DEVELOPMENT OF A GENERIC AND SCALABLE MODELICA BASED MODEL OF A TYPICAL FRENCH RAILWAY STATION BUILDING

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ABSTRACT

This paper presents the energy modeling and simulation of a railway station building through thermal and electrical loads calculations. To address this problem, we have developed architectures of thermal and electrical models using Dymola/Modelica environment. Thermal model is based on the elementary components of Modelica Buildings Library associated with other internal (GDF SUEZ) and external libraries. As for the electrical model, we implemented a new library to predict and calibrate on real data provided by measurements the power consumption of several equipment into a railway station. In order to test the capabilities of the model, a reference railway station is selected to assess the thermal and electrical consumption of the building. Finally, we identify the electrical services with interesting potential for energy savings and load flexibility, and some suggestions for improving the consumption are pointed out as well.

INTRODUCTION

The energy performance's improvement for existing and new buildings has become one of the major concerns for policies of energy management and sustainable development. The SNCF (French National Railway Company) is an important consumer of electricity in France with 9 TWh per year, and particularly ranked first consumer during peak hours. In future years, its energy bill will increase because of business growth of the railway network and the probably rising cost of electricity due to the market evolution. Railway stations and buildings account for approximately 20% of SNCF's energy consumption with an invoice which is about 100 M€per year.

In order to meet the requirements of national energy regulations (French Building Thermal regulation 2012) for new railway station buildings, but also to anticipate evolutions regarding energy market, it is necessary to find innovative solutions to reduce the energy bill. Thus, optimization of the energy consumption is becoming mandatory for the engineering of the railway stations. Moreover, the SNCF also examines whether it can take an active role in the smart grids by becoming both producer and actor of the electricity flexibility.

It is within this context that the international chair Econoving launched an important research program. The main objective is to provide short-term improvements of energy performance by energy savings and to identify services within the railway station with interesting potential for load flexibility. Subsequently, it will establish mid-term research for integrating the optimized energy management into a local micro-grid of an ecodistrict.

The aim of this article consists in understanding and improving the knowledge concerning the energy consumption behaviour of a typical French railway station building. Thus, energy modelling of the main building of the station is considered through detailed thermal and electrical load calculations. Furthermore, new functionalities will complete the model in order to optimise, forecast, schedule, manage in real time the energy generation and consumption function of energy cost fluctuation.

The paper is organized as follows. Firstly, a state of the art of existing work on modelling and numerical simulation of energetic behaviour of buildings and equipment within a railway station is carried out. This state of the art is then extended to the evaluation of different commercial modelling environments. The choice of the latter is widely discussed and justified as well.

In the same section, the main assumptions together with the thermal and electrical models developed in order to simulate the energy performance are presented. Details of model architecture are given with an overview on Dymola/Modelica. Then, the monitoring campaign is presented with a brief description of experimental setup.

The third section of the paper is dedicated to description of a railway station selected as reference for simulation test case. Then, various scenarios of simulation are also described.

In the fourth section, simulation results obtained with the test case are presented. Firstly, heating and cooling loads calculated by thermal model are discussed with some proposals of improvement. Then, the results of power demand for some electrical equipment are presented with the calibration on real data provided by measurements. At the end of this section, the repartition of consumption per usage is given, and opportunities for improvement are also adressed.

Finally, our conclusions are presented and possible future work is discussed.

STATE OF THE ART

Railway stations are often seen as the buildings, but they are in fact larger functional units designed to combine all the functions focused on access to the train such as: travel information, buying of transport tickets, various commercial services, access by escalators and elevators, as well as equipment related to the safety of rail traffic.

Furthermore, a railway station is also a real multimodal exchange center that facilitates intermodal practices between different kinds of transport: bus, tramway, subway, electric vehicle and bicycle.

The functional whole which is the railway station consists of a main station building (passengers building, offices, businesses, technical rooms, equipment, platforms) and approaches to the station (parking lots, shopping centers, neighborhoods). Currently, our perimeter of modelling is limited to the main station buildings with its equipment.

In the literature review, many authors focus on modeling and simulation of energy performance in residential and commercial buildings (offices, schools, hospitals, etc.). In contrast, those interested specifically in railway station buildings are few.

In this section, a literature review of previous work and those in progress on the railway station is presented. This state of art is divided into two major parts : work carried out nationwide (i.e. in France) and those conducted globally.

