SKETCH SYSTEMIC OPTIMAL DESIGN INTEGRATING MANAGEMENT STRATEGY, THERMAL INSULATION, PRODUCTION AND STORAGE ENERGY SYSTEMS (THERMAL AND ELECTRICAL): APPLICATION TO AN ENERGY-POSITIVE TRAIN STATION

Frédéric Wurtz[1], Julien Pouget[2], Xavier Brunotte[3], Maxime Gaulier[1], Yann Rifonneau[2], Stéphane Ploix[4] and Benjamin L'Henoret[2]
[1]G2elab, ENSE3, Saint Martin d'Hères, France
[2]SNCF - Innovation & Recherche, Paris, France
[3]VESTA-SYSTEM, Grenoble, France
[4]G-SCOP, INPG, Grenoble, France

ABSTRACT

The aim of this paper is to develop a new concept of sketch tools for the very steps of the design process. The originality lies in the use of optimization to define a global design of the building, the energy system and the control strategy. Therefore, an adapted model of the building has been realized, not directly using fine dynamic models (like those that can be found in tools TRNSYS, DOE2.2 and EnergyPlus...), but more coarse equations adapted to the sketch design phase. Those models are based on static and macroscopic equations investigating energetic and financial balances. In order to optimize the global cost, this model will be used coupled with optimization techniques. An application of an energy positive railway station will be presented demonstrating that it is possible to make a global sketch design (size and characteristics of the walls of the building + size of the energy systems + optimal control strategy over a typical day) extrapolating over a 30 years cycle of live of the building.

KEY WORDS : design, methodology, design sketch, building and energy system, global design, optimisation.

INTRODUCTION

This paper introduces a new concept of "Energy Sketch Optimisation Tool" (ESOT) dedicated to the very early steps of the design process that we will call the "Energy Sketch Phase" (ESP) . The goal is to legitimate the very early steps of the design process, when the main characteristic of the energetic system of the buildings have to be estimated thanks to an ESOT. We will show how it is possible to realize an ESOT, using a global model of the system. This model is based on static and macroscopic equations taking interest into energetic and the resulting financial aspects. Such model is applied to each component of the system. It contains equations and constraints. Each component model are then put together to represent the whole system, thanks to similar energetic and financial ports. This global model has been coupled with optimization algorithms. This allows finding a global sizing of the characteristic of the building, the size of the energetic systems, as well as an efficient energy management strategy. The objective function is the global cost of the system over its life cycle integrating the investment cost, the maintenance cost, and the cost of the energy used. This approach is illustrated on a railway station.

NEW CONCEPT OF "ENERGY SKETCH PHASE" (ESP)

Context of the study

Energy efficiency in the building sector was identified as a priority. This is due to the consumption of primary and electrical energy, respectively 43 % and 66% of French energy consumption. Energy issues in the building sector require introducing a new approach to help design of the buildings in the very early sketch up steps of the design process [HAU-01].

Need of the "Energy Sketch Phase" (ESP)

We proposed to introduce the "Energy Sketch Phase" (ESP). It is an equivalent concept of those existing in architecture or design [HAU-01], but we propose here to extend it by introducing the energy aspect.

The goal of this design phase is to define simultaneously energetic sketch up of the different building systems:

- main characteristics of the thermal insulation of the building;
- main dimensions of energy systems (PV, wind turbine, thermal boilers, energetic storage…) ;
- optimal strategy for energy management.

Role and position of the ESP in building design process

For a new building, the study process is decomposed in different steps. The figure 1 shows the quantity of information available for a building (area, material, type and size of energy equipment…) for each step of the study. At the start in sketch up phase, designers do not have a lot of information, but their choices have an important impact on the cost and energy efficiency of the building (figure 1). Theoretical studies on the design activity [VIS-04] show that this initial study represents a small part (approx 5%) of the final project cost. Nevertheless it is a critical step because these initial decisions determine 75% of the total project expenses. It is therefore important to investigate, in these early phase of the design process, as many possibilities as possible. The innovation of this paper is to propose to do this, with the right level of model coupled with optimization tools, what will help the designer to choose the best solutions in the early steps of the design process. This choice can be made in order to increase the building energy efficiency or decrease the life cycle cost. Thus, it is in sketch up steps that, for a building design, main decisions are taken. It is only after that, that the other classical phases of a project such as preliminary design, final design, tender document… will be launched.

