^{chill} P_{nom}^{chill}, 0) \tag{9}$$

where ϕ^{chill} denotes the coefficient of performance and P_{nom}^{chill} represents the nominal electric chiller power. Other cooling systems can be easily added to the developed tool.

In the case of the CHP plant the generated electricity is proportional to heat $\dot{Q}_{heat}^{CHP}$ (6) and defined by:

$$P_{power}^{CHP} = \frac{1 - f^{CHP}}{f^{CHP}} \dot{Q}_{heat}^{CHP} \tag{10}$$

3.1.5. Demand coverage

Different energy sources are used to meet the cooling and heating demands (see Section 3.1.4). The technologies currently considered by the tool use either electricity (heat pump, electric space heating, chiller) or gas (CHP, boiler) to generate the necessary heat transfers.

The gas consumption of the CHP system depends directly on generated heat $\dot{Q}_{heat}^{CHP}$, conversion efficiency η^{CHP} and heat production ratio f^{CHP}:

$$P_{gas}^{CHP} = \frac{\dot{Q}_{heat}^{CHP}}{\eta^{CHP} f^{CHP}} \tag{11}$$

In the case of the boiler, the gas consumption can be written with efficiency η^{boiler} as an input power:

$$P_{gas}^{boiler} = \frac{\dot{Q}_{heat}^{boiler}}{\eta^{boiler}} \tag{12}$$

The resulting total input power related to the gas consumption by the CHP system (11) and the boiler (12) is given by:

$$P_{gas} = P_{gas}^{CHP} + P_{gas}^{boiler} \tag{13}$$

[2] Note that the heat demand corresponds to the amount of supplied heat if statement $\dot{Q}_{heat} = \dot{Q}_{heat}^{CHP} + \dot{Q}_{heat}^{h-pump} + \dot{Q}_{heat}^{boiler} + \dot{Q}_{heat}^{space-h}$ holds. Otherwise, the building cannot be sufficiently heated resulting in an undesired temperature decrease in its interior.

In the case of the heat pump, the electric demand depends on generated heat $\dot{Q}^{h-pump}_{heat}$ and coefficient of performance ϕ^{h-pump}:

$$P^{h-pump}_{elec} = \frac{\dot{Q}^{h-pump}_{heat}}{\phi^{h-pump}} \tag{14}$$

With generated heat $\dot{Q}^{space-h}_{heat}$ and conversion efficiency η^{h-pump}, the demand of the electric space heating is:

$$P^{space-h}_{elec} = \frac{\dot{Q}^{space-h}_{heat}}{\eta^{space_h}} \tag{15}$$

The electric demand of the chiller depends on removed heat $\dot{Q}^{chill}_{cool}$ and the coefficient of performance ϕ^{chill}:

$$P^{chill}_{elec} = \frac{\dot{Q}^{chill}_{cool}}{\phi^{chill}} \tag{16}$$

The required electric power consists of the direct consumption (4), the electric generation of the CHP plant (10) and the demands from heat pump (14), electric space heating (15) and chiller (16):

$$P_{elec} = \max(P_{power} - P_{CHP,elec} + P_{h-pump} + P_{space-h} + P_{chill}, 0) \tag{17}$$

The max-statement in (17) applies only if the electric generation of the CHP plant exceeds the sum of considered demands. In that case the CHP plant covers the entire electric demand of the building leading to $P_{elec} = 0$.

3.1.6. Energy supply costs

The energy supply costs depend directly on the demands for gas and electricity (P_{gas} (13) and P_{elec} (17)) determined previously (see Section 3.1.5). The costs both for gas and electricity consist of a standing charge, i.e. fixed costs for providing a continuous energy supply, and the costs directly related to the consumed amount of energy.