Railway stations in France

Two new French TGV stations have been recently built and put into service in 2011. These are the Besançon Franche-Comte TGV railway station and the Belfort Montbeliard TGV railway station. They were designed according to an ambitious approach of sustainable development. These are the two first French railway stations certified as High Environmental Quality.

Building of the new railway station of Besancon Franche-Comte TGV was designed for optimal use of energy. Planned strategies in terms of energy management in this building enable to obtain an annual consumption lower than 50 kWh/m^2, allowing to qualify this railway station as low energy consumption building. The railway station is equipped with a set of technology making best use of renewable energy sources: ground-coupled heat exchanger, wood-fire heating, photovoltaic modules and solar thermal panels. Indeed, nearly 75% of energy consumption is arising from these energies.

Otherwise, for the Belfort Montbeliard TGV railway station, the main objective of the task undertaken involves the implementation of devices using natural resources in order to minimize the need of heating and cooling load. The technologies developed were similar to those of Besançon.

Wurtz et al., 2012 also worked on energy modeling development within the framework of optimal and simultaneous design of building envelope, especially illustrated with a railway station. Finally, always in the idea to develop an energy management system, (Hadj et al., 2012) studied the case of a railway station central heating system with wood cogeneration and gas heater sources.

Railway stations worldwide

In a recent paper, (Liu et al., 2011) presented a study on the modeling and numerical simulation of Nanjing South Railway Station (NSRS) building. The latter is one of the famous large-scale transportation hub in China. These authors were interested to the optimization of NSRS's HVAC systems using DeST (Designer's Simulation Toolkit), a building energy simulation tool developed by Tsinghua University, in conjunction with other software. They attempted to explore a more effective design strategy for energy consumption simulation. The simulation results obtained in this research allowed to highligth that air infiltration is the most important factor impacting the total energy demand of the railway station. Otherwise, the effect of the envelope's optimization turned out less on reducing energy consumption. Finally, an analysis of the indoor thermal comfort was also addressed. These authors focused exclusively on the building envelope of the train station and its optimization. The energy consumption occasioned by other electrical equipment such as lighting, escalators, elevators, distributors, etc., was not considered in this study.

Fu and Deng, 2009 also studied the energy consumption of Guangzhou railway station in China. Through datagathering and analyzing the whole-year situation of building energy consumption, they found that air-conditioning, lighting, power equipment, elevators constitute the four major parts of the electricity consumption. Energy consumption of the lighting system proven relatively small compared to air conditioning ones which is the largest. They concluded that there was irrationality and waste phenomena in the design, operation and management of air-conditioning, lighting and power equipment. This work do not address the modeling in contrast to those of (Liu et al., 2011). Results are mainly from energy data measured in the railway station.

There are others research on the modeling of railway stations in China, such as (Li et al., 2009). In this study, the authors used a CFD method to evaluate the evolutions of indoor temperatures of the environment of a railway station in terms of three air conditioning systems. The main purpose was to introduce an efficient way to evaluate and optimize the design of air conditioning system in order to improve the comfort of passengers. The use of CFD models is interesting and accurate but has a major disadvantage which is particularly the computation time.

The project of Stuttgart railway station (Ingenhoven, 2005) is part of the project "Stuttgart 21" concerning the modernization of the city. This project has many features related to sustainable development like using materials of low environmental impact, optimal management of energy and water.

Finally, other authors such as (Nakano et al., 2006), (Deb and Ramachandraiah, 2010) were based on simple models derived from statistics and surveys carried out with passengers and then evaluate their thermal comfort.

In terms of goals, the common thread between all these works reviewed is a search of solutions that optimize the energy consumption of the railway station and its systems. There are very few studies that have investigated the modeling of electrical equipment such as lighting, escalators and elevators, except of energy audit carried out by (Fu and Deng, 2009) on the Guangzhou railway station. Moreover, none provides long-term management strategies optimized energy, and nor integration of smart grid in their studies. This latter point constitutes a major issue because it allows adapting consumption needs of railways stations buildings and their eco-districts.

Now we present our methodology of modeling which will takes into account all of these aspects.

ENERGY MODELING OF RAILWAY STATION BUILDING

In this section, the choice of modeling tool is first presented with supporting arguments. Second, the methodology of thermal and electricity loads modeling into a railway station are described.

