COUPLING BETWEEN A GRAPHICAL SIMULATION ENVIRONMENT SIMULATOR AND AN OPTIMISATION ALGORITHM

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ABSTRACT

The main aim of this study is to derive some simple rules for an optimal management of direct electric heating in residential buildings.

Optimal management should minimise the running cost of heating while maintaining comfort, in the case of control strategies involving intermittent heating.

This study has been carried out with the help of numerical simulation in a graphical environment [1] in order to study the behaviour of a whole system, referred to as a simulator, which consists of the building zone, the heating system and the controller. We chose an optimisation function of a mathematical software [2] to determine the optimal value of the operating cost . The coupling between the simulator and the optimisation algorithm is done automatically during the simulation in order to determine the optimal management scenario.

The relevance of the work lies in the coupling between the simulator and the optimisation algorithm. This coupling was made possible thanks to the structuring of the simulator following a modelling methodology and parametering rules developed by CSTB [3]. The methodology enabled an efficient modelling of the system to carry out the optimisation analysis automatically on a large number of cases.

The analysis by "experiment plans" on the simulation results obtained allowed the definition of rules for the optimal management of direct electric heating.

This paper mainly presents the modelling methodology implemented. It lays emphasis on the use of existing mathematical tools. It does not give the results of the study but analyses one of the stages of intermittent heating considered in the study.

NOMENCLATURE

GV: Heat loss coefficient of the building zone [W/K].

IN: Inertia of the building zone (Kg/m^2].

T_{ext}: Outdoor temperature [°C].

T_{max}: Maximum overheating temperature [°C].

T_r: Setback temperature [°C].

T_c: Comfort temperature (=19°C).

HP: High tariff rate period when the cost of a kWh is high. In this study, it ranges from 6 a.m. to 10 p.m.

HC: Low tariff rate period when the cost of a kWh is low. In this study, it ranges from 10 p.m. to 6 a.m.

HP/HC: ratio of cost of kWh between high tariff rate and low tariff rate

F_n: Start time of morning heating period [hour]

$F_{n\,0}$: Start time of morning comfort period [hour]

D_j: Start time of morning period without heating [hour]

D_{j0}: End time of morning comfort period [hour]

F_j: Start time of evening heating period [hour]

F_{j0}: Start time of evening comfort period [hour]

D_n: Start time of night period without heating [hour]

D_{n0}: End time of evening comfort period [hour]

δ : Time interval between the shift "low tariff rate/high tariff rate" and the start time of morning period. [hour]

INTRODUCTION

Optimal programming schedules must minimise the running cost of heating and provide comfort. They must take into account the occupants' presence/ absence scenarios, the tariff rates of EDF (Electric Supply Company), the weather conditions and the characteristics of the residential building.

Figure 1 below shows the general shape of the optimal management scenario with the anticipation of rising and falling triggers. The management scheme considers low tariff periods as a criterion for a possible boost of the heating system.

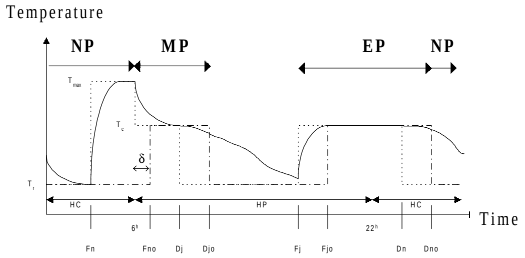


Figure 1

—·— : Daily comfort temperature set point

- - - - : Daily optimal temperature set point

—— : Daily optimal temperature evolution

NP : Night Period **MP**: Morning Period **EP** : Evening Period

The programming scheme is said to be optimal if the running cost is minimised while comfort constraints are satisfied. The parameters describing this scheme are the unknowns that need to be determined.

Figure 1 suggests that the problem can be broken down into three specific problems:

- End of night setback period with shift "low tariff rate period/high tariff rate period".
- End of day setback period.
- Beginning of setback period (day or night).

Night setback is further studied according to two approaches: Overheating during low tariff rate period or linear change in temperature during low tariff rates period.