Problematic of the sketch phase in the design process

If the sketch up phase is an important step in the building design process, there are practically no tools available in the state of art for helping designer in this design phase. This is due to the following practical and fundamental difficulties, that makes in particular the use of fine dynamic simulation tools (like TRNSYS, DOE2.2 and EnergyPlus...) problematic

- the building, and the project in general, is not well defined and precisely defined, it is just sketched ;
- the designer must use an effective model, with a right level of precision, in order to explore different solutions with an optimization tool ;
- in the same time the model mustn't be too accurate, because all the parameter's building are not known [HEN-12];
- the simulation must be done on life cycle cost.

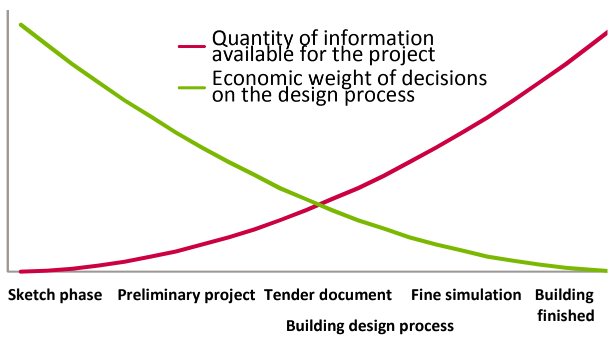

Figure 1 : Impact on the cost and quantity of information for the different step of building design

<u>THE NEW CONCEPT OF "ENERGY SKETCH OPTIMISATION TOOL" (ESOT)</u>

For the ESP, this article proposed to develop a concept of energy sketch tool using:

- Models for energy sketch up, which must be of a right nature (right assumptions and right level of modeling) and must carry information such as constraints compatible with the goal of sketch ;
- Optimization approaches such as decision support.

That is why we will define here the concept of "**<u>E</u>**nergetic **<u>S</u>**kech **<u>O</u>**ptimization **<u>T</u>**ool" (**<u>ESOT</u>**). The precise characteristics of an ESOT are:

- <u>it is a tool dedicated to the very early steps of the design process</u> (preliminary design, study of feasibility of projects, of programs, …)
- <u>using optimization techniques for exploring the highest numbers of possibilities</u> of design: the more solutions are explored, the better it is.
- <u>by allowing a variations of the highest possible number of parameters</u>: the more degrees of freedom we have, the more we will be able to find good compromises and choices at system level. Especially for buildings, and from an energetic point of view, an ESOT must allow to optimize simultaneously
  - the main characteristics of buildings (thickness and quality of isolation of the walls, size and quality of the windows, …). The model is quite rough, and should not be so fine and precise as models used in fine dynamic simulation tools (like TRNSYS, DOE2.2 and EnergyPlus...). Here we typically use lumped equivalent thermal models, with analytical equations that give the thermal resistance and capacitance depending from the size of the wall and the windows and the thermal characteristics of the used materials. Here the idea is more to have models that give the right tendency, than fine quantitative values (anyway certainly unreachable in the ESP due to the unknowns and the uncertainty existing in this step of the design process).
  - the size of the energy systems (PV, heaters, HVAC, …)
  - the supervision strategy

- if possible over the life cycle of the building
- the ESOT must be quick and rapid, so that the design can quickly change the constraints, the assumptions, the objectives: because in preliminary design, many hypothesis, and scenarios have to be explored.

The feasibility of such an ESOT is a real challenge. We will show how we have faced this challenge with right answers for 3 bottleneck questions:

- the right level of modelisation,
- the right optimization approach
- the use of sensitivity calculation techniques.

ENERGETIC SKETCH UP MODEL FOR AN ESOT

Definition of energetic sketch up model for the components

For this energy sketch phase, we introduce for each component of the system, a new type of model. This one is defined for energy optimization and it includes:

- Economical equation to estimate the life cycle cost for the component, which is the sum of investment costs and operation costs (this is a way to sketch a calculation of life cycle cost, even if the demolition and recycling is not included for the moment) ;
- A physical model for each component that includes: the main physical dimensions for energy efficiency, energy flow for electrical and thermal energies of the component. This model can be used with an optimization tool to explore a wide range of solutions ;
- Constraints that may result from the component environment (size of the solar panels mustn't be greater than surface of the roof), and from the system own limitations (all energy storage devices have limited energy amount) ;

Definition of energetic sketch up model at the system level

At system level, we need to connect the components to each other in order to compose and to define the global system. For this, we defined two kinds of ports for connection at system level: Energetic Port and Economical port (see figure 2).