Modeling tool

The choice of an appropriate modeling tool is needed to simulate thermal and electrical behavior of a complex system such as buildings of a railway station. Indeed, the building of a railway station and its equipment are similar to a set of embedded systems. The characteristics of these systems involve multiple domains such as heat and mass transfer, thermodynamics, fluid mechanics, electrical, control and communication systems. However, a modeling environment more suitable to study the behavior of this system should be an environment able to represent more intuitively such a complex system. First, by allowing a user to add quickly models for new components. Then, also enabling rapid reconfiguration of components in order to form new systems.

In the context of our work, two modeling tools seem relevant to resolve and simulate thermal and electrical behavior of a railway station. These are Trnsys and Dymola/Modelica.

Trnsys (Klein et al., 1976) is a modular and flexible tool used for solving problems of heat transfer in the building envelope. It contains many libraries of models allowing the evaluation of the buildings energy performance. Its disadvantage is that models are mainly focused on the heat phenomena. It also has a difficulty to address physical issues requiring implementation of small time steps (particularly for the building model) which are necessary to simulate properly the power demand. Models are often simplified that they do not capture the dynamic behaviour and part-load operation of the response of feedback control systems. Finally, because of oriented calculation procedures, changing the nature of a physical problem by trying to keep the same models is very complicated.

Dymola (Elmqvist, 1978) is a multi-disciplinary tool for the detailed resolution of physical problems such as thermal, mechanical, electrical, thermodynamic, hydraulic, pneumatic, and control systems. The Dymola environment uses the open Modelica modeling language. It provides the possibility of using small time steps and the equations that describe the behavior of a system are formulated in a declarative way and are automatically resolved. A priori, the computational procedures are not oriented. Many libraries of models (Michaelsen and Eiden, 2009), (Wetter et al., 2011) are available for modeling multi-zone buildings and HVAC systems.

These models have a very high readability with increased easy maintenance, which allows rapid reconfiguration in order to form new systems.

Considering the advantages and inconveniences of each tool analyzed, Dymola/Modelica has been chosen for our modeling work. Further arguments justifying this choice can be found in (Wetter, 2011) which presents what a future environment for building system modeling and simulation may look like. It examines in particular the limitations of existing building simulation programs to model and simulate the performance of integrated building energy and control systems and how recent advances can overcome these limitations.

Thermal model

The thermal model developed is based on elementary components of Modelica Buildings Library (Wetter et al., 2011) combined with other internal (GDF SUEZ) and external libraries. Figure 1 shows a view of the main module of the model. The thermal behaviour of the railway station building is analyzed depending on several factors shown as input signals : weather data (yellow bus), air infiltration and ventilation (top blue circles), internal gains (left top), heating power (left bottom), control signal of shading devices (bottom).

Moreover, the outputs (right bottom) which are indoor temperatures are used to carry out a closed loop control for the heating power as a function of temperature setpoint and comfort level.

Figure 1 Architecture of thermal model of railway station building

The internal gains are calculated using occupancy profiles of railway station according to office schedules and passenger's flow.

Electrical model

The modeling methodology adopted for predicting the power and the consumption of railway station building is based on a bottom-up approach. Figure 2 shows an overview of the architecture of generic electrical model that we have developed on Dymola/Modelica.

Models of each electrical appliance are encapsulated in a single generic configurable module.

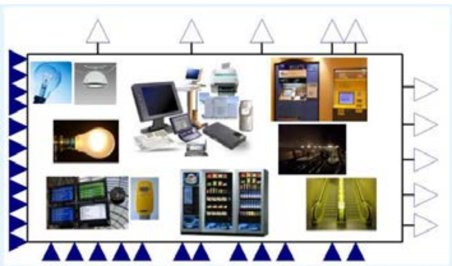

Figure 2 Overview of the architecture of generic electrical model in Dymola/Modelica

The inputs represent the various matrix operations (stop/start, etc.) and the outputs indicate the instantaneous power demand of each electrical equipment. Then, using a post-processing, the model computes the aggregated electrical power demand of the railway station building. This formalism allows the modeling of consumers per zone but also per service. In addition, it also facilitates the implementation of control strategies for energy management independently.

