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COMBINING FORMAL DEFINITION OF A SIMULATION MODEL WITH HEURISTICS TO IMPROVE BUILDING SUSTAINABILITY

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ABSTRACT

Sustainability is complex because it relates with environmental, social and economic variables. Each one of this areas is, by itself, complex due to the huge amount of factors that one wants to analyze. Because of the combination of the levels with the factors, an exponential grow in the amount of scenarios appears. In this paper we describe a methodology that helps us to deal with this complexity applying three key concepts, formal representation of the simulation models, optimization algorithms and high performance computing. We present an infrastructure named NECADA that supports the methodology. This approach can be applied to a building refurbishment or to define optimal parameters in new buildings. The specialists must work only with the formal representation of the model, and from it, the system will be able to find optimal scenarios using a selection of the build-in heuristics that can be applied for the problem resolution.

1 INTRODUCTION

The nations and the regions have a key role in the decision making process to reach the 20/20/20 targets that are defined on the Energy Performance of Building Directive (EU 2010) and the Energy Efficiency Directive (European Comission 2012), signed by the European Union member States within the European regulatory framework.

In the context of the current European normative 2010/31/CE (EU 2010), specifically on the energy efficiency of buildings, that regulates on the article 9, that at 31 of December of 2020 all new buildings must be near to NZEB (Net Zero Energy Building, nNZEB). Due to this, the state members must propose the policies to update the existing buildings and recommend the rules for the new buildings (Salom et al. 2011; Sartori, Napolitano, and Voss 2012; Salom, Cubí, and Sánchez 2011; Salom, Cubí, and Sartori 2012). Also, the data published by the International Energy Agency (IEA 2012) is forecasting an increase in the energy consumption of over 40% during the next two decades. With this context, Decision Support Systems that help in the definition of optimal (or quasi-optimal) parameters in the construction sector are absolutely needed, Simulation, Optimization, and Data Analysis techniques are absolutely needed to give answers to this complex issues.

However, it is noteworthy that the energy and environmental simulation areas are demanding and complex due to several aspects. First of all because the models usually depend on several factors, and those factors are present on a number that are usually bigger than in other areas. This makes experimentation become more complex, usually increasing the computational time needed to obtain the answers. Weather, construction features, users behavior, active climate elements, house appliances, etc. are just some examples of the different factors that must be considered in order to achieve a solution. Secondly, because the personnel involved in the definition of those models belongs to different areas, making the model definition complex. This implies the need to stablish a common language to start working. Finally, because the data to be used on the models can be diverse (coming from a heterogeneous source) and the amount of data can be huge, making the model execution a hard task.

To achieve this, formal models must be defined that allow the collaboration and the information sharing between all the involved actors. These models also must take care of the normative situation, the current economic situation, the climate change, etc., allowing the definition of realistic scenarios and strategies that must be analysed. This analysis, and the huge amount of alternatives to be considered, must be coherent with a methodology that allows to obtain knowledge from the huge dataset, simplifying the cooperation of specialists coming from several different areas.

In this paper we use a framework, named NECADA (Fonseca i Casas and Fonseca i Casas 2015) that that can be used to analyse thousands of different scenarios taking care of the sustainability parameters defined on the European directives. To do so we combine the use of formal languages, co-simulation techniques, high performance computing and heuristics to obtain good alternatives that allows the public administrations and the general users to improve the behaviour of buildings and urban areas regarding sustainability parameters.

NECADA generates comparative results, showing the effects of each constructive aspect on the total consumption of the building. Starting from there, the user can define different configurations for the design. In each configuration the specialist can change, just as an example, the constructive solutions, the thickness of the wall, the orientation or the meteorology of the location of the building. In order to not reinvent the wheel, NECADA uses co-simulation techniques, using EnergyPlus (EnergyPlus 2014) as an engine for calculation of power consumption, OpenFoam as an engine for calculation of CFD (Computational Fluid Dynamics), Radiance as lighting calculation engine, among others. NECADA aims to work within a cloud computing architecture and be able to perform several calculations at a time through the management of different parallel instances or, if more computing power is required work in a cluster of computers (Fonseca i Casas et al. 2015). However, although NECADA infrastructure can use High Performance Computing techniques to accelerate the answers, Optimization techniques must be applied to obtain a solution in an accurate time spam. To do so SDLPS (Fonseca i Casas 2008; Fonseca i Casas et al. 2013), the Co-simulation engine that rules NECADA models, implements some heuristics that are capable of obtaining accurate answers in half of the time needed to find the optimum value doing the force brute execution of the experimental design.