In the case of the gas supply, the costs for the complete year on an hourly basis are given by:

$$C_{gas} = \mathrm{g}(P_{gas}, p_{gas}, c_{gas}) \tag{18}$$

where g(·) is the considered cost function, p_{gas} denotes the unit price and c_{gas} represents the fixed charge (specified in the building configuration). Analogously, the costs for the electricity supply are defined by the function:

$$C_{elec} = \mathrm{h}(P_{elec}, p_{elec}, c_{elec}, \varphi_{elec}) \tag{19}$$

with unit price p_{elec}, fixed cost c_{elec} and contracted power φ_{elec}. Cost function h(·) considers an excess power penalty and allows defining time-of-use tariffs (TOU) with different unit costs and fixed charges for each period. Finally, the total cost of the energy supply for the building for an entire year on an hourly basis is given by:

$$C_{total} = C_{gas} + C_{elec} \tag{20}$$

3.2. Sensitivity analysis of energy consumption and costs

The sensitivity analysis integrated in the tool studies the effect of variations in the building configuration on the energy consumption and the costs. The results allow identifying critical building parameters which can be then used to reduce consumption/costs and improve energy efficiency. The sensitivity analysis is based on the elasticity defined as:

$$E^Y_X = \frac{\Delta Y}{Y}\frac{X}{\Delta X} \tag{21}$$

where E^Y_X represents the elasticity of variable Y to changes in parameter X. The use of the elasticity concept allows an easy comparison of results without the need of additional data normalization. The tool calculates the elasticity of the energy demand and supply costs with respect to a wide range of building parameters:

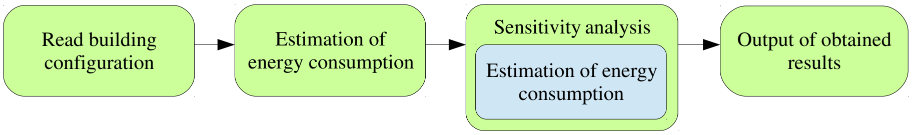

Fig. 2. Main implementation steps for energy consumption/costs estimation and the sensitivity analysis.

- **Architecture:** thermal transmittance, g-values of windows.
- **Building usage:** luminosity, luminous efficacy, relative humidity, air changes per hour, permitted temperatures.
- **Facilities & services:** power and conversion efficiency/performance coefficient of installed systems
- **People:** consumption of hot water per person and day, average electric demand per person.
- **Economic data:** unit price and fixed costs for gas and electricity, taxes.

The sensitivity analysis compares the energy consumption and costs obtained with a modified building configuration with the results of the base case, i.e. the original parameters. The energy consumption and supply costs are determined by using the estimation procedure presented in Section 3.1. Hence, elasticity (21) can be rewritten as:

$$E_X^Y = \frac{Y_m - Y_b}{Y_b}\frac{X_b}{X_m - X_b} \tag{22}$$

where subindices b and m denote the base case and the scenario with a modified parameter, respectively.

3.3. Implementation

The estimation of the energy consumption and the sensitivity analysis have been implemented in the Matlab environment (version R2013b). Matlab is a powerful mathematical program suitable for rapid development of algorithms and procedures that provides easy handling of large matrices and data structures as the ones used by the proposed tool. The general structure of the developed tools and the steps carried out by the implemented procedures are shown in Fig. 2.

In the first place, the program reads the building configuration ranging from the architectural aspects to the tariff information (see Section 3.1.1). Secondly, the configuration of the building is employed to determine energy consumption and corresponding costs for an entire year on an hourly basis. Afterwards, the program determines the sensitivity of the energy consumption and costs with respect to the changes in the building configuration. Finally, the tool saves the detailed results which can be used by other programs for further analysis or visualization. The estimated consumption gives an idea on the origin of the demand, the used technologies and the resulting costs. The results of the sensitivity analysis can be employed to improve the energy efficiency of the building or reduce the supply costs.

4. Results

The implemented program has been used to estimate the energy consumption and supply costs of several buildings in Spain. The case studies include buildings with different characteristics and in different climate zones such as an office building in Madrid, a hotel in Mallorca and a shopping centre in Santander. This section presents results obtained with the office complex exposed to Madrid's largely varying climate with relatively cold winters and very hot summers and large temperature differences between day and night.