The system includes models for insulation, boiler, solar panels, batteries ... Figure 2 shows the structure of the model for electrical battery. The designer chooses different models in order to compose the energy sketch up for the entire building. The generation of equations and constraints is then performed automatically from economic and energetic ports.

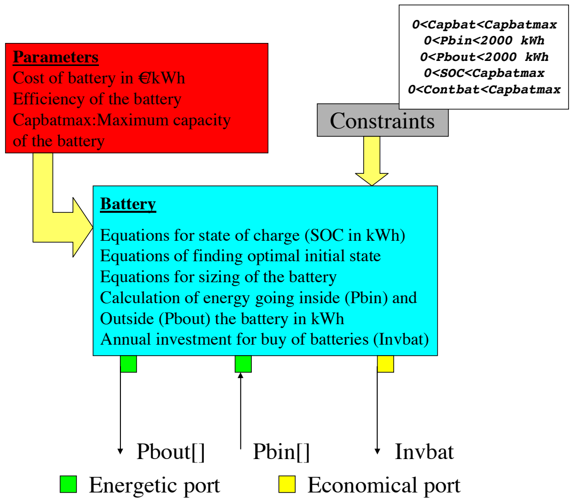

Figure 2 Structure models of components

Example of the model of the PV panels

The physical equations: Model of PV panels is based on physical and economical equations. The electrical production is computed for each hours of a day (1) :

$$for\ i \in [0;23], E_u^{PV} = \eta^{PV} \cdot R^{PV}[i] \cdot S^{PV} \qquad (1)$$

Where, E_u^{PV} is the electrical production for a day (Wh), η^{PV} the PV panel efficiency, $R^{PV}[i]$ the solar radiation (Wh/m²/h) and S^{PV} the PV panels array.

The PV panel cost is defined by the initial capital cost :

$$C_{i\cos t}^{PV} = \left(C_{\cos t1}^{PV} + C_{\cos t2}^{PV}\right) \cdot S^{PV} \qquad (2)$$

Where, $C_{i\cos t}^{PV}$ is the intial capital cost (€), $C_{\cos t1}^{PV}$ the installation cost per array (€/m²) and $C_{\cos t1}^{PV}$ the purchasing cost (€/m²).

The typical optimisation variable is the PV panel array. With this model, the ESOT will be able to define a physical size for the component.

The contraints: the main constraint associated to the PV panel model, is that the surface of the solar panel must be smaller thant the total surface of the roof.

Example of the model of battery

The physical equations: Model of battery is also based on econcomical and phyical equations. But, the optimisations variables linked to the model are two vectors: the power's battery input and output for each hour. In this case, the goal is to optimise the battery energy management.

$$for\ i \in [0;23], E_u^{Bat}[i+1] = E_u^{Bat}[i] + E_{in}^{Bat}[i] \cdot \eta^{Bat} - \frac{E_{out}^{Bat}[i]}{\eta^{Bat}} \qquad (3)$$

Where, $E_u^{Bat}[i]$ is the energy storage per hour (Wh), η^{Bat} the battery efficiency, $E_{in}^{Bat}[i]$ the input energy per hour (Wh) and $E_{out}^{Bat}[i]$ the output energy per hour (Wh).

The battery capacity is computed with the relation:

$$Q_u^{Bat} = \max(E_u^{Bat}) \quad (4)$$

Where Q_u^{Bat} is the battery capacity (Wh).

Finaly the battery cost is computed with relation (3).

$$C_{i\cos t}^{Bat} = \left(C_{\cos t1}^{Bat} + C_{\cos t2}^{Bat}\right) \cdot Q_u^{Bat} \quad (5)$$

Where, $C_{i\cos t}^{Bat}$ is the intial capital cost (€), $C_{\cos t1}^{Bat}$ the installation cost per battery element (€/Wh) and $C_{\cos t1}^{Bat}$ the purchasing cost per element (€/Wh).

The contraints: Examples of constraints on the model of the battery are given on Figure 2 with SOC= $E_u^{Bat}[i]$, Pbin= $E_{in}^{Bat}[i]$, Pbout= $E_{out}^{Bat}[i]$. A typical example of constraint is: 0<SOC<Capbatmax, meaning that at each time, the state of charge of the battery can not exceed the state of charge maximum of this battery.

Example of the Model of the building

The physical equations: The model of the building is a classical thermal equivalent model. The equivalent thermal resistance of the wall and of the windows depends from the sizes and characteristic of the buildings. We have also introduced empirical laws, giving the evolution of the prices of the walls and the windows as a function of the thermal resistance. This allows to evaluate the price of the building, and to connect this price to the global cost of the building.
Constraints: constraints are typically put on the size of the walls, the windows.

