NECADA. OPTIMIZATION SOFTWARE FOR SUSTAINABLE ARCHITECTURE

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ABSTRACT
In this work, we present a hybrid infrastructure, named NECADA, which supports the execution of a detailed simulation model representing all building processes on a supercomputer, cloud, cluster of computers or desktop environments. The aim of this infrastructure is to find optimal values for various building parameters and the associated impacts to reduce the energy demand or consumption of the building or the residential area. The infrastructure combines both, formal languages and co-simulation in order to obtain a complete unambiguous definition of the model, using the best tools to simulate any model component.

INTRODUCTION
NECADA is a simulator that allows to optimize all the processes related with the construction, with the goal of minimize his environmental, economic and social impacts. This allows defining NZEB (Net Zero Energy Buildings) allowing accomplishing the new European directive 2010/31/UE, related to the energy efficiency of the buildings. The goal of this directive is to achieve on the 2020 a reduction of 20% of the CO$_2$ emissions of 1990, plus a 20% on energy savings and a 20% of the use of renewable energies.

A cloud application is built in order to parameterize the model easily by non-experts users and to take care of the computational instances needed in any scenario depending on the resources needed.

The building is completely defined using Specification and Description Language (SDL), a graphical and formal language that simplifies the understanding of the model. The model contains the complete representation of the process related to the building sustainability, allowing introducing in the decision process all the elements that the modellers considers important.

The engine can use different optimization algorithms and works with EnergyPlus or Trnsys®, among others calculus engines.

The versatility of NECADA allows that the model can be executed over several configurations: (i) as a service on the NECADA website, as a desktop application using the simulation engine (formerly named SDLPS) (ii) on a cluster of computers; (ii) on a supercomputer or (iv) as a desktop application. This is mainly done thanks to the capability of SDLPS of distribute the execution of the simulation model over different nodes.

In this paper, we present the architecture of the tool and we review some real projects, as an example, where we apply the methodology and the tool. On these examples, we are focused on the different alternatives NECADA offers to execute the model.

OUR APPROACH
NECADA allows evaluating, analysing and optimizing the sustainability of a system (city, building or product) taking care environmental aspects (the demand or the energy consumption and the analysis of the cycle of life of the materials and the natural resources used), the economical and the social aspects. The software is developed through the definition of four main modules, (i) environment module, (ii) buildings module, (iii) recycling module and (iv) compensation module.

Environment module
This module allows analysing the climatic data needed to perform the further calculus. This allows us to take care of the climatic change on the other modules. Specifically we take care of all environmental parameters we need like the solar radiance, the winds, the temperatures, etc. always for the specific area of the analysis.

Buildings module
This is the main module of the simulator. It is composed by several phases that encompasses the different stages for a building or residential area.

- Phase 1: optimization of the model design.
- Phase 2: optimization of the construction process, evaluation of the materials and the constructive solutions done.
- Phase 3: optimization of the maintainability and use.
- Phase 4: optimization of the deconstruction process.

Recycling module
All the needed processes related to the reuse and recycling of the waste generated during the building life cycle must be taken in consideration. This...
The starting point in the complete process of optimization is the fulfillment of thermal, acoustic, lighting and air quality comfort; so that we ensure that the spaces studied are always based on criteria of user comfort (mandatory compliance regulations and energy and environmental optional certificates). To define the different modules and they related processes Specification and Description Language (SDL) is used, see (Doldi, 2001) (ITU-T, 1999). SDL is a graphical language that allows defining the different models through a set of diagrams. This graphical capability simplifies the readability of the models. Also, SDL is a formal language that allows an easy integration and combination with other languages. It is also a standard ITU-T, which ensures its stability and the existence of tools to automatically implements the SDL models. SDL allows us to define the necessary specifications for programming the different modules to analyze the design of our building, and so, validate them as a CO2 zero emissions building (or as close as possible). The software we use, allows an automatic implementation of the model, reducing the risk of errors and simplifying the verification and validation processes. The use of a formal language is essential to easily integrate all the knowledge of the members of the multidisciplinary team that is working in the software development (computer scientists, industrialists and architects).