An additional case is considered in the study: low tariff rate during lunch break (noon to 2 p.m.). It is not represented on Figure 1.

The study is thus sub-divided into five specific problems. Each one is dealt with independently. This paper does not give the final results on the relevance of intermittent heating. It focuses on the setting up of the simulation and the parametering of the system. The "end of night setback with overheating during low tariff rate period" case is taken as an example to illustrate the simulation procedure and results analysis.

DESCRIPTION OF THE "END OF NIGHT SETBACK WITH OVERHEATING" CASE

In certain cases, the practice of night setback can prove to be more expensive than continuous heating strategy because the boost period often partly occurs during the high tariff rate period.

For this problem, figure 2 shows the shape of the scenario for one day corresponding to the user's minimal comfort requirements.

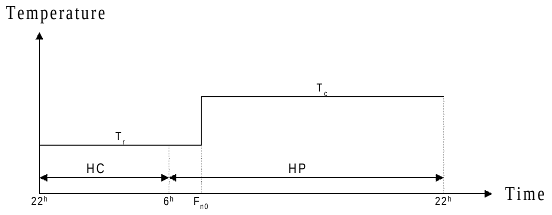


Figure 2

The objective for this problem is to determine the necessary anticipation to minimise the running cost. It could imply a slight overheating at the end of the low tariff rate period. The optimal management scenario for one day has the following shape:

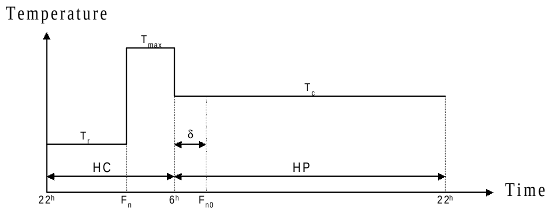


Figure 3

Regarding this problem, our task consisted in optimising the parameter of scenario F_n so as to obtain comfort at F_{n0} time of start of occupancy, as well as minimising the operating cost.

The buildings studied are either detached houses or flats in a collective residential building. They are derived from a typological description of the main residential building in France [4].

For this problem, the cases studied correspond to combinations of parameters identified for the sensitivity analysis: external parameters linked to the building and to the weather conditions and internal parameters linked to the optimal management scenario. Solar heat gains and internal heat gains are being neglected.

External parameters:

GV: Building heat loss coefficient (W/K)

IN: Building inertia

T_{ext}: Outdoor temperature (°C)

Internal parameters (cf. figure 3):

T_{max}: Overheating temperature (maximum temperature allowed)

T_r: Setback temperature

δ: Time interval between the shift from low tariff rate to high tariff rate and the beginning of the occupied period where the resultant temperature shall be equal to T_c

HP/HC: Ratio of the cost of a kWh between low tariff rate and high tariff rate.

Two representative values are chosen for each parameter (approach using "experiment plans ") and a neutral median value to test for linearity.

Table 1 gives all the values chosen for each parameter in the sensitivity analysis:

Table 1

T_{ext}	IN	GV	T_{max}	T_r	δ	HP/HC
±5	±1	±1	19 or 22°C	16 or 19°C	0 or 2h	1.8 or 8

IN=-1 or IN=1 corresponds to an intermediate or high inertia respectively

GV=-1 or GV=1 corresponds to a value of the heat loss coefficient equal to GVref-10% or GVref-25% respectively

GVref is the reference heat loss coefficient (W/K).

GVref = 200W/K for the detached house

GVref = 77W/K for the flat in a collective residential building

IMPLEMENTING THE SYSTEM IN A GRAPHICAL ENVIRONMENT

Implementing the system in a graphical environment requires some expertise to make an efficient use of the semantic nature of graphical programming.

The following paragraph briefly presents the description methodology in graphical environments. A methodology for describing HVAC systems has been developed at CSTB in order to achieve a relevant representation of the building and its technical facilities in a graphical environment.