The heuristics that can be implemented on the frame of the problem, can behave well depending on the nature of the data, also, depending on the nature of the variables that are going to be optimized. In this case, and due to the nature of our problem we focus on multiple-objective optimization problems, see other approach to obtain accurate answers on time on (Almada et al. 2016). In the specific area of energy, and building simulation, there are several work done see (Bernal-Agustín and Dufo-López 2009) for a review. The use of genetic algorithms (Fan, Pathak, and Zhou 2009) or Particle Swarm Optimization adaptation, like (Zhang et al. 2015) are some of the techniques most widely used, always with subtle idea to define a Decision Suport System that simplifies the energy management (Chang 2014; Mattiussi, Rosano, and Simeoni 2014).

In this paper we present an infrastructure that allows the definition, using a formal language, of the parameters that we want to later analyze on an optimization experiment.

2 METHODOLOGY

The methodology is based on the use of formal languages to define a holistic approach to the problem. In our approach, the conceptual model, and the codification of this conceptual model is done automatically through the use of SDLPS (Fonseca i Casas 2008). The overall representation of the methodology is presented in Figure 1.

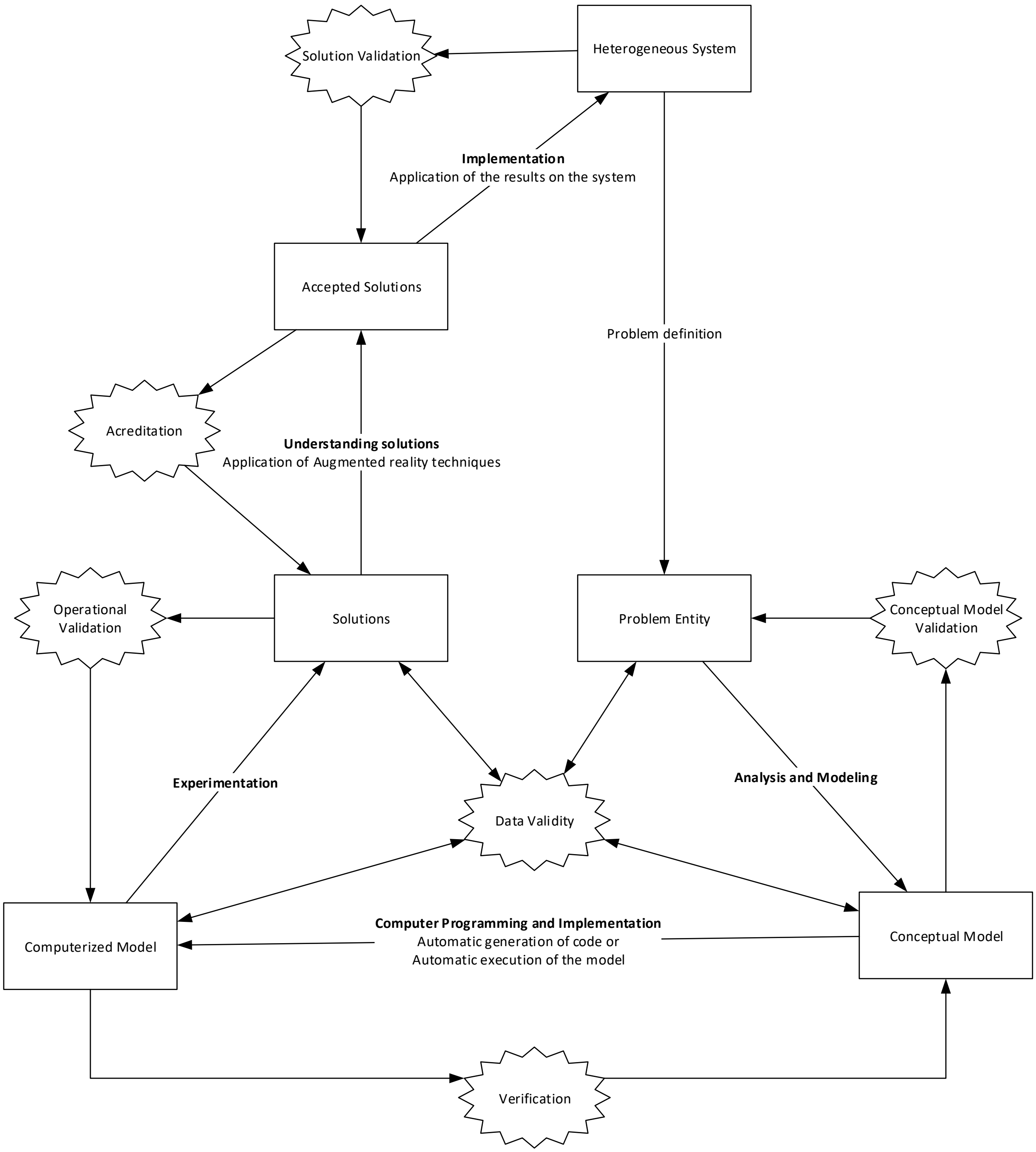

Figure 1. Methodology applied on the frame of the project.

The proposed methodology is an evolution of the proposed phases that must be followed in a simulation model presented by (Sargent 2009). There are 6 key points that support the entire approach. First we consider that we deal with an **Heterogeneous system**, mainly composed by several pieces that can provide information from several sources. This Internet of Things (IoT) paradigm implies the need to interconnect and use several interconnected elements, maybe using a Middleware. From an analysis of this system is defined the **Problem entity** that defines the scope of the problem and clearly states the goals that direct the analysis. From this definition a detailed **Conceptual Model** is done. This model is a key element since it represents all the knowledge we have regarding the system filtered by the problem entity definition. All the specialist can discuss regarding the model through the graphical representation of their relations, simplifying the interaction with personnel that are not related with simulation , optimization or statistical techniques. From this model a **Computerized model** is built. In our approach this codification is done automatically thought SDLPS. From the execution of this Computerized Model some **Solutions** emerge. This will represent the set of possible solution that fits with the problem definition. Not all of these solutions will be accepted by the client or the expert on the system. Finally, once the client believes the model, a subset of the solutions provided by the DSS, the **Accepted Solutions**, will be accepted for its final implementation on the system