Similar to BCVTB (Wetter, 2011), a tool that connects several simulation programs in the same environment (co-simulation), NECADA works with internationally well-known calculation engines for thermal optimization like EnergyPlus (Energy, 2012), Trnsys® o Doe-2. It will use the calculation engine Radiance for lighting calculation and OpenFoam to calculate fluid dynamics, see Figure 2. NECADA uses optimization algorithms that are widely used in other software like GenOpt (Anon., 2011) o Dakota (Anon., 2011). These optimization algorithms are automatically applied over the experimental design. NECADA database contains the main features of the materials and the building systems used on the studies: (i) physical properties; (ii) characteristics and associated environmental impacts (CO2, NOx ...), cost of production, transportation, maintenance and waste treatment; (iii) characteristics and associated economic impacts and (iv) characteristics and associated social impacts.
The calculation process is performed locally or using cloud servers, so that allows us to perform multiple simulations and expedite the process of calculation. Since the software used as the main engine of calculation and geometry definition can be accessed over the web or locally, it becomes a potential tool of great interest for universities and research groups with research lines related to building and sustainable energy.

Innovation and technology used

The simulator is not just a tool to assess, but it will tell the optimal characteristics that must fulfill our building in relation to isolation characteristics, materials characteristics, final energy consumption, economic impacts, etc. The main objective is to provide optimal constructions passive systems to cope different weather situations without resorting to air conditioning systems or active fossil energy consumption. Active systems are also fully considered on the models. The main innovative aspects are:

- The optimization of building energy efficiency, combined with environmental, economic and social impacts.
- The consideration on the model of four building phases (design-build-use-deconstruction).
- The consideration on the model of the waste treatment and compensation of the potential impacts generated, allowing to have a complete control of the Life Cycle Analysis study.
- The use of a formal language (SDL) simplifying the work in a multidisciplinary team with a modular approach.

SYSTEM ARCHITECTURE

Prior to start is needed to understand what is, from the point of view of NECADA a project, an experiment and a permutation.

A project is mainly a set of data that in one way or another we want to analyse. As an example, a project can be composed by a set of climate files, building models (representing the geometry of the buildings), material files and constructing solutions. The aim of a project is to analyse, through the execution of several experiments, what could be the best alternative for a specific goal.

On a project, the user can define a set of experiments. Each experiment is based on a subset of the building models, climate files and constructing solutions that exists on a project. Mainly we are defining here a specific scenario. We want to test (usually) thousands of alternatives to understand what is the optimal solution. Each one of these alternatives is a permutation. Mainly the simulation engine parameterized the model according to each one of these permutations and executes them continuously until all the permutations of an experiment are done or the optimal solution is found. Then NECADA reports the results. As an example, an experiment can try to analyse what is the best subset of permutations to be considered for a specific climate area. Each experiment defines different environmental conditions, while the permutations analyses the effects of this environmental conditions on the different buildings parametrizations.

NECADA contains several key elements that permits the simplification of the model definition by a non-expert user, assuring that no elements of the model are modified (committing the model integrity). The conceptual structure of the system architecture is represented in Figure 3. The user mainly interacts with a web application, formerly named Optisim, that...
allows to define the main parameters of an experiment to be conducted in a user friendly way. Optisim, based on a model-view-controller structure, implements the main interface managed by the users. When a user defines a new project, all the data is stored on the database and on the server directories. Two plugins allows interacting with the data generated by the different calculus engines that can be used on NECADA. IDFPlugin prepares the project to be understood by the calculus engine to be used (currently Trnsys® or EnergyPlus). Then, the data, with the correct structure is send to SDLPS who manages the execution flow of the experiment following the simulation model. The connection with SDLPS is done through its API. Once the execution finish, SDLSP uses ResultsParser plugin to write the results obtained from the different calculus engines in the correct format and show them to the user in a readable way. As is shown in the Figure 3., the model is connected to a database that contains the materials information, needed to perform the calculus. Thanks to the modularity and the versatility of the architecture, all the infrastructure can be executed easily on a cluster (or in a single computer), on a server (over Internet as a service) or over a cloud infrastructure (in that case we use Microsoft Azure® platform). In addition, SDLPS can be prepared to generate code to execute the models on a supercomputer like the Marenostrom. This simplifies hugely the use of this infrastructure in a research project, involving the modification of the simulation model (in fact the core of the application), and allowing a faster and local execution of initial exploratory experiments for a specific project. 