For the modeling of power consumption of a specific zone of the building, the user must simply follow these steps:

- Create an instance of the generic model,
- Provide information on the consumers in the zone. According to this information, the inputs and ouputs ports are automatically generated,
- Set-up each equipment parameters: number, standby power, nominal power, etc.,
- Finally, define on the outside of this model the operating signals (occupation, period of use, etc.) and if required other exogenous variables.

Modeling of several distinct zones is done by creating multiple instances of this generic model. Thus, the model developed has a flexible and reusable nature. In addition, new consumers can easily be added to the database models progressively during the development phase.

The challenge of such modeling approach is the development of operational matrix (signal sources and causes) that can reproduce well adequately load profile of the appliance studied and magnitude of operating powers. Then, calibration studies with actual measurements can adjust the parameters of the model.

Experimental setup

In order to calibrate the models, measurements are carried out by SNCF in order to monitor the consumption of each equipment. The measured variable is the power consumption in kWh.

DESCRIPTION OF TEST CASE

Description of the railway station building

The railway station building considered in this study is located in the Paris region (Figure 3). It receives between 50 000 and 60 000 passengers per day.

Figure 3 Facade and main entrance of building

The building has been divided into 12 thermal zones as shown in the Figure 4.

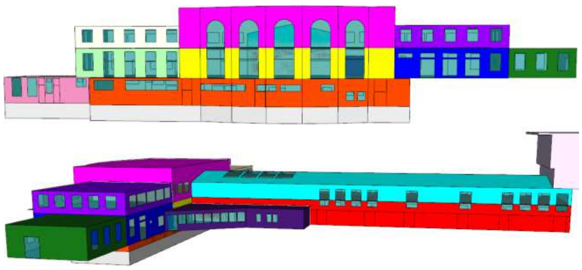

Figure 4 Front view and side view of the building

The total surface considered is 3 895 m². Only 30% of this surface is heated and 4% is cooled.

In order to determine the characteristics of the building envelope, an energy audit was conducted. The material properties of walls, floors, roofs, glazing systems and window frame are respectively given in Table 1 to Table 4.

Table 1 Envelop characteristics

Building element	Interior	Exterior
	U [W/m².K]	
Wall	0.708	0.756
Floor	0.753	0.789

Table 2 Material properties of roofs

	Roofs of offices	Roofs of others
U [W/m².K]	0.66	0.756

Table 3 Material properties of glazing systems

	Single glazing	Double glazing
U [W/m².K]	5.75	2.64

Table 4 Material properties of window frame

	Aluminium	PVC	Wood
U [W/m².K]	5.88	1.91	5.13

Furthermore, scenarios of presence and occupancy rate of the building have been established after many investigations conducted into the railway station. The internal gains are evaluated according to the density of people, lighting and equipment. They are injected into the zones as sensible, convective, latent and radiant heat. The heating of offices is ensured by means of a gas boiler. Heat is emitted by hot water radiators, but some electrical back-ups are also present in certain premises. For the offices, heating and cooling are continuously supplied with a stop between early May and late September. The heating setpoint is set at 21°C during the period of occupation and at 16°C otherwise. For cooling, the setpoint is set at 27°C.

The studied railway station has no mechanical ventilation systems. The ventilation occurs naturally and is conditionned by the opening of windows by occupants. This aspect is tough to implement during this phase mainly because of the difficulty of assessing airflows generated. Further research will take into account the improvement of this aspects.

The proposed solution consists of using a variable ventilation rate according to criteria on the evolution of the outdoor temperature and the indoor temperature. Thus, for offices we implemented the control algorithm as follows :

- If the outdoor temperature is lower than the indoor temperature, the windows are open,
- If the room temperature exceeds 27°C, an airflow rate of 3.6 vol/h is considered, 0.6 vol/h otherwise.

For other zones where the travelers transit, the ventilation rate is considered constant throughout the year : 1 to 6 vol/h depending on the zone.

SIMULATION RESULTS AND DISCUSSION

Results of thermal model

Figure 5 shows the results giving heating and cooling demand of the railway station building over one year.

