Proceedings of the 2018 Winter Simulation Conference
M. Rabe, A.A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, eds.

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

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ABSTRACT

Sustainability is related with environmental, social and economic variables. Each one of these areas is, by itself, complex due to the huge number of factors that one must analyze. Because of the combination of the levels with the factors, and the needed replications, an exponential growth in the number of executions appears. In this paper we describe a methodology that helps us to deal with this complexity applying three key concepts, formal representation of 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 work with the conceptual model, and from it with the system; following the method, they will be able to find optimal scenarios using a selection of build-in heuristics that can be applied for the problem resolution.

1 INTRODUCTION

The current European normative 2010/31/CE (EU 2010) and the Energy Efficiency Directive (European Comission 2012), specifically on the energy efficiency of buildings, regulates on the article 9 that at 31 of December of 2020, all new buildings must be near to NZEB (near 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. 2011a; Sartori et al. 2012; Salom et al. 2011b; Salom et al. 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 these complex issues.

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 a huge number of factors. This makes experimentation complex, usually increasing exponentially the computational time needed to obtain the answers. Weather, construction features, user's behavior, active climate elements, house appliances, and others, are just some examples of the different factors that must be considered to achieve a solution. Secondly, because the personnel involved in the definition of those models belong to different areas, makes the model definition complex. This implies the need to stablish a common language to start working. Finally, because the nature of the data to be used on the models can be diverse (coming from a heterogeneous source) and the amount of the data can be huge, makes the model execution a hard task.

To achieve this, formal models must be defined to allow the collaboration and the information sharing between all the involved actors. These models must take care of the normative situation, the current economic situation, climate change, and so on, allowing the definition of realistic scenarios and strategies

978-1-5386-6572-5/18/$31.00 ©2018 IEEE

that must be analysed. This analysis, and the huge number of alternatives to be considered, must be coherent with a methodology that makes it possible to obtain knowledge from the huge dataset, simplifying the cooperation of specialists coming from different areas, and allowing the representation of the causality.

In this paper we present an methodology implemented on an infrastructure named NECADA (Fonseca and Fonseca 2015), that allows the definition, using a formal language, of the parameters that we want to later analyze on an optimization experiment, define the co-simulation elements to be used on the calculus, and considering the execution approach to be done. NECADA can be used to analyse thousands of different scenarios taking care of the sustainability parameters defined in 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 allow 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, the methodology must allow, through co-simulation techniques, using the more widely used calculus engines, like 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. If more computing power is required, it can also work in a cluster of computers (Fonseca 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 2008; Fonseca et al. 2013), the co-simulation engine that rules NECADA models, implements some heuristics that can obtain 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 depends on the nature of the factors 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 works done, see (Bernal and Dufo 2009) for a review. The use of genetic algorithms (Fan et al. 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 support system that simplifies the energy management (Chang 2014; Mattiussi et al. 2014). These techniques can be introduced on the methodology to improve the response time on the complex problems we try to solve.

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 are done automatically using SDLPS (Fonseca 2008).

The overall representation of the methodology is presented in Figure 1. 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 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.