The responsibility of the management of the simulation and the co-simulation is for SDLPS. NECADA model is composed by a set of SDL diagrams that defines the structure and the behaviour of a theoretical building as is described on (Fonseca i Casas, et al., 2014). In addition, for each specific building is needed to detail the construction solutions to be analysed, the climate area where the building lives, its orientation and of course, its structure (mainly based on .idf files or Trnsys® files), among many other factors. NECADA model details a permutation that can be executed by SDLPS using, depending on the case, the calculus engine that the modeller wants to use.

![Figure 3. System architecture. The user interacts with NECADA model through the Optisim interface. SDLPS acts as a co-simulator platform that allows to execute the SDL model containing the detail of the building main processes and the calculus engines used to detail the energy consumption (like EnergyPlus or Trnsys).](image)

**SDLPS simulation engine**

The implementation of the model is based on software named SDLPS ([http://sdlps.upc.edu](http://sdlps.upc.edu)) that was developed in the inLab FIb (inLab FIb, 2012) of the Polytechnic University of Catalonia (Fonseca i Casas, 2008) (Fonseca i Casas & Casanovas, 2011). This tool understands a subset of SDL-2010.

Regarding the infrastructure used, it is remarkable that SDLPS has been built using C++ and C languages. The code related to the model (represented using the C language for tasks and SDL blocks for procedures) is used in the model through a DLL, and the generation of the SDL-XML model is performed on SDLPS through the interpretation of the standard representation of Microsoft Visio® 2013 (.vsdx files). Two elements composes the new VSDX format: a ZIP...
archive and XML content. Formally, this package is defined by the Open Packaging Conventions (ISO/IEC 29500-2:2008) standard. In addition, vsdx bases the XML content on the existing Visio XML Drawing (VDX) format (ISO/IEC, 2008). As a result, the Validation and Verification of the model can be performed mainly by reviewing graphic diagrams in Microsoft Visio®. This dramatically simplifies the interaction between the different specialists involved in the project.

Figure 4. SDLPS interface with the model loaded.

As we can see in Figure 4, the simulator shows the SDL diagrams of the model that are going to be simulated. Thanks to SDLPS, no specific implementation for the simulation engine is performed. This simplifies the verification process needed in every simulation project, see (Balci, 2010). In Figure 5 is presented the modelling process (Sargent, 2007); the simplified steps required in a simulation project are represented in red as a result of the use of this methodology.

Figure 5. Simplified version of the Modeling Process (Sargent, 2007).

The validation of the model is performed through the analysis of its SDL representation. Because of the modular and graphical structure of the language, all of the actors involved in the project can participate in this validation, despite their expertise using any given programming language. The verification is assured because the tool understands SDL diagrams. This methodology assures the complete and unambiguous formal definition of all the elements involved in the simulation model.

To define the scenarios that we will compare, SDLPS allows the definition of complex experimental designs. For each one of these experiments, a native SDLPS plug-in generates an idf (with the data needed according the experiment) and puts this file in a directory that contains all of the other data needed to execute the experimental scenario.

The current optimization algorithms implemented on SDLPS are Hill Climbing, Simulated Annealing and NSGA-II, but this can be easily expanded. Once the user selects what is the experiment that must be executed, SDLPS executes this experiment following one of this optimization algorithm (or force brute).

Optisim

The web, based on the model-view-controller paradigm allows a non-specialist to parameterize the model, create new projects, define the permutations, execute the experiment and analyse the results. Figure 6 shows the project management windows.

Three different user roles will be defined on the platform, the administrator, the enterprise and the residential user. As they names indicates, the Administrator user can define any kind of element on the system and allows the management of the database that encompasses the materials to be used on the simulations. Enterprise user can define the experiments, allowing the definition of the permutations to be executed by SDLPS simulation engine. Residential users are not allowed to modify any parameter on the database or on the experiments, but can access to a subset of the projects and understand the nature of the proposed modifications in his building or residential area.