This methodology is the result of a PhD thesis [3]. It has contributed to a good analysis of the problem and has given guidelines for a proper use of graphical programming techniques to describe the system.

The method relies on the General System Theory to define a "Building System". A building is indeed a complex entity where the building envelope, the technical facilities and the occupants interact in a complex way, within a given outdoor environment. An analysis of the building must consider the latter as a whole, including all these elements and theirs interactions, hence the need to refer to the basic notions of the General System to tackle such an "organised complexity". This theory defines a system as a set of elements organised according to a goal and immersed in an environment. There are three key words in this definition:

1) The goal/**purpose** enables the definition of the features (quantities to be analysed, example: temperature, consumption, cost) to be taken into account when describing the system for a particular analysis.

2) The set, often called the **structure** of the system, must form a coherent and autonomous unit. The notion of organisation implies interactions, interrelations between elements.

3) The **environment** defines the real or conceptual borders of the system. It serves to identify the boundary conditions of the system.

Figure 4 represents the generic Building System adapted to the graphical environment. The description follows the definition of the general system exposed above. It puts forward "the goals, the structure and the environment" of the system.

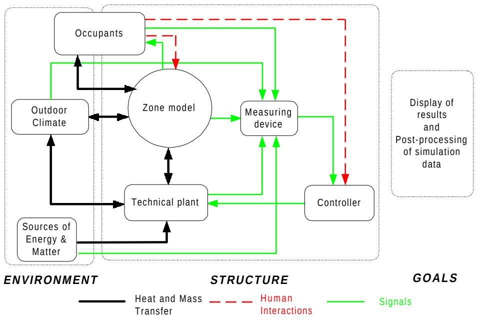


Figure 4: Generic representation of the Building System

The generic system comprises the major elements that participate in most studies related to the field of control and energy management in buildings.

Interactions on the generic scheme correspond to energy/matter flow and information flow following the General System theory. In the method developed for graphical environments, the interactions between elements closely resemble the actual technological interactions in order to improve the understanding of virtual systems. The links on the graphical interface are vectors of data that represent the fluids flowing in HVAC systems (air and water), the electric network, and communication networks A meteorological data vector and a vector symbolising the human interactions are also being considered.

Both developers and users benefit from this generic system description:

- Developers have a common description method, which will facilitate the exchange of models or parts of a system.
- Users, whether expert or novice, can read any system easily since the latter follows the same layout as the generic system.

We use the generic scheme and the system modelling approach to build the virtual system suitable for our study.

The purpose of the virtual system is:

- Calculation of energy consumption on the defined period of the day (one of the five problems identified).
- The length of the optimal boost period.
- The corresponding running cost (minimum cost).

The environment of the system is modelled by the outdoor temperature variations which are the only outdoor stresses, and by the choice of the ratio low tariff rate / high tariff rate which is characteristic of the energy source.

The structure of the system consists of the following elements:

- The thermal zone model represented by a second order model (thermal-electric analogy) with 3 resistances and 2 capacitors [5].
- The emitter model (electric heater) which is a first order model (one time constant).
- A PI-type controller model.
- A constant time clock model.

Figure 5 is the layout of the heating system in a graphical environment.

PARAMETERING MODELS

The previous paragraph dealt with the description of the building and its technical facilities in a graphical environment. The methodology also discusses the parametering of models of components and of a whole system. A hierarchy of parameters has been proposed to enhance the understanding of models and thus promote their use. There are four types of parameters:

- Intrinsic parameters: they characterise each component individually.
- Parameters related to the sizing of a system: they are distributed over several elements but must be evaluated simultaneously in order to obtain a properly sized system.
- Parameters related to the tuning of a system: they appear on elements of the control system. They are evaluated once the sizing of the HVAC system has been carried out.
- Parameters for analysis in a particular study: they are the parameters available on the uppermost level of the user-interface, that is, the first interface that the users see. They are defined according to the studies.

Different levels of abstraction are devised on the graphical interface to distinguish between the different types of parameters. The superposition of the layers of graphical interface enables the developer to structure the transfer of parameters to components.