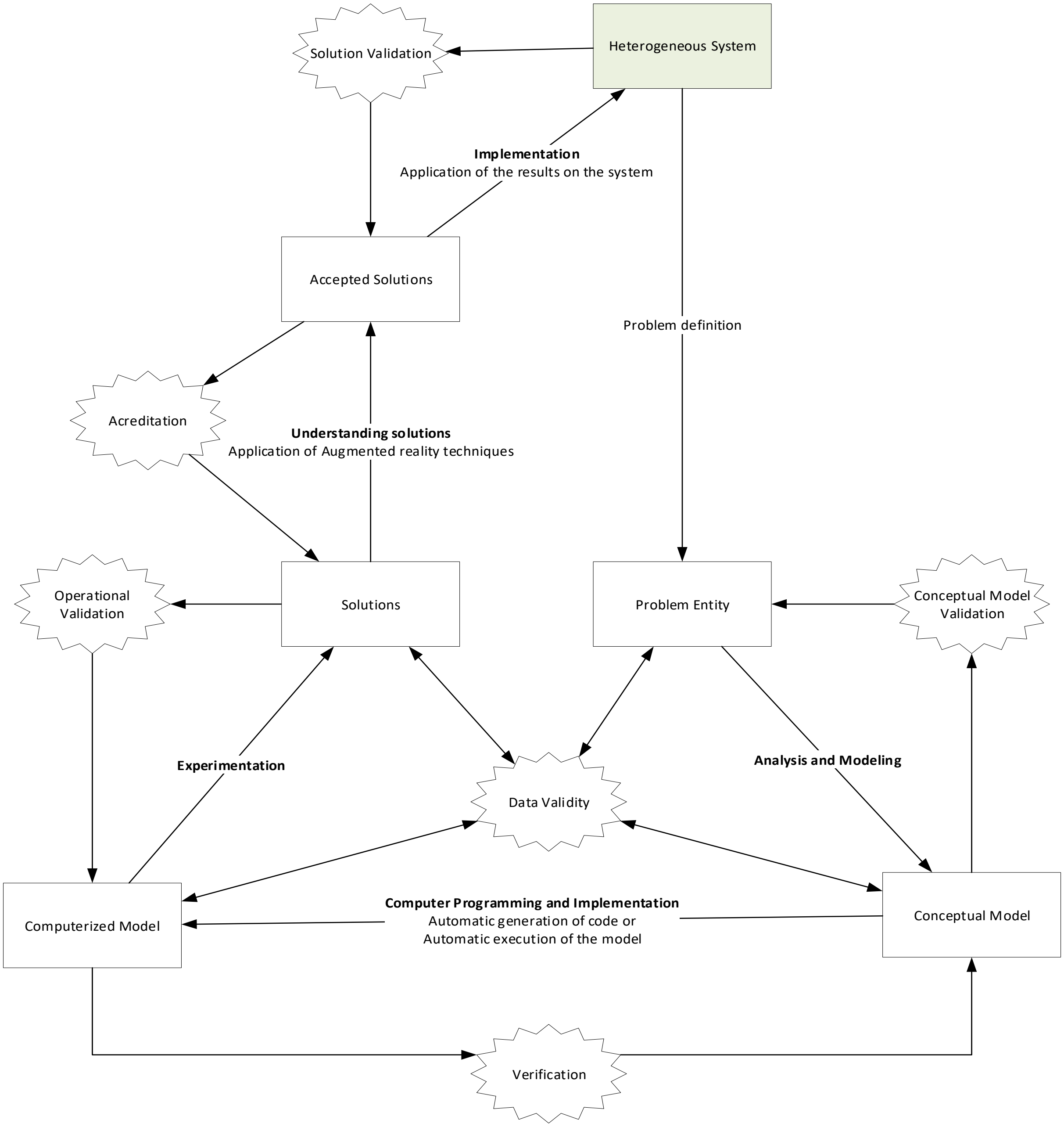


Figure 1: Methodology applied on the frame of the project. The iterative process allows to perform always a validation of the sub products one obtain in each step of the process. The process starts with the heterogeneous systems that one wants to analyze (on green in the figure).

This model is a key element since it represents all the knowledge (and represents the causality relations) 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 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.

We are going to focus now on how we can connect the conceptual model with the use of optimization techniques, and more specifically, the use of heuristics. 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. This system represents a building, that can be just one 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 are specified the detailed aspects related to the building use, the energy consumption of the inhabitants, the waste generation, and so on. 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.

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 et al. 2014).

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 et al. 2013). Specifically in the building area an interesting approach using DEVS is presented on (Goldstein et al. 2010; Ahmed et al. 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, see (Fonseca 2015; Boukelkoul and Redjimi 2013).