The considered middle-sized office building has the following configuration:

- **Architecture:** 43 m long (north/south sides), 15 m wide (east/west sides), 21 m high, 9 floors (2 subterranean floors), 30 % of the façade is covered by solar control windows (g-value of 40 %), thermal transmittance of 0.5 $W/m^2/K$ (roof) and 1.2 $W/m^2/K$ (windows).
- **Building usage:** useful area mainly used for offices (2670 m^2), corridors (700 m^2), parking (640 m^2), stairways (588 m^2) and meeting rooms (460 m^2). From 8 am to 8 pm the temperature is maintained between 21 °C and 23 °C, otherwise between 18 °C and 26 °C, relative humidity constant at 50 %, luminous efficacy is 70 lm/W and hourly air changes ranging from 4 (offices, corridors, stairways) and 8 (lunch room and laboratories).

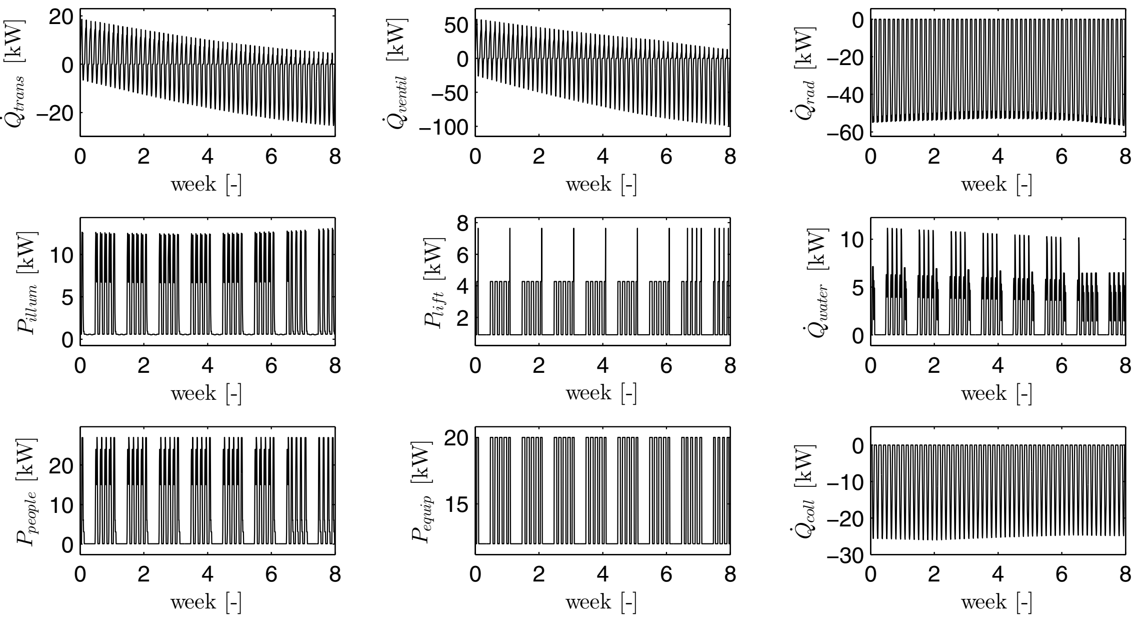

Fig. 3. Estimated heat transfers and energy demands for the office building during the months of June and July.

- **Location:** city centre of Madrid, 655 m above sea level, February: temperatures from 1.2 º C to 12 º C and relative humidity of 65 %, August: temperatures between 17.8 º C and 33.7 º C with relative humidity of 35 %.
- **Facilities & services:** lifts (45 kW nominal power), other devices (10 kW demand), additional equipment (10 kW demand on workdays from 7 am to 9 pm, 2 kW otherwise), boiler (200 kW nominal power, efficiency of 0.95), chiller (200 kW nominal power, COP of 3.5), solar collectors (30 kW nominal power, efficiency of 0.85).
- **People:** 250 office employees, 10 cleaners as well as other staff (employees in canteen: 10, laboratories: 3, security: 2, reception: 2, maintenance: 1), hot water consumption of 3 l/day by most employees, higher values only for cleaners (50 l/day) and canteen staff (100 l/day), additional energy consumption of employees between 100 W (office staff, security, reception) and 500 W (laboratories), general absenteeism rate of 5 %.
- **Economic data:** general gas tariff (80.97 €/month, 0.0496 €/kWh), time-of-use (TOU) electric tariff with six periods (contracted power of 100 kW, fixed charges from 6.37 €/kW/year to 38.10 €/kW/year, unit price between 0.059 €/kWh and 0.15 €/kWh), electricity tax of 4.8 % and general VAT of 21 %.