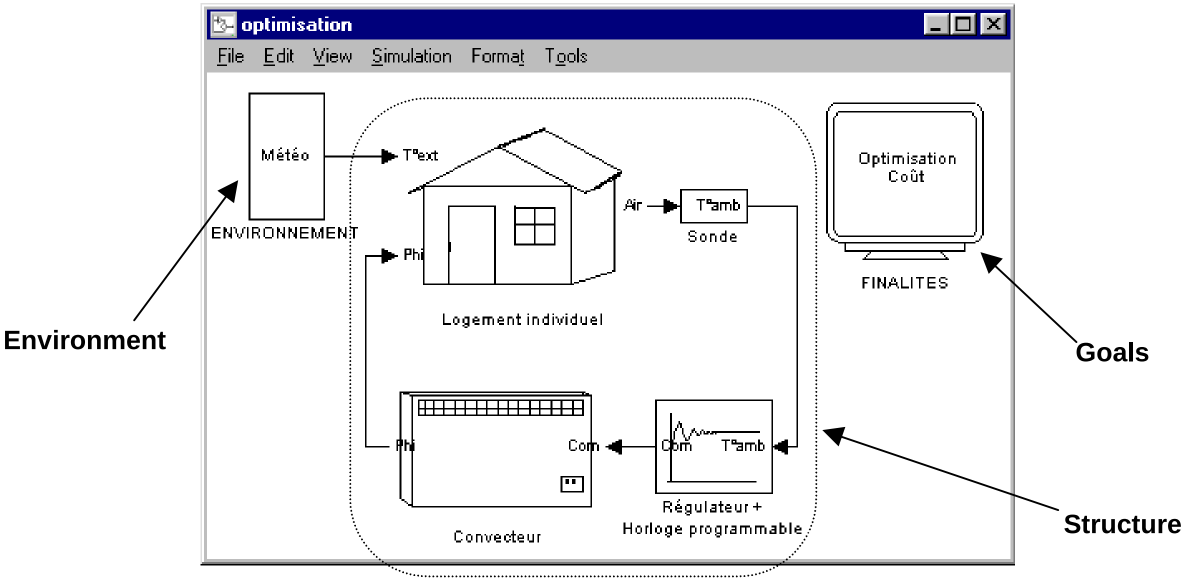


Figure 5: Graphic representation of the electric heating system

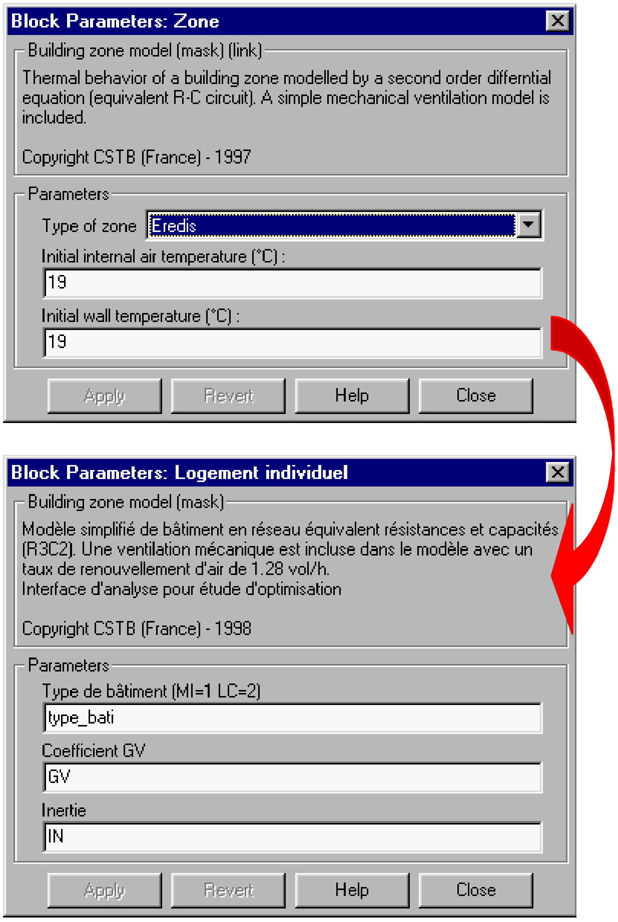
In this study, the required system is built up from component models available in the SIMBAD library [6] developed at CSTB. The parametering of the models is adapted according to the needs of the study. Table 2 is a list of the parameters of the models involved in the system.