The Validation and Verification processes that rules the methodology are the **Conceptual Model Validation**, the **Operational Validation**, the **Data Validity**, the **Verification**, the **Accreditation** and the **Solution Validation**. All these steps must be assured to guarantee that the Accepted Solutions are correctly applied on the system to give an accurate answer to the Problem Entity.

In this paper we focus on how we can connect the Conceptual Model with the use of Optimization techniques following the proposed approach, and more specifically, the use of heuristic algorithms. We focus on a Problem Entity that tries to solve the sustainability problems related to a building or an urban area.

3 CONCEPTUAL MODEL

The Conceptual Model we use follows the holistic view of the system that is represented in Figure 2. For a building, that can be just on instance in our model if we are focused on the simulation of an urban area, we define four phases:

1. **Design**: In this phase we detail the definition of the building and the different aspects that must be considered in order to start the construction process.
2. **Construction**: This phase details all the processes needed in order to construct the building. The materials, the transportation, the water and the energy, among many other factors must be considered.
3. **Use – life**: In this phase, the detailed aspects related to the building use, the energy consumption of the inhabitants, the waste generation, etc. are specified In this phase a lot of work is done in order to improve the use of the building by the users, some gamification techniques can be applied, see (Muchnik et al. 2016).
4. **Deconstruction**: The last phase for a building, that encompasses all the needed processes in order to recover all the materials used and define the needed treatments for those materials that cannot be directly reused.

All these phases must be detailed in order to obtain an accurate answer from the point of view of sustainability.

From this abstract representation of the simulation model, we can go further and, following our approach, define a simulation model that represents the system. In this case we use Specification and Description Language (SDL) (ITU-T 2011; Doldi 2001; IBM Co. 2016). Figure 3 represents the first level of the SDL model defined on NECADA platform to perform the simulations. The complete specification and the details of the model can be found in (Fonseca i Casas et al. 2014).