The energy consumption of the office building and the supply costs were estimated by using the developed tool. The energy demands and heat transfers for June/July are shown in Fig. 3. In this period heat losses due to transmission ($\dot{Q}_{trans}$) and ventilation ($\dot{Q}_{vent}$) are decreasing whereas the energy received by solar radiation ($\dot{Q}_{rad}$) and the energy captured by the solar collectors ($\dot{Q}_{coll}$) are fairly constant. The demands from illumination (P_{illum}), lifts (P_{lift}), hot water ($\dot{Q}_{water}$), employees (P_{people}) and other devices (P_{equip}) show large variations between workdays and weekends.

The estimated energy demands and heat transfers are then divided in heating, cooling and electric power (see Fig. 4). It can be observed that the heat demand $\dot{Q}_{heat}$ decreases from approximately 60 kW to less than 10 kW during the months of June and July. In the same period the necessary cooling $\dot{Q}_{cool}$ increases from 80 kW to 180 kW. The direct electricity demand P_{power} shows the typical workday/weekend pattern with a maximum demand of 60 kW.

Heating $\dot{Q}_{heat}$ and cooling $\dot{Q}_{cool}$ demands are covered in the building by using a gas-fired boiler and a chiller, respectively. The distribution of the estimated demands on different energy sources is given in Fig. 5. Gas-generated power P_{gas} is used exclusively for heating whereas electric power P_{elec} is employed for cooling and to cover the direct electricity demand. The resulting total annual energy costs for the considered building sum up to 73592.33 € with 21639.77 € for the gas supply and 51952.56 € for electricity.

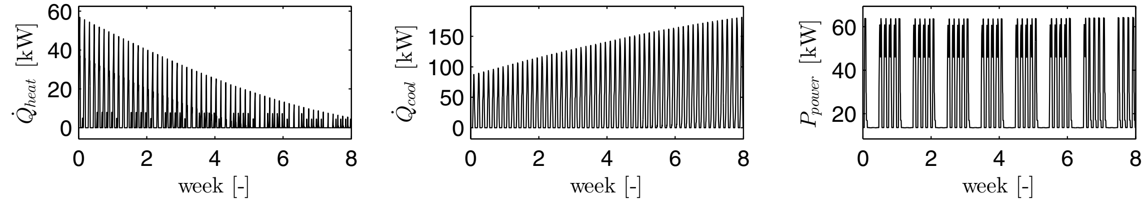

Fig. 4. Estimated heating, cooling and direct electricity demands for the office building during the months of June and July.

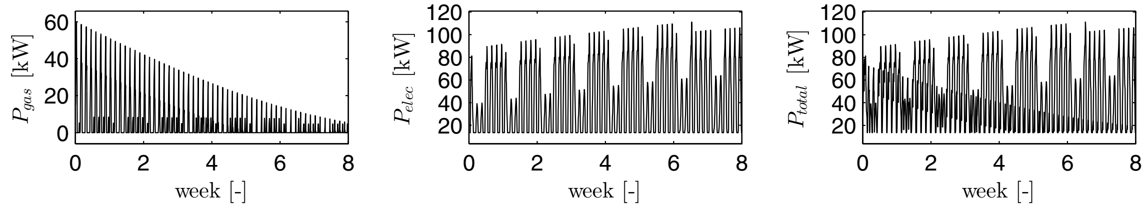

Fig. 5. Demand coverage (gas, electricity and total).

Table 1. Results from the sensitivity analysis of the office building: values for the base case and for the changes obtained by parameter modifications.