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

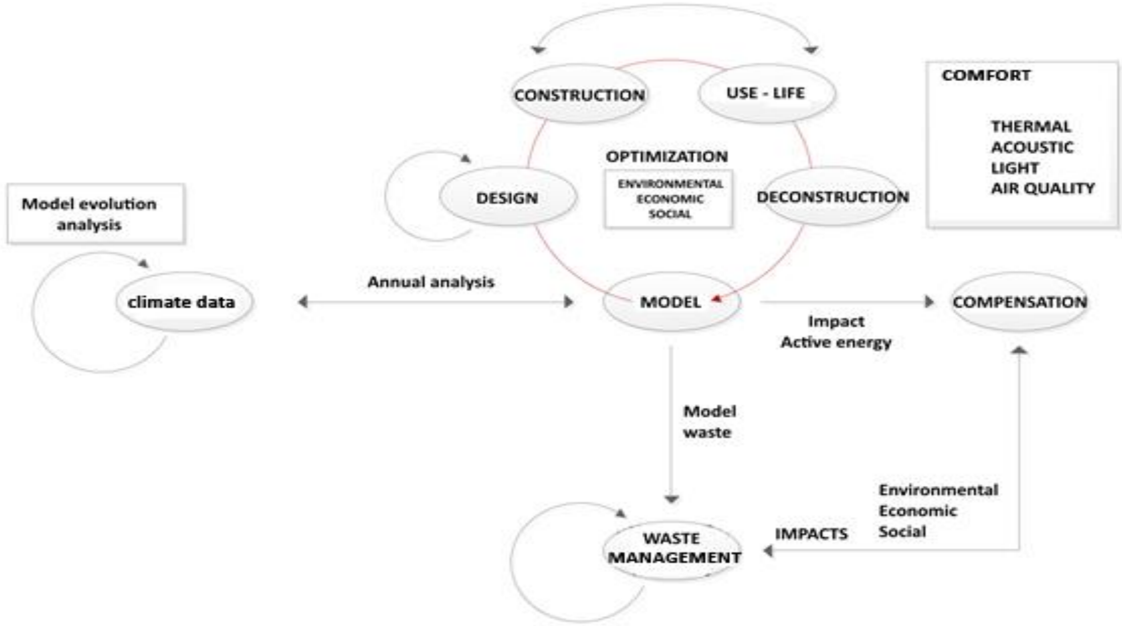


Figure 2: Simplified view of the holistic representation of a building model.

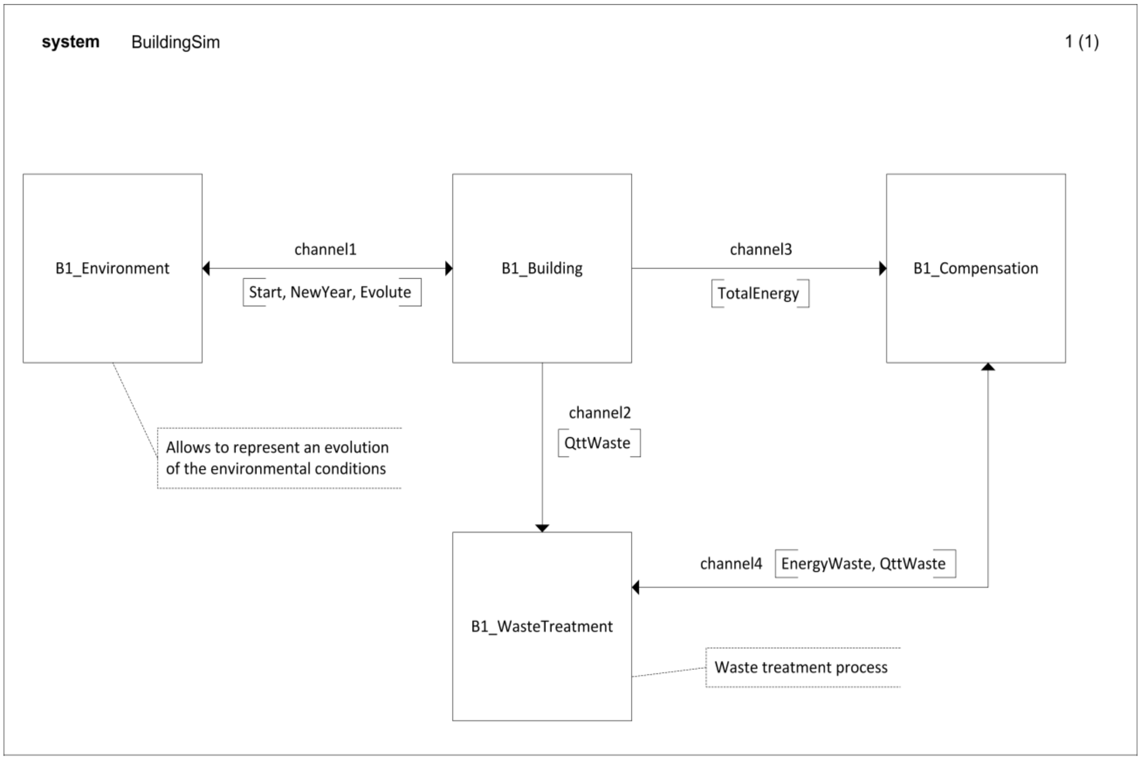
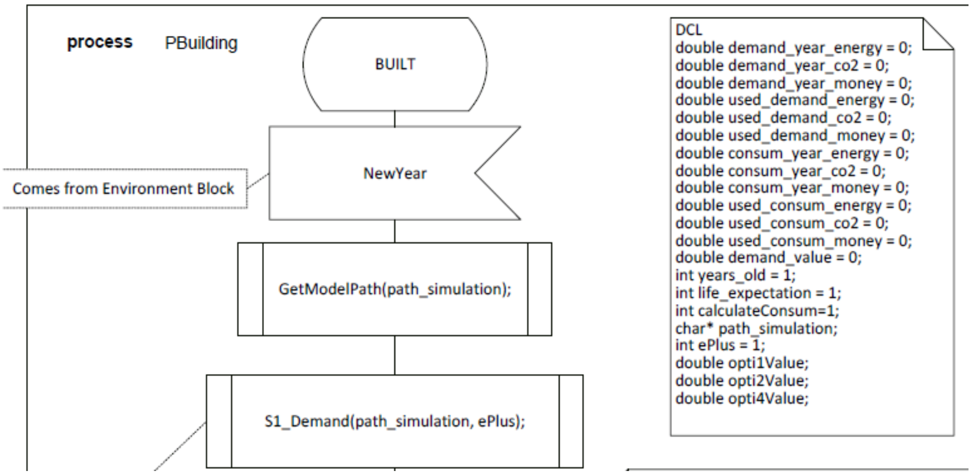