Figure 6. NECADA web interface for defining a new project.

To define the permutations the user must add different data to the system, like climate files or BIM files. With this information, the system is able to define the maximum number of permutations to be considered. Often the number of permutations that must be executed in a force brute scenario is be huge (in some
real cases we participate more than 6000 different permutation for a single experiment). This means that the time needed to obtain the answers will be huge, in some real projects more than 20 days. This is not acceptable in some projects. NECADA have two easy to use alternatives to solve this problem, the use of computational power or optimization algorithms. Computational power can be achieved through the parallelization of the experiment, executing the permutations in different computers, using the cluster possibilities of the infrastructure, see (Fonseca i Casas, et al., 2015). This can also be transparent to the user, executing this cluster in a cloud infrastructure, simplifying its management. The second alternative is based on the use of optimization algorithms that lead to obtain an optimal (or quasi-optimal) solution.

CASE STUDIES

The infrastructure has been used successfully used in several real projects, involving enterprises of the construction sector. Three cases are stated here, showing links to find more information, (i) e(co) building, (ii) ACCIONA facade and (iii) IREC typologies.

The first project we discuss here is the analysis done of the (e)CO building for the Solar Decathlon competition ((e)CO team, 2012), see Figure 7.

Figure 7. (e)CO 2012 solar decathlon building

The (e)CO project is a prototype of self-sufficient housing designed by the Vallès School of Architecture of the Polytechnic University of Catalonia that was been submitted to the prestigious Solar Decathlon Europe competition, SET-2012. The project was being developed by students in collaboration with interdisciplinary research groups, private companies, public administration bodies and other agencies. It draws on the vast experience gained in the previous contest—Solar Decathlon Europe 2010—in which the project LOW3 (Low Impact, Low Energy, Low cost), submitted by the same research group; (e)CO, won the 1st prize for Architecture (Masseck, 2010). The goal is to develop a self-sufficient housing model based on the principle of zero economic and ecologic footprints. The mechanism to achieve this zero footprint goal is to offer more efficiency, more performance and more comfort using less material, less energy and less money by designing a home in which the organization of the building systems takes care of the life cycle. Using NECADA we calculated the relation between cost and consumption and detect the influential factors of the model as can be reviewed on (Fonseca i Casas, et al., 2014). In this project we use SDLPS to simulate the different scenarios, no Optisim interface was used here.

ACCIONA facade

We use the platform to define a simulation model with ACCIONA to analyze what is the best alternative to maximize the solar benefit regarding temperature and illumination (mainly in no extreme temperate climates) for a facade. In this project, again several alternatives must be compared and NECADA become a key element to understand and calibrate the facade elements. Regarding this, a system validation was done, analyzing if the results obtained was accurate enough, thanks to the construction of two real prototypes of the facade.

Figure 8. Prototype of the facade build on Seville.

Thans to this we can assure the validity of the results obtained with the simulator and detect discrepancies that can be analyzed. As an example we show on Figure 9 a comparison chart between the data obtained on the simulator and the data obtained on the prototype.

Figure 9. Comparison between the data obtained on the simulator and the sensors placed on the prototype. On red is represented the temperature obtained on the model, on blue the temperature obtained on the prototype sensors.

Mention that the model help us to detect some problems on the sensors placement, problem that was solved satisfactorily. This is not new on our group, a similar case where on a system validation we detect problems on the system data was (Fonseca, et al., 2011), where we detect some issues in one of the cases due to a problem on the UTM data.
In this case we use NECADA methodology to define and simulate the models over a server infrastructure.

**IREC typologies**

With IREC (Catalonia Institute for Energy Research) NECADA has been used to define the behavior of different building typologies regarding the energy consumption. In this case a high demanding calculus scenario is presented, where is needed to analyze more than 60000 different configurations.