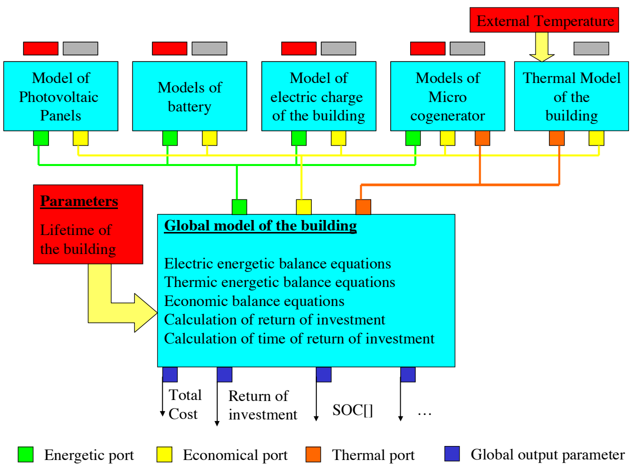

Figure 3 : Global model of the building

THE RIGHT OPTIMIZATION TECHNIQUES FOR AN ESOT

Deterministic algorithms for being able to solve problems with a high number of parameters and constraints quickly

One important property of an ESOT, is to be rapid, because in ESP, the needs of designers are:

- to compare quickly different solutions
- to iterate rapidly in order to analyze different assumptions about energy costs or technology costs for example
- to test the feasibility of the formulation of their problem: is the problem consistent is the main question, what means is the problem with no contradiction and with at least one feasible solution respecting the objectives and all the constraints.

It is for those reasons that we use deterministic algorithms like SQP [POW 85] (Sequential Quadratic Programing) for non linear models, or MILP [HA-10] (Mixed Integer Linear Programing) when the models are linear. Those algorithms are first of all very quick, but are also able to manage problems with high number of parameters and constraints: typically from hundreds to thousand. Since we want to make a global design, the ability to manage a high number of parameters and constraints is very useful, especially in an ESOT in which we want to optimize simultaneously the building, the size of the energy system, and the management strategy.

Why not using stochastic algorithms in ESOT

Stochastic algorithms, like genetic algorithms, or particle swarm algorithms are interesting optimization algorithms, especially if we consider their capability to found global optima. But there are not the most efficient for ESOT, since:

- they need many iterations, so there are not rapid
- they not able to work with a high number of parameters and constraints (typically it is difficult for them for more than 10 parameters and constraints)
- the problem of local or global optima is not the first problematic in sketch phase since:
  - o the sketch models are the most often smooth, or even linear with no local optima
  - o the main problem is more to verify that it exist at least one solution to the problem (that the problem is well posed), than to find a global optima in a model that is a rough model with still a lot of unknowns and uncertainties.

Efficient techniques for calculation of sensitivity for non linear models

When the model is non linear, one key point in order to be able to make optimizations with a high number of parameters and constraints with a deterministic optimization algorithm like SQP is to make a right evaluation of the sensitivity of the models. For this, very efficient techniques can be used. We have develop and used here those techniques, from symbolic derivation to automatic differentiation that allows to generate automatically the right sensitivity for calculating gradients and jacobians, even for models described by algorithms [EN-10].

APPLICATION : ENERGY PLUS RAILWAY STATION

Description of the application

The presented application has been developed of an energy positive railway station. The global building integrates components like photovoltaic panels, co-generators, batteries, … It has a global heating system and it is connected to the electric network. The electric load is modelised thanks to a global load curve in which we have capabilities of report of loads.
The model and the applications have been developed in the framework CADES [DEL-07] (cf. http://www.cades-solutions.com).

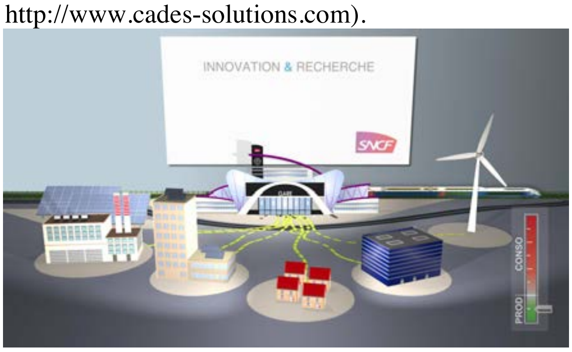

Figure 4: The use case – Studies for a positive energy railway station

Process for creating the optimization tool

Figure 5 describes the process for obtaining the optimization tool: thanks to a generator available in the CADES solution, the models of all the components are compiled. For our application, the model are non linear. That is why, the right formal sensitivity of the models are also automatically generated using formal computing or automatic code differentiation [DEL-07][EN-10]. The models are composed at the system levels and linked with the SQP optimization algorithm.
The resulting optimization application has the following characteristics:

- 355 input parameters
- 186 output parameters.