Table 2

Model	Parameters	Type			
		Intrinsic	Sizing	Tuning	Analysis
Thermal zone	Type of zone	X			
	Initial air temperature	X			
	Initial mean temperature	X			
Constant time clock*	End of night setback: F_n			X	X
	Beginning time of comfort period: δ			X	X
	Setback temperature: T_r			X	X
	Comfort temperature: T_c			X	
	Overheating temperature: T_{max}			X	X
Central controller*	Gain (1/proportional band)			X	
	Integration time			X	
Controlled mechanical ventilation	Air flow rate		X		
Electric heater	Type of heater	X			
	Nominal power		X		

* Model specific to the study

The original building model contains a list of typical buildings. The user chooses one building via the "Type of zone" parameter and the model assigns values of resistances and capacitances to the equivalent electric circuit.



Block Parameters: Zone

Building zone model (mask) (link)

Thermal behavior of a building zone modelled by a second order differntial equation (equivalent R-C circuit). A simple mechanical ventilation model is included.

Copyright CSTB (France) - 1997

Parameters

Type of zone: Eredis

Initial internal air temperature (°C) : 19

Initial wall temperature (°C) : 19

Block Parameters: Logement individuel

Building zone model (mask)

Modèle simplifié de bâtiment en réseau équivalent résistances et capacités (R3C2). Une ventilation mécanique est incluse dans le modèle avec un taux de renouvellement d'air de 1.28 vol/h.
Interface d'analyse pour étude d'optimisation

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Parameters

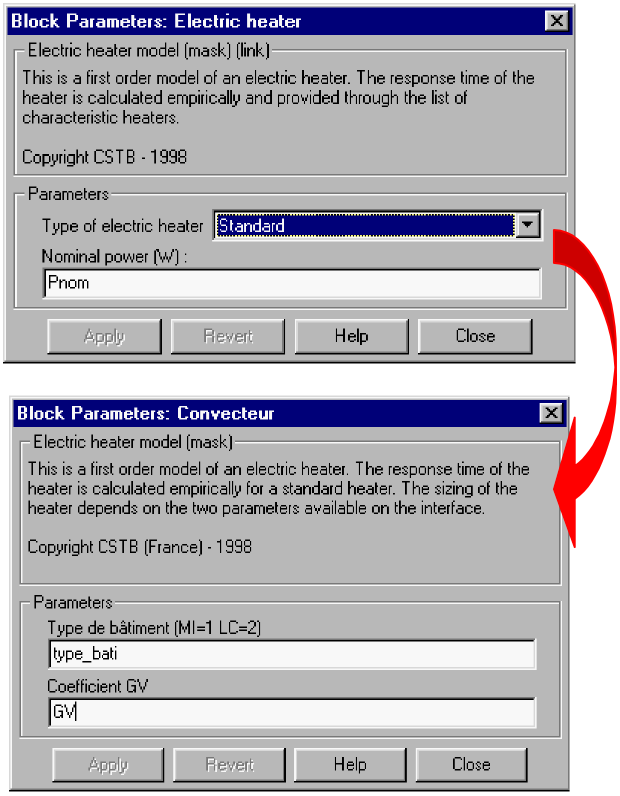
Type de bâtiment (MI=1 LC=2): type_bati

Coefficient GV: GV

Inertie: IN

Figure 6: Adapting the user interface for parameters of the building zone model

This study requires adapted building types (GVref-10% and GVref-25%). The user needs to choose the type of building ("type_bat" on figure 6). Two further parameters of analysis are the heat loss coefficient (GV) and the inertia of the building (IN). A supplementary dialogue interface is added to the model. The definition of these three parameters enables the building model to use the suitable values of resistances and capacitances.