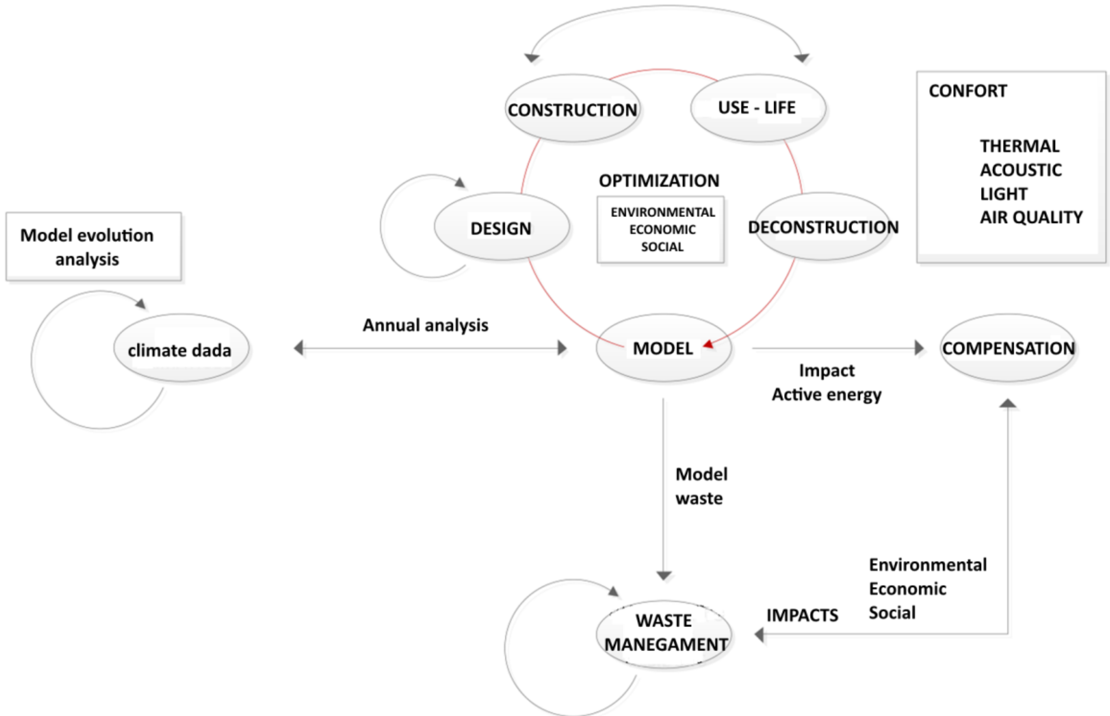

Figure 2. Simplified view of the holistic representation of a building model.

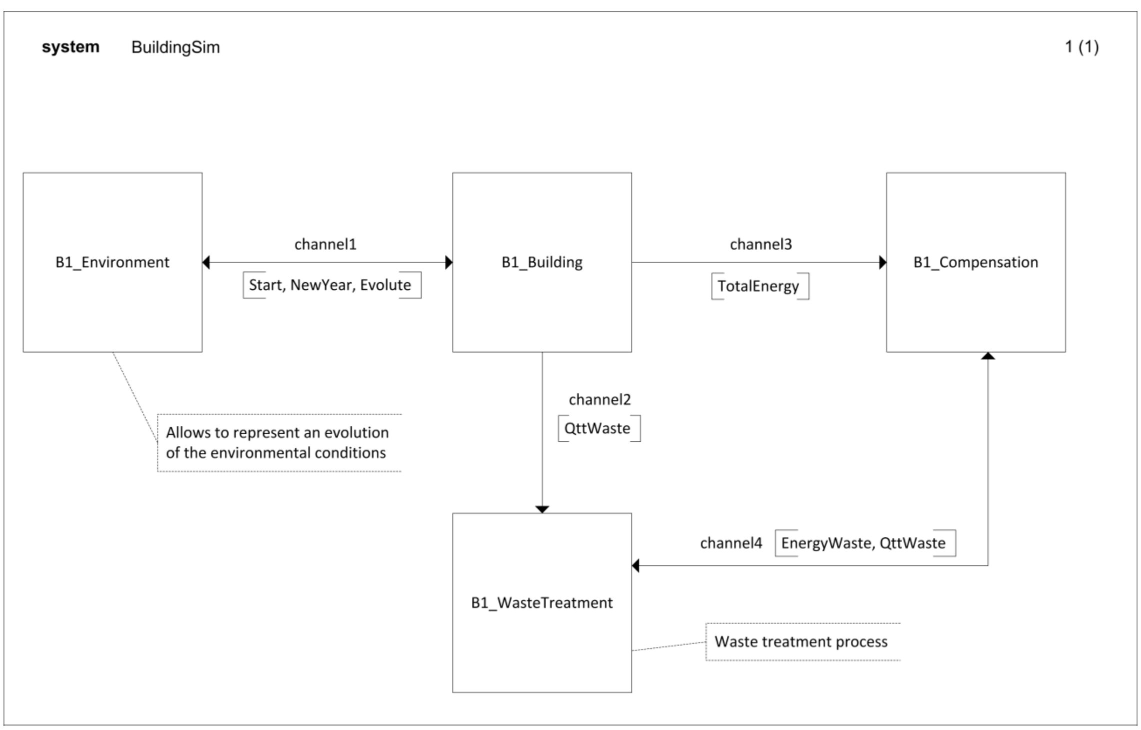

Figure 3. SDL representation of the model. First level, the system diagram.