Those high number of input and output parameters is typical for an ESOT. Here we have a lot of parameters because some parameters, like the state of charge of the battery, the energy bought to electric network, … are vector parameters with 24 components (one component for each hour of the typical day taken into account for optimizing the strategy of control over 24 h).

The resulting optimization tool

Figure 6 gives the structures and some views of the optimization tools obtained. At the left side of figure 6, we have examples of parameters that are typically constant during one optimization (curves of dynamic tarification of energy for typical days, area available for the building, cost of technology, …). On the right side, we have typical examples of optimal parameters obtained for one optimization: we have here typically the optimal characteristics of the building (walls, windows, …), the size of the energy system and the optimal management strategies for the typical day taken into account (with a discretization step of 1h for 24h).

EXAMPLES OF ENERGY SKETCH STUDIES USING ESOT (OPTIMIZATION)

Parametric optimization: a powerful tool for energetic sketch-up phases

For showing the efficiency of the ESOT tool, we will give some results of typical sketch-up studies that can been made in the very early steps of the design process. The problematic is to have tools in order to decide at the level of a big company, owning a lot of buildings (like a railway company that can own a lot of railway stations), if it is interesting or not to start big programs of renovation, or new construction in order to go towards energy positive buildings. The problem is difficult, since those strategic questions needs to study a lot of scenarios, depending typically on hypotheses on:

- the evolution of cost of the technologies,
- evolution of the tarification and of the pricing policies of energy.

We will show how we can use the previously built ESOT, in parametric optimizations, in a very efficient and innovative way in order to have arguments for answering to those questions, with a global system overview (taking into account the optimal sizing of the building, the energy system, and the global control strategy over the life-cycle of the building).

Study of scenarios depending the price of the PV technology

With the ESOT, we will make a set of successive optimization, in which the cost of the technology of the photovoltaic panels (c_inv_PV in k€/m²) is a parameter. The goal is to evaluate all the optimal solutions and scenarios for the cost of this technology varying between 0.2 k€/m² and 1.1 k€/m². This is typically one question that designers and deciders can have in mind in very early design steps: what are the different scenarios possible, when we considered all the possible values of the cost of a technology. In other words, it is a way to study the uncertainty linked to the cost of the technology.