This demanding scenario lead us to use a distributed schema in order to obtain the results in an adequate time spam. The first time that we confront with a simulation model where the required calculation time was too large with respect to the time we had to be able to offer the answer, was the simulation of the Barcelona Airport (Fonseca i Casas, et al., 2014). In this project we use a set of machines to run different identical replications of the same model but with different random number generators, with the aim of obtaining the necessary replications for the analysis.

Our collaboration with the IREC was in the frame of MARIE project. MARIE is a strategic project of the European Union financed by the program MED (Mediterranean Territorial cooperation). The project focuses on improving the energy efficiency of buildings in the Mediterranean area. In this case, the problem is not the number of replications of model that we need to perform, but the large number of different scenarios that we want to evaluate. This is due to the huge amount of variables that we can consider in a building. In a first approach to one of the typologies we wanted to evaluate, the time was about 20 days using a force brute approach. So, this was an excessive time given that not only should we respond to this initial typology. In this first stage we can apply different optimization heuristics in order to reduce the calculus time, like Simulated Annealing, Hill Climbing or NSGA-II among others algorithms that currently are implemented on SDLPS. However we want to use this scenario to validate the accuracy of the different optimization algorithms we can apply, hence we need to execute all the alternatives. In order to solve the problem, we divide the experimental design in independent pieces that may run on different machines, and then we join all the answers on a single computer.

We use one of the teaching rooms, installing on each computer the simulation systems that we need. SDLPS, our Simulator, with the model of energy efficiency for buildings, which acts as a co-manager simulation starting the other simulation systems. After that is needed to install Trnysys®, the calculus engine that we use in this project and, finally, it was necessary to install BitTorrentSync®, a peer-to-peer synchronization system that would allow us to centralize the results and the definition of the scenarios on a single central computer. Given that in the classroom had 25 computers, each one of these would run 240 simulations. The time it took to each PC to complete their task was less than 8 hours, but to prepare the configurations on each PC and install the programs was needed more than 10 hours. Figure 10 shows the room with the PC’s configured and with the results obtained in the screens, see also (Fonseca i Casas, et al., 2015).

**CONCLUDING REMARKS**

This work presents a novel approach and the infrastructure that implements this approach based on co-simulation and a formal representation of a model, to analyze the LCA of a building or urban area. The versatility of the system allows an execution of the model on a single computer, a cluster of computers, over a cloud or in a supercomputer infrastructure. This is quite interesting to reduce the related computing costs for a project, allowing to adapt the required infrastructure to the project real needs. As an example we cite three projects we are involved, that uses NECADA with different needs regarding the calculus power of the simulation infrastructure.

It is also remarkable the fact that the complete, graphical and unambiguous definition of the model thanks to a formal complete and standard language such as SDL, simplifies the interaction and the participation of all the actors involved in the development of the model. The experts can understand the model, represented graphically on vsdx Microsoft Visio® diagrams that depicts the SDL model. Thanks to this the specialists can be involved not only on the definition of the experiments to be done, but also on the definition of the details of the model to be used and the results to be obtained. This simplifies the detection of errors on the model. Also, the versatility of own a comprehensive definition of the model, using a formal and complete language like SDL, allows to extend the model to take in consideration other aspects of environmental, social and economic impacts. Also since SDL is a standard language, other tools can be used to implement the model, like (CINDERELLA SOFTWARE, 2007), (PragmaDev SARL, 2012) or (IBM, 2009) among others.

Regarding the co-simulation capabilities of NECADA infrastructure, the communication between the
different calculus engines are controlled on the model itself. This allows the optimization of the analyzed system following the European normative CEN/TC 350 (UNE-EN 15643-2, UNE-EN 15643-3, UNE-EN 15643-4).

ACKNOWLEDGEMENTS

This work has been partially supported by the Secretaria d’Universitats i Recerca de la Generalitat de Catalunya, by the MED Programme of the European Union under the MARIE strategic project (agreement Nº 1S-MED10-002), and by the project ISEED, Japan-Spain Energy Efficient Development for ultra-low Energy Buildings (agreement between Spain and Japan, funded partialy by CDTI).

Finally, the study was done thanks to the InLab FIB of Universitat Politècnica de Catalunya providing the computational resources and helping to set up the co-simulation.

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