The use of SDL is not a restriction in any sense, other formal languages can be used to define the model, like DEVS (Concepcion and Zeigler 1988) or PetriNets (Cabasino, Giua, and Seatzu 2013). Specifically in the building area an interesting approach using DEVS is presented on (Goldstein, Khan, and East 2010; Ahmed, Wainer, and Mahmoud 2010). It should be noted that there are mechanisms to transform the models represented with SDL to other widely used formalisms (such as DEVS and Petri nets). Therefore, that methodology transcends language itself being of general application.

Specifically on SDL the definition of the different variables that are going to be used on the different processes are done through the DCL's blocks, see Figure 4. Those variables are known by the specialist who desire to introduce them on the model definition or in the analysis that can be done later through the optimization, using in our case heuristics.

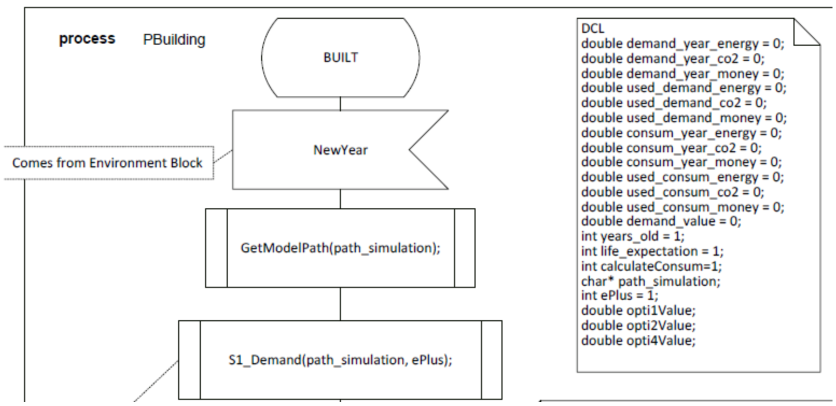

Figure 4. Definition of the different variables to be used on the model on the PROCESS SLD diagram using the DCL block.

All the variables that are defined on the DCL blocks on the different processes can be used as factors to define an experimental design, and all the factors can be introduced in the optimization algorithms in order to find the optimal solution reducing the amount of experiments to be conducted.

4 THE EXPERIMENT

To depict the use of the infrastructure we use a real example that tries to analyze the behavior of a building regarding energy consumption. The experimental design is shown in Table 1. The definition of this design is done through an XML that allows the definition of all the combinations taking care of the levels we want to use on of each factor.

Table 1. Experimental design used on the experiment.

FACTOR	VALUES
TYPOLOGY	Tip_B-320_mod.idf
WALLS MATERIAL	M1, M2, M3, M4, M5
ROOF MATERIAL	C1, C2, C3, C4
WINDOWS	H1, H2, H3
WINDOWS MATERIAL	H1, H2, H3
SITUATION	ESP_Barcelona.081810_SWEC.epw, ESP_Madrid.082210_SWEC.epw
ORIENTATION	0, 45, 90, 135, 180, 225, 270, 315

The **typology** is a file that follows the EnergyPlus BIM structure, allowing the definition of the building typology we are going to model, and since we are mainly focused in a single typology we do not modify this factor. The weather files that define the **situation** factor (ESP_Barcelona.081810_SWEC.epw, ESP_Madrid.082210_SWEC.epw) are based on (Energy 2014). These files define the weather to be used in our experimentation. We want to analyze the behavior of our typology in these two climatic zones (Barcelona and Madrid).

The **walls material** factor defines the kind of materials that must be considered on the building, 5 different alternatives are going to be analyzed. **Roof material** considers four different alternatives that summarizes the main alternatives to be used to build the roof, considering the building typology. **Windows** and **windows materials** represents the size of the windows and the type of windows we are going to use. Finally, **orientation** defines the different alternatives the specialists want to consider regarding the final orientation of the building.