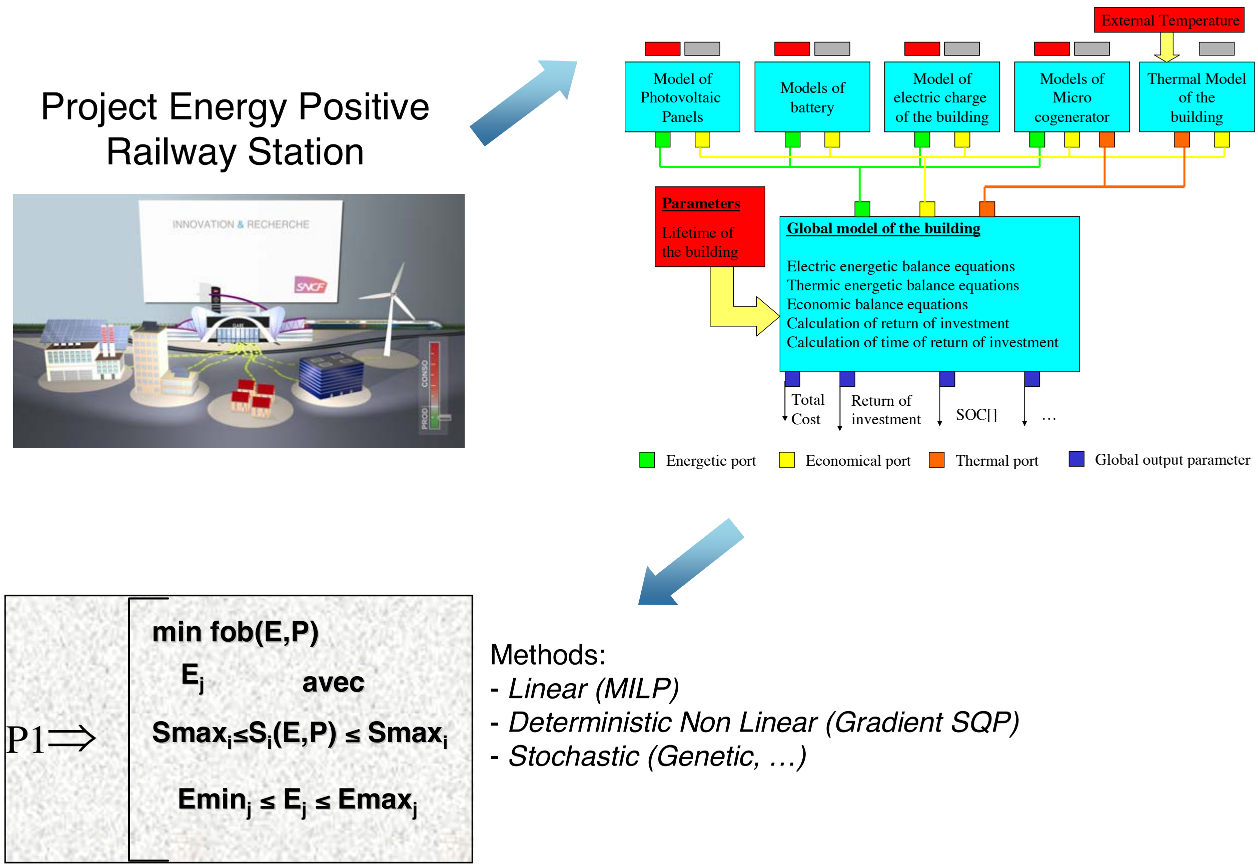

Figure 5: The process for creating the optimization tool

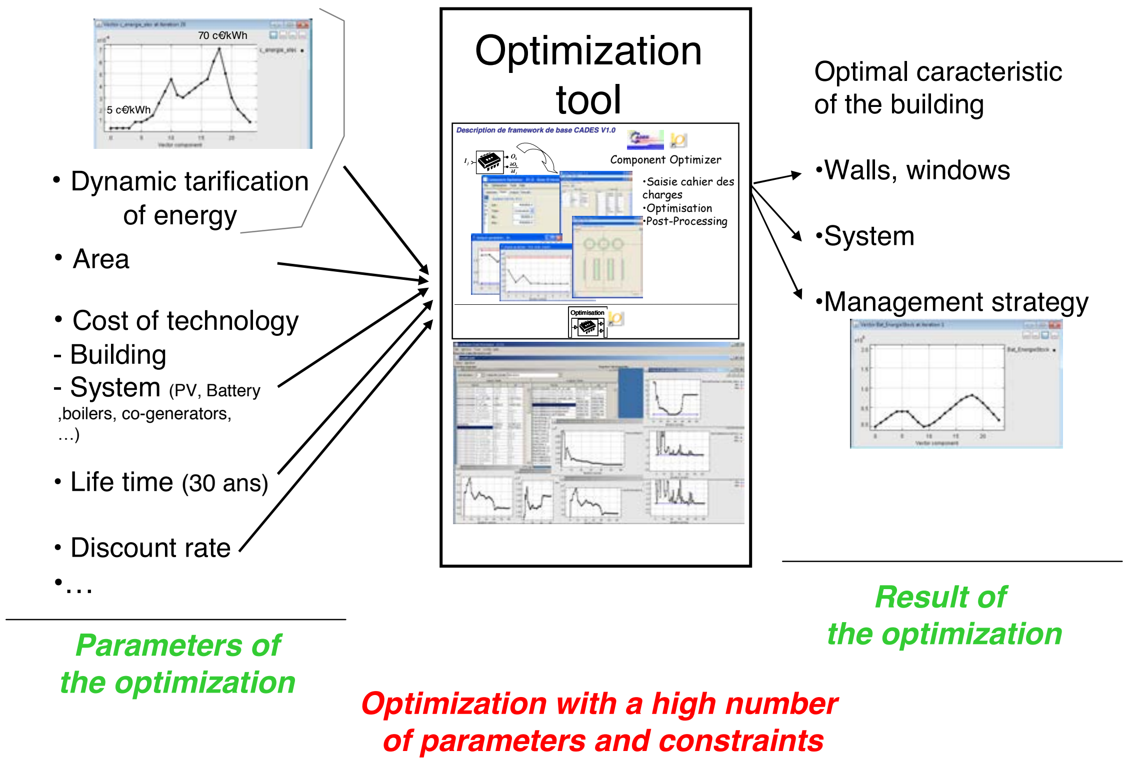

Figure 6: The optimization tool obtained

To answer to this questions, for each possible value of c_inv_PV we have made an optimization for finding the optimal size and characteristics of the building and of the energetic components and the optimal management and supervision strategy of the building. As an example, fig.7 show the optimal size of the" photovoltaic panels as a function of c_inv_PV and figure 8 and figure 9 give examples of optimal control strategies found for the battery.

Rapidity of the optimization

All the results of figure 7 to figure 10 are obtained, wit our ESOT in only 13 seconds. During this time 20 optimizations have been made (depending of 20 different values of c_inv_PV varying between 0.2 k€/m² and 1.1 k€/m²). In global 70 calls to the models and the calculation of the jacobian have been. Thanks to SQP, and the formal sensitivity implemented in our tool, our ESOT succeeded to the promise and the challenge of speed.

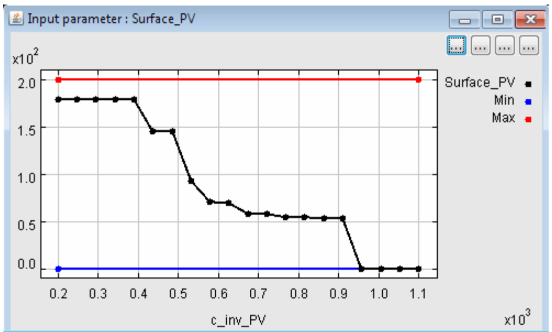

Figure 7 : Optimal size of the photovoltaic panel (in m²) as a function of the cost of technology of solar panels (in k€/m²) – Each point corresponds to an optimization

We see that the optimal size of PV panels decreases when the cost of the technology is increasing, with a kind of "stairs step effect" that can be precisely evaluated thanks to our optimization approach. We have to say also that those results depend , of course from the assumptions made in the model (about