Case/parameter	Change	$\dot{Q}_{heat}$	$\dot{Q}_{cool}$	P_{power}	P_{gas}	P_{elec}	C_{gas}	C_{elec}	C_{total}
Base case	—	323.9 MWh	226.3 MWh	256.3 MWh	341.0 MWh	320.9 MWh	21639.77 €	51952.56 €	73592.33 €
Windows transmittance	+1 %	0.11 %	0.02 %	0.00 %	0.11 %	0.00 %	0.11 %	0.00 %	0.04 %
Windows g-value	+1 %	-0.23 %	0.71 %	0.00 %	-0.23 %	0.14 %	-0.22 %	0.11 %	0.01 %
Luminous efficiency	+1 %	0.00 %	0.00 %	-0.17 %	0.00 %	-0.13 %	0.00 %	-0.12 %	-0.08 %
Air changes/hour	+1 %	0.87 %	0.24 %	0.00 %	0.87 %	0.05 %	0.83 %	0.05 %	0.28 %
Boiler efficiency	+1 %	0.00 %	0.00 %	0.00 %	-0.99 %	0.00 %	-0.94 %	0.00 %	-0.28 %
Chiller COP	+1 %	0.00 %	0.00 %	0.00 %	0.00 %	-0.20 %	0.00 %	-0.17 %	-0.12 %
Gas unit price	+1 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.95 %	0.00 %	0.28 %
Electricity unit price	+1 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.18 %	0.13 %
Contracted electric power	+1 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.72 %	0.51 %
Minimum temperature	−1 º C	-12.45 %	5.01 %	0.00 %	-12.45 %	1.01 %	-11.77 %	0.68 %	-2.98 %
Maximum temperature	+1 º C	0.00 %	-10.02 %	0.00 %	0.00 %	-2.02 %	0.00 %	-1.73 %	-1.22 %

The sensitivity analysis (see Tab. 1 for some of the obtained results) showed that modified air/temperature conditions (minimum/maximum temperatures in the building and number of air changes per hour) and variations in the windows g-value lead to considerable changes in the energy demands $\dot{Q}_{heat}$ and $\dot{Q}_{cool}$. Improved devices for heating/cooling (boiler efficiency and chiller COP) are suitable to reduce the energy consumption P_{gas} and P_{elec}. In the case of costs C_{total}, important savings can be obtained by modifying the contracted electric power and the permitted minimum and maximum temperatures. Variations in the number of air changes per hour, boiler efficiency and gas unit price affect moderately the costs. Other measures based on windows characteristics (thermal transmittance and g-value), luminous efficiency, chiller COP and electricity unit price have a rather small effect on the total energy costs.

5. Discussion

In the developed tool, in contrast to most commercially available products, special attention has been paid to the energy demand generated by building occupants. It combines contributions to the demand originated from both the architectural characteristics and the people interaction with the building. Prediction of the energy demand generated by building occupants is frequently simplified using consumption patterns. In the presented tool a large number of parameters allow defining user groups with different energy demands. Each group can be customized with their own working time, ratio of absenteeism, hot water consumption, electric demand and other parameters.

The exact prediction of the occupant behaviour is not possible, but the definition of different users provides the opportunity to obtain a more realistic user demand. The explicit inclusion of the user demand can improve the fit between measured building performance and model prediction. The presented results underline the importance to include the occupant energy demand in the estimation procedure. In the examined case study other components such as transmission or ventilation contribute in a greater extent to the overall demand. However, the observed peak demand justifies the explicit consideration of the energy consumption related to the presence of people.

The sensitivity analysis provided insight about possible measures to improve energy efficiency and reduce overall consumption. In the presented case study, important energy savings could be achieved with changes in the ventilation, windows properties and cooling/heating devices. The obtained results showed the general usefulness of the developed tool. At the current development stage, further testing and validation with experimental data will be necessary to reach the next level of technological maturity.

6. Conclusions

This paper presents a tool for estimating building energy consumption and supply costs. The proposed approach takes into account environmental interactions (i.e. heat transfer between building and environment), workplace conditioning, personnel consumption, other energy demands, on-site dispatchable and non-dispatchable generation.

The developed procedure estimates the energy demand for a building for an entire year on an hourly basis. The tool determines the demand covered by the installed on-site generation technologies and external energy sources. The costs for the building energy consumption are calculated using predefined energy tariffs. The integrated sensitivity analysis allows identifying critical parameters that can be used to reduce energy consumption and supply costs.

The results obtained in a case study demonstrated the usefulness of the developed tool, especially in the identification of critical building parameters suitable to improve energy efficiency and reduce operational costs. Besides, the tool showed the magnitude of the occupant demand and the importance to include it in the estimation procedure.

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