Figure 3: SDL representation of the model. First level, the system diagram.



```
DCL
double demand_year_energy = 0;
double demand_year_co2 = 0;
double demand_year_money = 0;
double used_demand_energy = 0;
double used_demand_co2 = 0;
double used_demand_money = 0;
double consum_year_energy = 0;
double consum_year_co2 = 0;
double consum_year_money = 0;
double used_consum_energy = 0;
double used_consum_co2 = 0;
double used_consum_money = 0;
double demand_value = 0;
int years_old = 1;
int life_expectation = 1;
int calculateConsum=1;
char* path_simulation;
int ePlus = 1;
double opti1Value;
double opti2Value;
double opti4Value;
```

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 defined on the declarations block (DCL) can be used later to perform the optimization, can be considered (if needed) factors.

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 one 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 Building Information Modelling (BIM) structure, allowing the definition of the building typology we are going to model; 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 all possible combinations, the number of scenarios to be analyzed would be 2880; however there are some combinations that are not allowed due to the nature of the materials, so the final number of scenarios to be considered is 336.

The typology we are going to analyze is an aisled residential building that is schematically represented by a 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 scenarios. Other typologies can be 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 OVER THE CONCEPTUAL MODEL

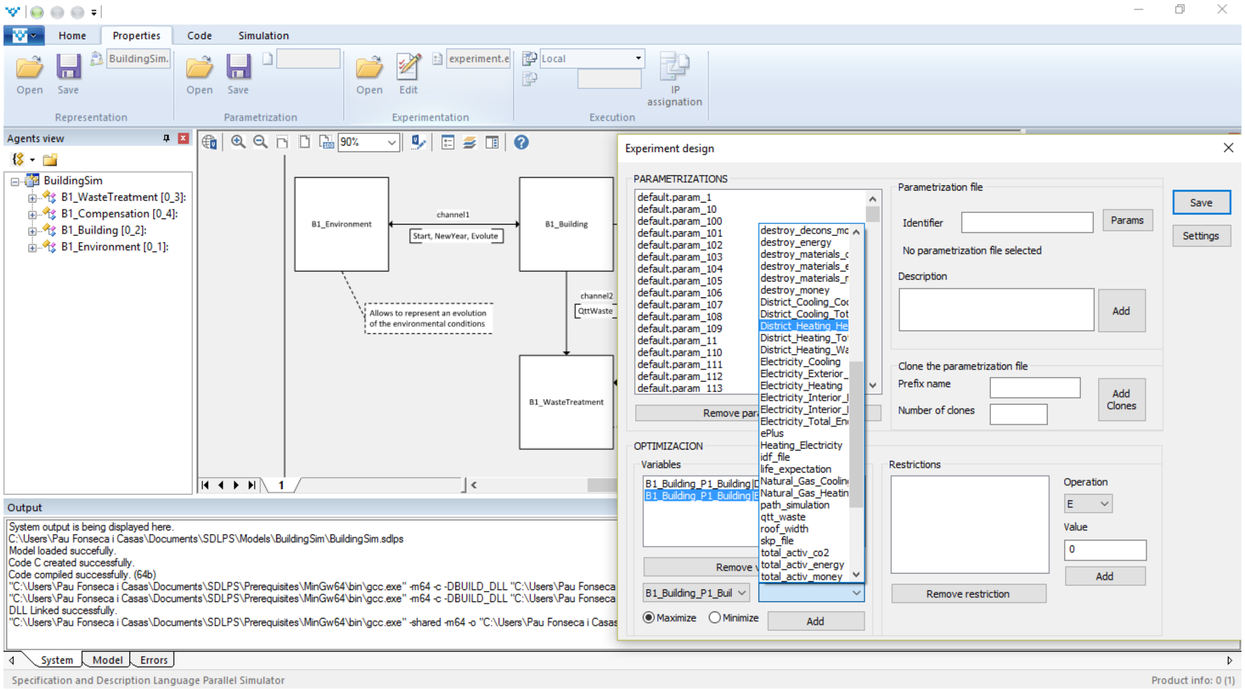
Hill climbing is a local search technique. It uses an incremental method to optimize a single solution. The algorithm starts with a solution that is randomly selected and iteratively, tries to find an optimal solution. This process is done modifying a single element of the exploration space. If the change returns a better solution, the change is accepted. We select Hill Climbing because its simplicity, allows 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*. In this specific case, Hill Climbing can be used because 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 controls the execution of other simulation and calculus engines needed 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.