tarification, about the characteristics of the typical dayrs taken into accont, …). Thus an ESOT has more to be seen has a tool for exploring the ideal model that the designers and deciders are able to build with all the approximations and the assumption they need to make, than an exploration of a fine and precise model that is not reachable in the first sketch steps of the design. So an ESOT is really much more a tool for helping understanding and taking decisions, than a tool for modeling tool of an existing object. If this is well understood, those designers and deciders can see, with their actual hypothesis and assumptions, that optimal PV size is 0 when c_inv_PV≥0.95 k€/m²: in other words, over this value, solar photovoltaic panels are no more profitable.

Global optimization over the life-cycle and with optimization of the supervision strategy

Those optimizations have been made by making the optimization of the cost of the building over its entire lifecycle (cost of investment + maintenance cost + exploitation), exclusion of the destruction and recycling phases. This has been done by making the optimization on one typical day, for which we give as inputs the supposed external temperature, electric load (with possibilities of report of a part of the load), the dynamic price of electricity for each hour. This day is typically extrapolated over one year, and we suppose that the building will be used 30 years.

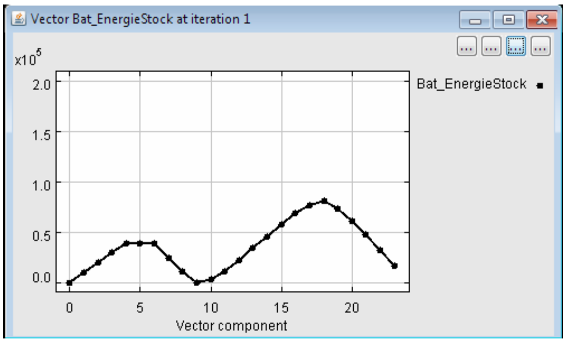

Figure 8 : Optimal strategy for the State of Charge (SOC) (in Wh) in the battery for the typical 24 h reference day (For c_inv_PV=0.2 k€/m²)