If we allow to define all possible combinations the amount of scenarios to be analyzed must be 2880, however there are some combinations due to the nature of the materials, that are not allowed, hence the final number of scenarios to be considered are 336.

The typology we are going to analyze is an aisled residential building that is schematically represented by an square of 10 meters by 8 meters with two floors. This is a very simplified typology that helps us to understand the overall approach. Considering that for each scenario we need about 5 minutes, we need one day and 4 hours to calculate the overall scenarios. Other typologies can be much more demanding, and the combinations can be large, like those presented in (Ortiz et al. 2016). This makes obvious the need to use some optimization procedure in order to reduce the time needed to obtain optimal or semi-optimal solutions. In our approach we are using heuristics to find quasi-optimal solutions, specifically on SDLPS are implemented Hill Climbing, Simulated Annealing and NSGA-II algorithms.

5 SDLPS, OPIMIZING THE FORMAL REPRESENTATION OF THE MODEL

Hill climbing is a local search technique. It uses an incremental method to optimize a single solution. The algorithm starts with a solution that is randomly selected and iteratively, tries to find an optimal solution. This process is done modifying a single element of the exploration space. If the change returns a better solution, the change is accepted. We select Hill Climbing because its simplicity, to present here it as an example, however the infrastructure allows to implement in C, C++ or .NET languages any other optimization algorithm that can be applied for the Problem Entity. We can use, as an example, Hill Climbing here on the basis that the shape of the curve does not present local maximum or minimum values. The Hill Climbing algorithm implemented in SDLPS is presented next.

```
void COptHillClimbing::Step()
{
    m_R = selectTweakCopyParamFile(m_S);
    if (m_R.IsEmpty()) m_End = true;
    Execute(m_R);
    bool const_violated = false;
    double rNumber = CCongruentailRandom::getInstance().uniform(0, 1);
    //If the restriction is violated it must be discarded
    double QualityR = Quality(m_R, &const_violated);
    double QualityS = Quality(m_S, &const_violated);
    double QualityB = Quality(m_Best, &const_violated);
    //We select always the best solution.
    if (QualityR > QualityS)
    {
        m_S = m_R;
        if (QualityR > QualityB) m_Best = m_S;
    }
    m_limit--;
}
```

Quality function is built-in on SDLPS and is defined through the combination of the variables that the user wants to optimize. Hill Climbing is a single optimization method, however, it can be used here to obtain one of the bests solutions, SDLPS combines the different answer variables to find an optimal candidate solution. Any heuristic implemented must own this method **Step()**, that is iterated until we find a candidate solution. As we can see in the code, we start with a random candidate solution. The selection of the next alternatives to be evaluated is based on the permutation of one of the levels of the factors we define on the experimental design, hence the experimental design defines all the possible scenarios that are suitable to be analyzed by the optimization method.

The execution of the experimental design is controlled through SDLSP who implements the heuristic and who control the execution of other simulation and calculus engines needed in order to obtain the answers in a Co-simulation approach. This allows any calculus engine or legacy simulation model to be included. In this example we are using EnergyPlus.

The definition of the experiment presented in Table 1 can be done on SDLPS as is shown in Figure 5. Here we can detail the variables that we must use to perform the optimization, the restrictions and the definition of all the scenarios to be considered. On the SDL model are defined the different variables that must be used on the SDL agent's PROCESS that defines the behavior of the different elements, all those variables can be considered in the optimization process, see Figure 4. Also we can detail restrictions for each one of those variables. Figure 6 shows the window that allows to select the optimization algorithm to be used.