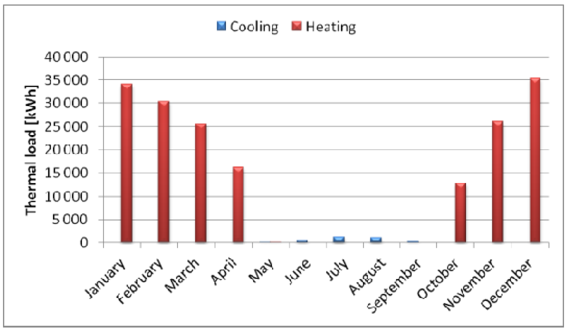

Figure 5 Monthly heating and cooling demand

Heating demand are similar to classic evolutions of demand in a building, we can observed high demands in winter, especially in December and January. There is a progressive decrease in the approach of the summer period and a progressive increase when approaching the winter period. For cooling, the station has high demand during periods of high temperatures, i.e. in July and August.

Table 5 summarizes the annual heating and cooling demand of the railway station building. These results have been validated with Trnsys where difference inferior to 10% was observed. Specific needs in cooling represent less than 2% of total thermal energy demand. Indeed, the conditioned floor area is only about 170 m².

Table 5 Annual total heating and cooling demand

Heating [MWh]	Heating [kWh/m².an]	Cooling [MWh]	Cooling [kWh/m².an]
180	150	3	19

We found that the maximum power demand for heating purposes is equivalent to 120 kW. Figure 6 shows the evolution of total hours of heater operation during the year by range of power demand and load rate. The load rate is defined according to the maximum power. The analysis of this curve allows us to conclude that the heating does not work for 46% of the time. Also, the maximum power is only called for 1% of the time over the year.

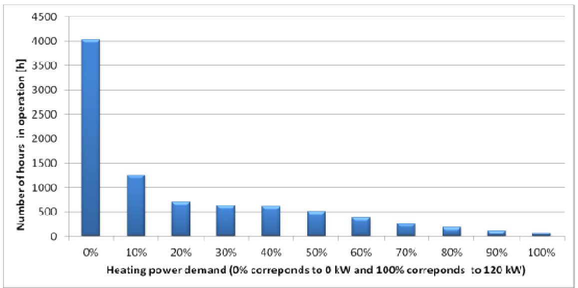

Figure 6 Number of hours versus ranges of heating power demand

Improvement of heating and cooling demand

In order to minimize the heating demands, we proposed some preliminary recommendations of improvement compared to the existing one. Table 6 gives the optimization scenarios considered for this study.

Table 6 Scenarios of optimization study

Case	**Recommendations**	**Gains**
1	Double glazing 4/16/4 Argon	-6.5%
2	Double the thickness of insulation material	-12%
3	Setpoint at 19°C during occupancy (for the zones occupied by the personnel, no temperature control for the travellers zone)	-16%
4	Combination of previous : Case1 + Case 2 + Case 3	-33%

The first case corresponds to a replacement of all systems of single glazing and double-glazing (4/16 /4 cm Air) by double-glazing (4/16/4 Argon).

The second case concerns the improvement of the envelope insulation by doubling the thickness of insulator of the exterior wall and roofing. The insulating material of the exterior wall is currently polystyrene with 4 cm thick, and the roof is made of 5 cm of glass wool.

Case 3 enables to evaluate the influence of a reduction of 2°C of the setpoint temperature.

Finally, the last case is a combination of all the previous cases. As we can see in Table 6, the practical implementation of the proposed solutions will help to reduce up to 33% thermal demands of the railway station building.

Results of electrical model

To quantify the savings potential of energy and load flexibility, it is necessary to analyze firstly the power consumption of each electrical equipment into the railway station. Figure 7, Figure 8 and Figure 9 show respectively the evolution of energy consumptions of advertising boards, platforms lighting, and escalators. The calibrated models are compared to real measurements and a good agreement between these results is observed.

It can be observed as well that the operation of advertising boards and lighting are practically controlled by a strategy of on/off. However, the model describing the behavior of these equipment is easy to implement, calibration is achieved by adjusting the start and stop time as well as power demand. Further equipment (travel information for example) whose consumption profiles are not presented in this paper have similar characteristics. Indeed, the use and consumption of these equipment are independent of the flow of passengers, weather conditions, etc..

In contrast, for escalators, there is a correlation between consumption and flow travelers as shown in Figure 9.