Block Parameters: Electric heater

Electric heater model (mask) (link)

This is a first order model of an electric heater. The response time of the heater is calculated empirically and provided through the list of characteristic heaters.

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Parameters

Type of electric heater: Standard

Nominal power (W) : Pnom

Block Parameters: Convecteur

Electric heater model (mask)

This is a first order model of an electric heater. The response time of the heater is calculated empirically for a standard heater. The sizing of the heater depends on the two parameters available on the interface.

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Parameters

Type de bâtiment (MI=1 LC=2): type_bati

Coefficient GV: GV

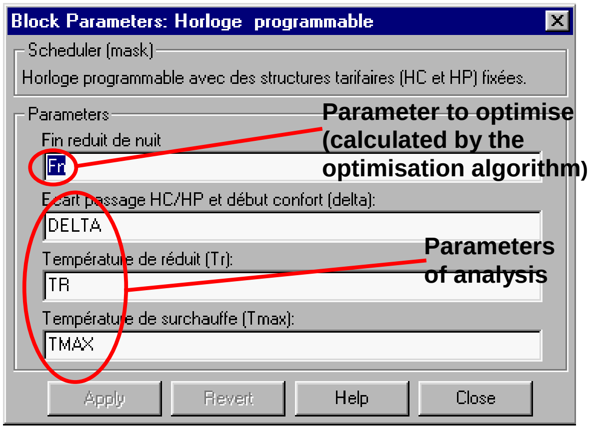
Figure 7: Sizing the electric heater via a new user interface

The electric heater is the only model that needs to be sized. The size of the heater depends on the type of building and the heat loss coefficient of the building. These are parameters of analysis in this study.

The user interface of the electric heater model is modified to show the two parameters of analysis. The nominal power of the electric heater is calculated automatically on an inner layer once the two parameters have been chosen.

The PI parameters of the PI-controller in this study are not relevant. Their values have been pre-determined in order to approach the behaviour of an almost ideal controller [7]. Generally, these values remain unaltered.

The constant time clock model is specific to this study. The user interface includes the parameters of analysis related to the management scenario (figure 3) and the parameter that must be optimised (F_n).


Block Parameters: Horloge programmable

Scheduler (mask)

Horloge programmable avec des structures tarifaires (HC et HP) fixées.

Parameters

Fin reduit de nuit: Fr

Ecart passage HC/HP et début confort (delta): DELTA

Température de réduit (Tr): TR

Température de surchauffe (Tmax): TMAX

Figure 8: User interface of the constant time clock including the parameter to be optimised

All the parameters of analysis appear on the user interface of the models (see table 2, row ‘Constant time clock’, and column: ‘Analysis’). The values of these parameters are not prompted directly on the interface. They are called variables and are given specific names so that they can be varied automatically from a script file.

COUPLING METHOD

The particularity of this study is the coupling of the system described in the graphical simulation environment, and an optimisation toolbox [8].

The simulation is done with one set of parameters on several days to avoid initialisation problems regarding simulated systems. Only results of the last day are analysed. The running cost is calculated for this specific day.

An optimisation procedure is applied on the cost of the day. The principle of coupling between the simulator and the algorithm is illustrated on Figure 9. The parameter to be optimised appears in the heating management scenario. As regards the problem of night setback, this parameter is F_n. The optimisation rule can be summarised as follows:

"Find F_n, such that the cost for one day is minimum and the resulting temperature at the beginning of the occupied period (F_{n0}) lies between 18.5°C and 19.5°C. F_n can cover the whole time interval [22h-6h]."

The need for comfort at the beginning of the occupied period represents a constraint on the optimisation algorithm.