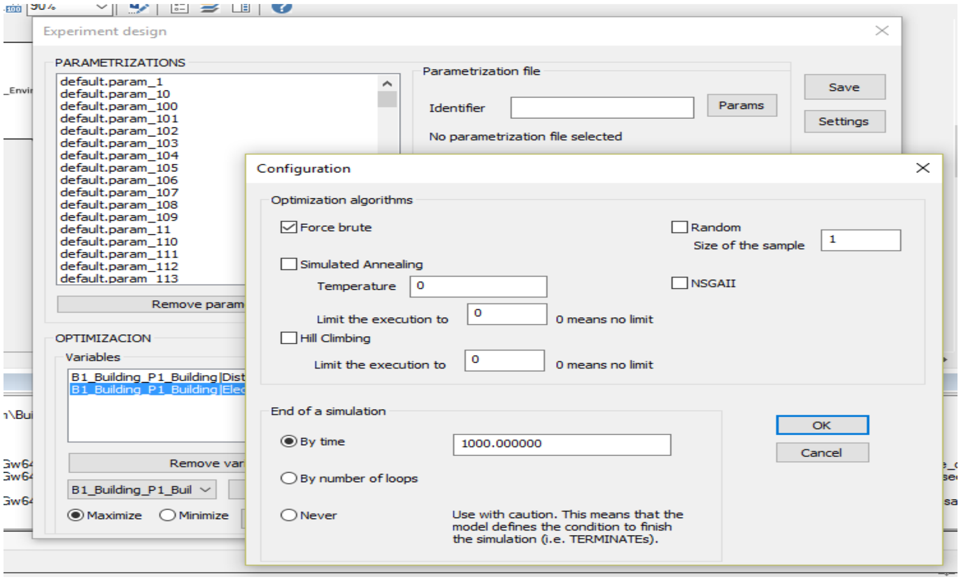
```
System output is being displayed here.
C:\Users\Pau Fonseca i Casas\Documents\SDLPS\Models\BuildingSim\BuildingSim.sdlps
Model loaded succefully.
Code C created successfully.
Code compiled successfully. (64b)
"C:\Users\Pau Fonseca i Casas\Documents\SDLPS\Prerequisites\MinGw64\bin\gcc.exe" -m64 -c -DBUILD_DLL "C:\Users\Pau Fonseca
"C:\Users\Pau Fonseca i Casas\Documents\SDLPS\Prerequisites\MinGw64\bin\gcc.exe" -m64 -c -DBUILD_DLL "C:\Users\Pau Fonseca
DLL Linked successfully.
"C:\Users\Pau Fonseca i Casas\Documents\SDLPS\Prerequisites\MinGw64\bin\gcc.exe" -shared -m64 -o "C:\Users\Pau Fonseca i Casas
```

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

6 DISCUSSION

When we face a Problem Entity on a heterogeneous system, the use of a conceptual model is absolutely needed 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 kinds 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 these 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, heuristics in our case, 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.