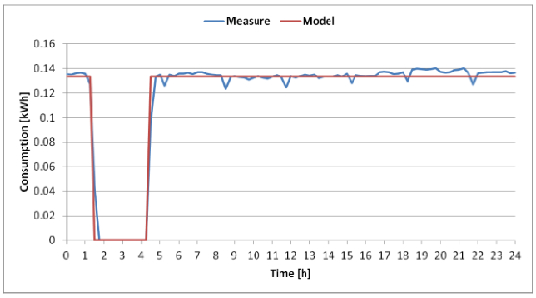

Figure 7 Energy consumption of advertising boards

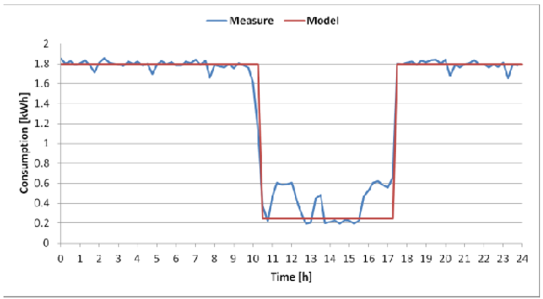

Figure 8 Energy consumption of platform lighting

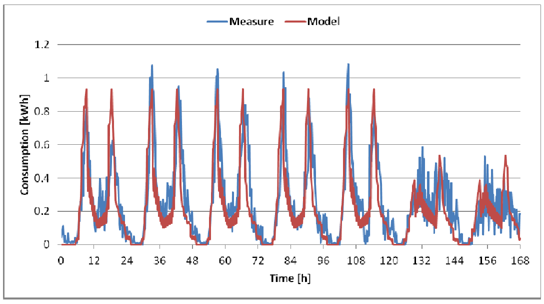

Figure 9 Energy consumption of Escalators during one week

The total power demand of an escalator is typically defined as the sum of a fixed and variable consumption. Fixed power demand occurs when the escalator is operating unloaded without passengers. Moreover, the variable power demand takes place when the escalator carrying passengers. This latter quantity depends on the movement direction of the escalator. The upward circulation of passengers leads to an increase of the power required, whereas a downward movement causes a decrease of power consumption (Al-Sharif, 2011).

Controlling the operation of an escalator can be achieved manually or automatically. In manual control, starting or stopping is performed by means of switches. The control can be done locally or remotely depending on whether the device is under surveillance or not. In automatic control, the operation of the escalator depends of the presence of users which are detected by infrared cells or contact mat placed before walking on the esclator. The escalator ensures the transport of all persons detected, then it is automatically stopped or reduced speed after idling short delay. In practice, the automatic mode helps to save energy but is not the best possible solution for the escalators with a high passenger flows because the number of starts can be important.

In Figure 11, we present the evolution over a day of power demand of escalators that depends to the presence of passengers.

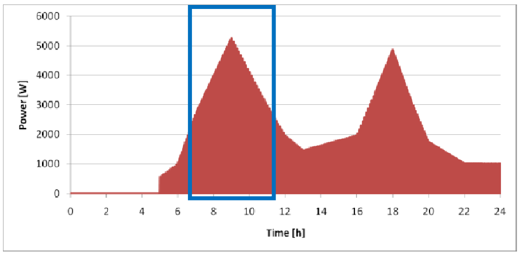

Figure 10 Power demand of Escalators during a working day

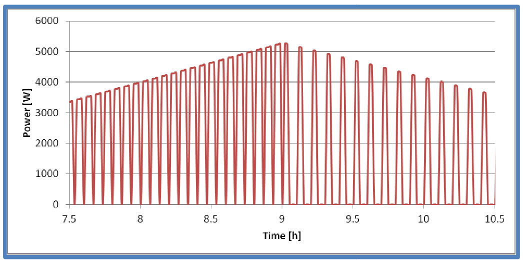

Figure 11 Power demand of Escalators between 7h30 and 10h30 am of a working day

The use is strongly intermittent during the day. We note that during peak hours, the frequency of escalators calls is high due to the large number of trains and passengers. This phenomenon can be seen between 8 and 9 am on Figure 11.

Similarly, the use of automated teller machines (ATMs) is also highly intermittent. However, the power involved during withdrawal operations is of the same order of magnitude as the standby power. Thus for the latter, it is not necessary to consider this effect in the modeling.

The total load curve of the railway station is obtained from the addition of the power demand of all electrical equipment. The peak demand observed is approximately 160 kW during peak hours. In off-peak periods, this value is reduced to a minimum value of 90 kW.