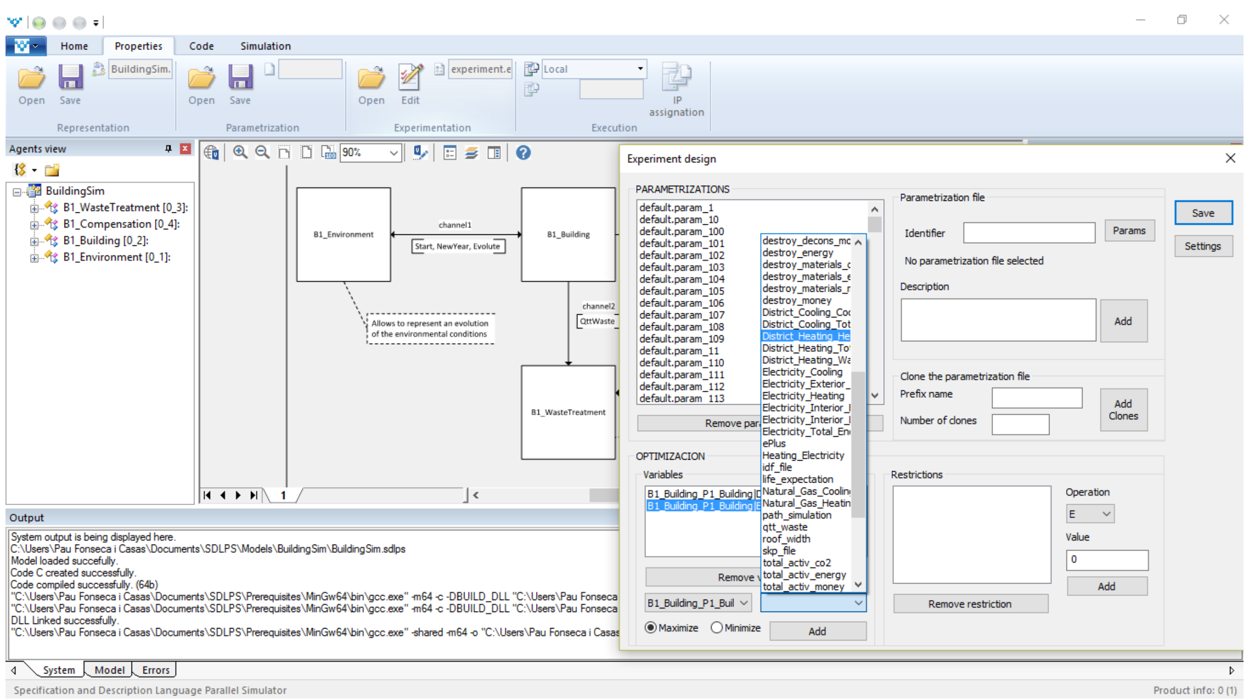

Figure 5. Configuration of the experimental design on SDLPS. The variables that can be used on the optimization are obtained from the formal representation of the simulation model.

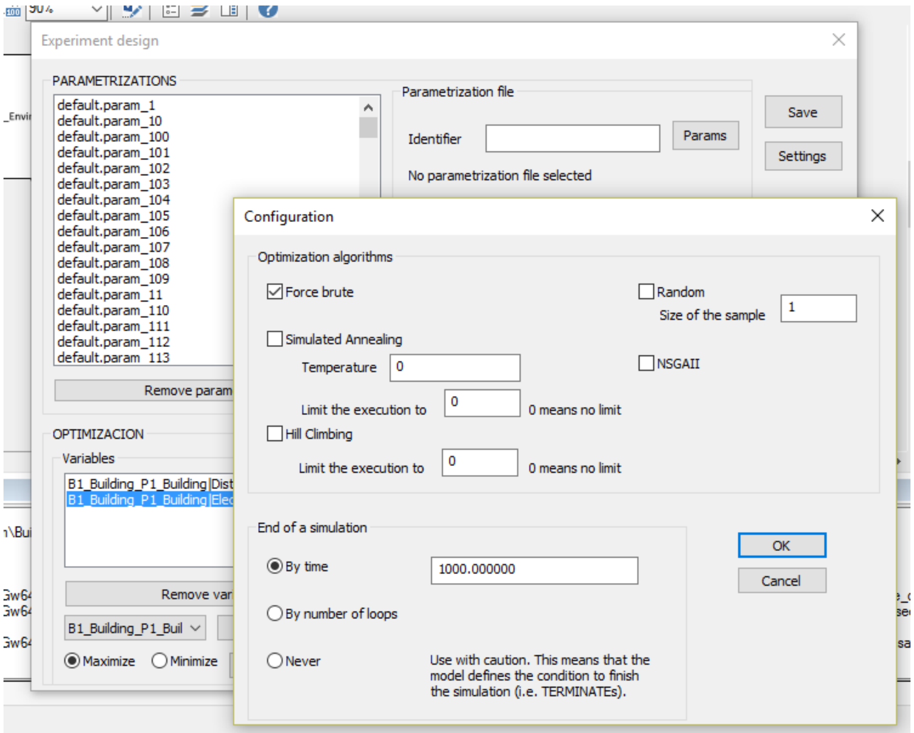

Figure 6. Definition of the optimization method to be used on SDLPS.