default.param_1
default.param_10
default.param_100
default.param_101
default.param_102
default.param_103
default.param_104
default.param_105
default.param_106
default.param_107
default.param_108
default.param_109
default.param_11
default.param_110
default.param_111
default.param_112
default.param_113

B1_Building_P1_Building|Dist
B1_Building_P1_Building|Elec
B1_Building_P1_Buil
● Maximize ○ Minimize

Identifier:
No parametrization file selected

☑ Force brute
☐ Simulated Annealing
Temperature: 0
Limit the execution to: 0 — 0 means no limit
☐ Hill Climbing
Limit the execution to: 0 — 0 means no limit
☐ Random
Size of the sample: 1
☐ NSGAII

● By time: 1000.000000
○ By number of loops
○ Never — Use with caution. This means that the model defines the condition to finish the simulation (i.e. TERMINATEs).

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

In that sense, the proposed methodology allows to define, on the conceptual model, the relations (showing the causality one wants to test) the experimental procedure and 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. The different steeps followed on this approach are connected through the different validation methods the specialist can do in the overall experimental procedure. This allows to accelerate the validation, verification and accreditation processes, increasing the confidence on the solutions we obtain, and allowing to achieve the final goal of a simulation study, that is the implementation of the solutions on the system. Regarding the specific experiment done in this example (that represents a family of problems that can be solved) it is interesting to remark that the use of Hill Climbing heuristic provides an optimal solution with a fraction of the executions, see Figure 7.

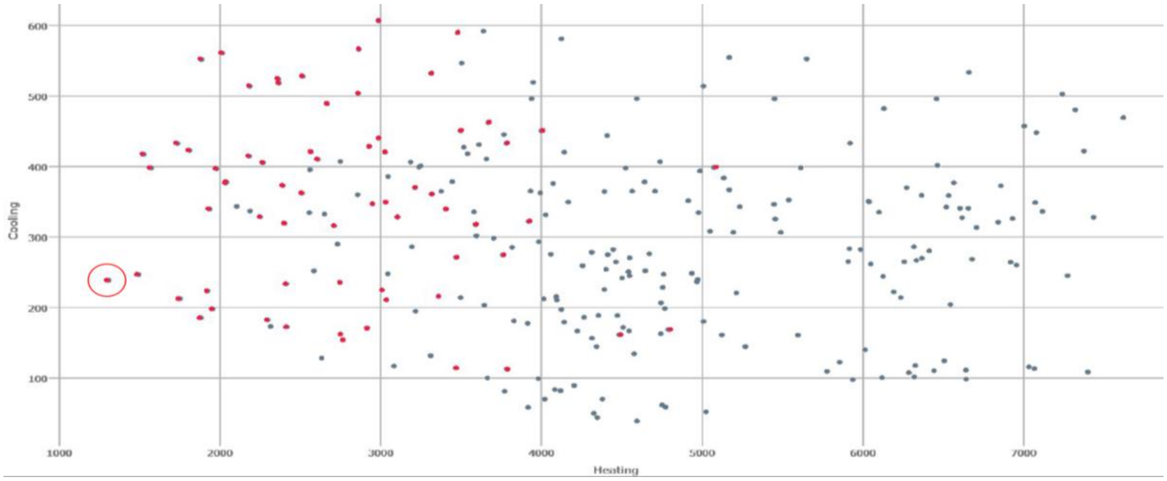


Figure 7: Experiment execution. The red dots represent those executed by Hill Climbing. An optimal value is one selected by the red big circle.

To obtain the complete dataset, with the execution of all the scenarios, the time needed was about 28 hours, but with the use of the heuristic a reduction of an 85% of the time needed to obtain the solution was achieved. The results have been obtained using NECADA desktop infrastructure. Since the time to obtain the results is drastically reduced, one can plan to use this kind of approach to dynamically obtain optimal solutions, depending on dynamical information obtained from different sources (IoT). On those approaches the simulation model that must be executed will change, depending on the parameters that the IoT sensors will provide. Hill Climbing, seems accurate to obtain optimal solutions, however more analysis will be needed to assure that it can be used in other specific experimental designs (more generic scenarios).

Finally, just mention that this type of typology is giving a 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. Currently we are conducting a research to conclude if Hill Climbing heuristic is behaving well not only in this situation, but in other experimental design scenarios, with the aim to define a classification. This classification will help the system to define what heuristic behaves better to answer a specific problem. Regarding the model, and thanks to the fact that can be easily expanded to analyze new elements (due to the methodology we follow), we are adding water management, a key element in sustainability related analysis.

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