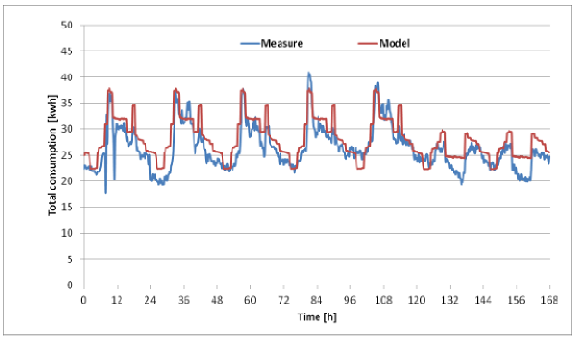

Figure 12 Station weekly load profile

Finally, Figure 12 presents the comparison of total weekly consumption between measurements and model results. The model reproduces the electrical demand of some services of the railway station fairly well. However, the accuracy of prediction could be improved further by enhancing the idenfication of uncontrollable loads.

Electricity consumption per usage

Calibrated electrical loads can be divided into two groups: controllable and uncontrollable loads.

For the first category, loads can be controlled using modeling and simulation. In such cases, equipment and usages causing consumption are well identified with their associated commands.

Concerning the second group, loads are not controllable by an energy management system. Indeed, such consumption is very difficult to model because of many uncertainties. For this research, these uncontrollable loads (restaurant, telecom, railway station specific process, etc.) are introduced into the modeling directly from the conducted measures.

Nevertheless, it is important to take into account all of these loads in the balance of energy consumption. This provides all relevant information for energy management system.

Figure 13 shows consumption repartition for each usage of the railway station. This distribution indicates that the consumption of non-controllable loads (mixed equipment) weights more than the half of the total electricity consumption of railway station.

Lighting is the second consumer with a share of 24%, followed by elevators and escalators (8%), information for passengers (7%), and then composters machines (3%).

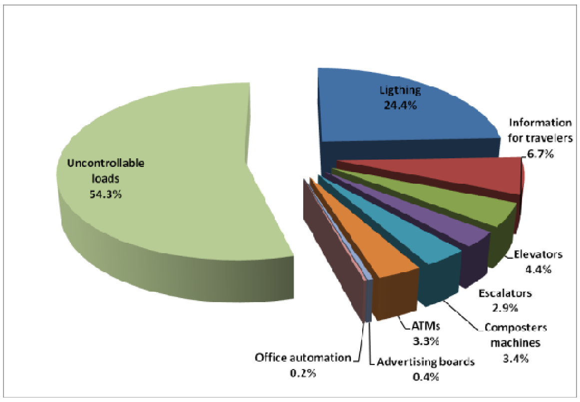

Figure 13 Electricity consumption per usage

Total annual electricity consumption is estimated at 985 MWh against 180 MWh for the heating loads. This allows to conclude that the consumptions caused by the thermal and electricity are respectively 16% and 84% of the total consumption of the railway station studied. This conclusion is very useful because its indicates that the effort of searching energy savings potential and flexibility must be primarly focused on electrical consumption.

CONCLUSION AND FUTURE WORK

This paper presents the development of a generic and scalable (the structure of this model will be adapted and used to model a portfolio of railway stations) Modelica based a multi-energy model of a typical French railway station building. The literature review of the existent research for railway station has shown an increasing interest in the understanding of energy consumption for this kind of buildings.

In this article, we have presented the main results of thermal and electrical models of the railway station selected as reference. The analysis revealed a low contribution of consumption due to heating and cooling loads. Whereas, a significant part of consumption is due to electricity demand of equipment. Thus, the electrical services which have the greatest potential for energy savings and flexibility have been identified. These are specifically controllable loads: lighting, elevators, escalators, information for passengers and composters machines.

For the work in progress, we have already highlighted that optimal management of these equipment during off-peak periods allows to achieve energy savings ranging between 5 to 10%. Moreover, in terms of flexibility towards the grid or aggregator, the railway station can offer a power peak shaving which can reach up to 10% of current peak demand.

Therefore, for allowing the railway station to become an actor of flexibility, it is necessary to develop energy management strategies in order to achieve an intelligent control of consumption, in particular when the railway station is integrated into a smart grid. The integration of decentralized generation such as photovoltaic, micro combined heat and power, etc. local production combined with storage system will also enable to increase the potential for flexibility. These aspects will be investigated and are the main goals of our future work.

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