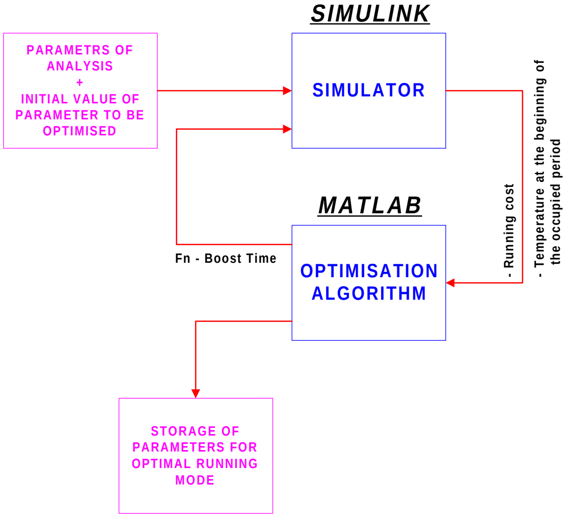


Figure 9: Coupling principle between the simulator and the optimisation algorithm

For a given set of parameters, the running cost and the temperature at the beginning of the occupied period for the last day are determined in the block "finalités" (Goals) on figure 5. They are then transferred to the optimisation algorithm that will determine the boost time F_n. The latter is sent to the constant time clock for the following simulation. The parameter that needs to be optimised is changed automatically from one simulation to another. It is calculated dynamically and iteratively between the simulator and the optimisation algorithm until the optimal value is obtained (the minimum).

ANALYSIS OF RESULTS

The problem of night setback with overheating requires 7 parameters of analysis for each type of lodging. The "overall plan " for the cases to be studied includes 2^7+1 cases, that is 129 calculations. We chose to use for the analysis a "half plan", that is 65 cases per type of lodging [9] for analysis.

The results of simulations involving the coupling between the simulator and the optimisation algorithm gave the value of the F_n-boost time parameter and the running cost generated by the optimal management scenario.

We determined the matrix of effects to carry out the analysis by "experiment plans". This matrix of the experiment plan 2^{7-1}consists of 64 columns.

Each column expresses the effect of several factors (parameters of analysis). The 64 contrasts obtained represent the algebraic sums of the effects of each factor. Assuming that the effects of order greater than 2 are negligible, we were able to bring forward the most influential parameters since the most interesting effects are correlated to the negligible interactions.

It appears that these parameters are the setback temperature (T_r), the time interval between the beginning of the occupied period and the shift from low tariff rate to high tariff rate (δ), and the maximum overheating temperature (T_{max}). These three parameters are the major inputs for the setting up of simple rules. Besides, the simulations show that the heat loss coefficient (GV) and the ratio of tariff rates (HP/HC) have negligible effects on the boost time.

Comparisons of costs between the optimal management scenario and a continuous heating strategy enabled the assessment of the worthiness of the optimal management scenario obtained.

Generally speaking, the study shows that the only interesting gains (financial gains higher than 10% with respect to the continuous heating strategy) in the case of night setback apply to collective lodgings where the occupied period starts within the high tariff rate period.

CONCLUSIONS

To conclude, we lay emphasis on the following points:

- The structuring of systems in a graphical environment according to the methodology developed at CSTB facilitated the construction of the simulator based on the needs of the study. It enabled an efficient use and adaptation of certain existing models without major complementary modelling.

- The development in a general simulation environment allows the user to benefit from the specialised toolboxes available in the environment and facilitates the coupling between systems written in a graphical environment and mathematical algorithms. We did not have to develop an optimisation algorithm . However, we had to chose the right algorithm suitable for this study (function ‘constr’ [|10] from the optimization toolbox [8]) and to solve the mathematical problems related to the optimization problem (initial condition values, local minima, etc.).

- A large number of simulations can be done rapidly and easily by using the general mathematical software. The description methodology helps to build the virtual system. More time is spent on the analysis of results.

- The advantage of using the statistical method by "experiment plans" for the definition of cases and for the analysis of the results was twofold. First the number of cases to simulate was reduced. Second, the most influential parameters regarding the development of simple rules for the optimal management of direct electric heating were identified.

ACKNOWLEDGMENTS

We are grateful to EDF for the financial support of this study.

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