6 DISCUSSION

When we face a Problem Entity on an heterogeneous system, the use of a Conceptual Model is absolutely needed in order to be able to follow the needed Validation and Verification processes, believe in the answers (Accreditation) and finally implement those Accepted Solutions on the system.

The problems we face on those kind of systems usually imply the execution of thousands of different scenarios that must be compared in order to give a subset of candidate solutions. The time needed to execute this solutions will be huge, due to the need to use several calculus engines on the models or legacy simulation models. This requires the use of optimization techniques, like heuristics, in order to reduce the time needed to obtain the answers. However, this definition of the answers and the definition of the expressions to be used on the optimization algorithms, must be connected and also, validated by the experts. In that sense, the proposed methodology allows to define, on the Conceptual Model, the variables that will be later, suitable to be considered as answers variables, and from those, the variables that will be used on the optimization process. This clear definition of the different steeps that will be done in the experimental procedure, allows to accelerate the Validation, Verification and Accreditation procedures, increasing the confidence on the solutions we obtain, and allowing to achieve the final goal of a simulation study, the implementation of the solutions on the system.

Regarding the specific experiment done is interesting to remark that the use of Hill Climbing heuristic provides an optimal solution with a fraction of the executions, suggesting that the shape have only one global minimum, see Figure 7, but a deeper analysis is ongoing to assure this.

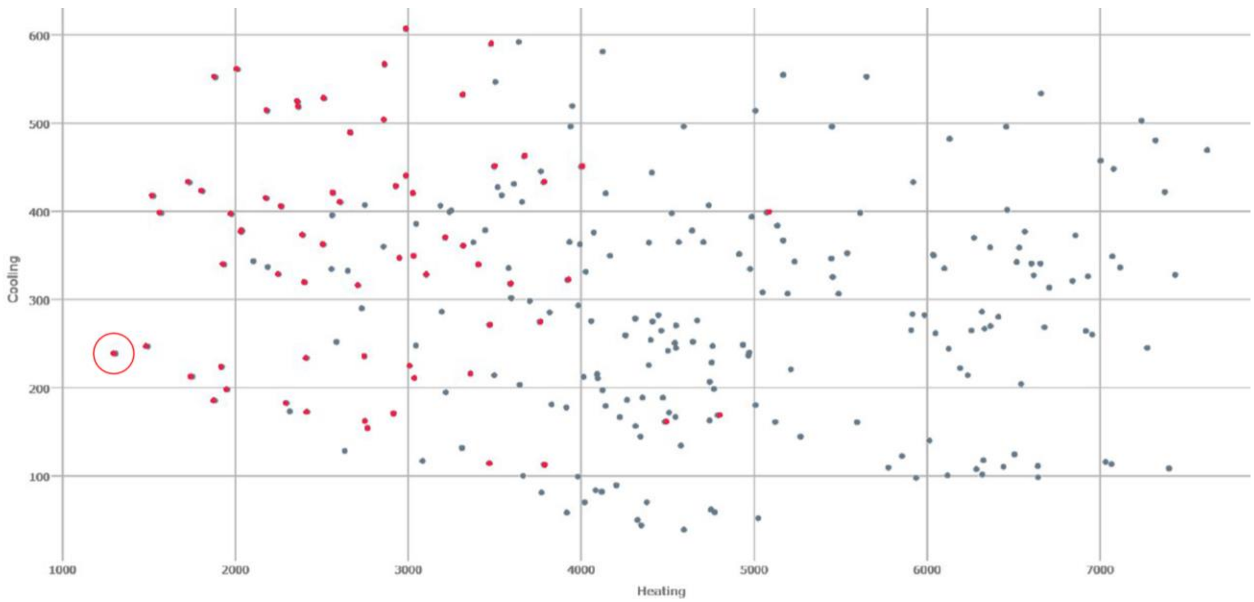

Figure 7. Experiment execution. The red dots represents those executed by Hill Climbing. An optimal value is the one in the red big circle.

The application of the heuristic on the experiment reduces a 85% of the time needed to obtain the solution. Just mention that this type of typology is giving an strong penalty to the heating, it means the needs to heat the house in relation to the cooling is 5 times bigger, aspect that is clearly represented on the obtained data.

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