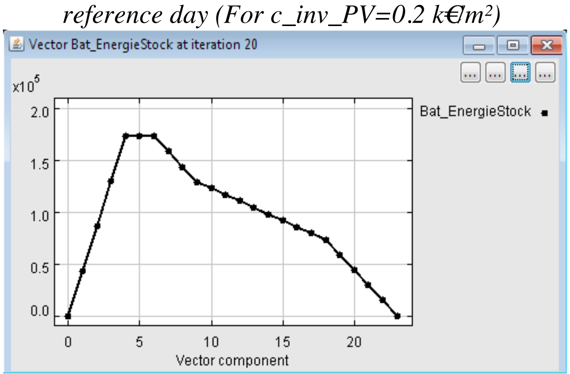

Figure 9 : Optimal strategy for the State of Charge (SOC) (in Wh) in the battery for the typical 24 h reference day
(For c_inv_PV=1.1 k€/m²)

Global optimization integrating the optimization of the characteristics of the buildings

Figure 10 shows an interesting result: it represents the evolution of the equivalent thermal resistance of the west wall of the building as a function of the cost of the PV technology. This resistance is decreasing. This result from a global system effect: when the cost of PV technology is increasing, is it more and more interesting to use a wood co-generator. Thus you have more and more cheap heat, and that is why it is possible to decrease the quality of thermal insulation. Figure 7 to 10, illustrates that the characteristics of the buildings are optimized simultaneously with the size of the energy system and the optimal strategy control

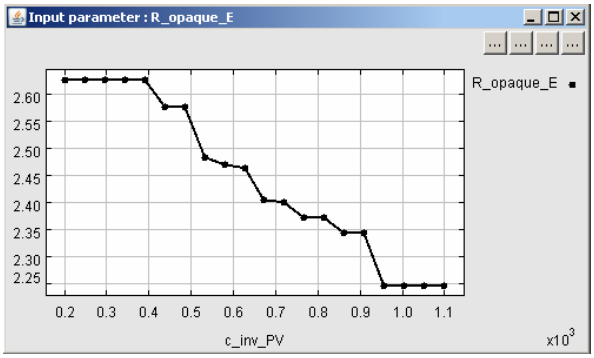

Figure 10°: Optimal value of west equivalent (in m².K/W) thermal resistance of the wall of the building as a function of the cost of technology of solar panels (in k€/m²) – Each point corresponds to an optimization

CONCLUSION

This paper demonstrate the important of Energy Sketch Phases (ESP), and the importance of **E**nergetic **S**kech **O**ptimization **T**ool (ESOT). Be able to built those ESOT is a scientific challenge, but we have demonstrate that it is possible to face it with right level of modelisation, and right optimization approaches using formal right sensitivity and deterministic algorithms. Thanks to this, it is possible to have design tools for the very early steps of the design process, able to make a global optimization (building + energy system + optimal management strategy) over the life cycle of the building with a very number of parameters and constraints. Thus, the design and decision, even in the early phases, can integrate the consequence of an optimal management then must be then implement in optimal control system of the building [EN-10].

REFERENCES

[HEN-12] Jan Hensen "Building performance simulation: current state and challenges", "Evaluating and Modelling Near-Zero Energy, Buildings; are we ready for 2018?", 30-31 January 2012 , University of Strathclyde, Glasgow (UK)

[HAU-01] Hauglustaine, J. M. « Outil d'aide à l'optimisation de l'enveloppe de bâtiment, au stade de l'esquisse d'avant-projet », 16e colloque Université-Industrie Applications de l'électricité dans les locaux résidentiels, tertiaires & industriels, 14 juin 2001.

[VIS-04] Visser W., "Dynamic Aspects of Design Cognition: Elements for a Cognitive Model of Design", INRIA, Rapport de recherche n° 5144 – Mars 2004 - 116 pages.

[DEL-07] Delinchant B., Duret D., Estrabaut L., Gerbaud L., Nguyen Huu H., Du Peloux B., Rakotoarison H.L., Verdiere F., Bergeon S., Wurtz F., "An Optimizer using the Software Component Paradigm for the Optimization of Engineering Systems", COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Vol. 26 No. 2, 2007, pp. 368-379.

[POW-85] M. J. D. Powell, "On the quadratic programming algorithm of Goldfarb and Idnani", Mathematical Programming Study 25 (1985), pp. 46-61.

[HA-10] L. D. Ha, S. Ploix, M. Jacomino, and H. Le Minh. Energy Management, chapter, "A mixed integer programming formulation of the home energy management problem", ISBN 978-953-307-065-0. INTECH, 2010.

[EN-10] " Automatic Differentiation Applied for Optimization of Dynamical Systems ", P. ENCIU, L. GERBAUD, F. WURTZ, IEEE Transactions on Magnetics, ISSN: 0018-9464, Vol. 46, Issue 8, August 2010, pp. 2943-2946