A SYSTEMS ENGINEERING APPROACH TO DISTRIBUTED CONTROL AND BUILDING PERFORMANCE SIMULATION

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ABSTRACT

The development of advanced control systems for building performance applications faces many challenges due to the high number of physical processes that interact with each other, and with the environment. From the control point of view, these applications are often composed of multi dynamic sub-applications that must be monitored and controlled properly in order to achieve occupants' well-being and better energy efficiency. However, as the environment and occupants change in a building, this increases the complexity in applying control systems. For this reason, this paper presents a conceptual framework using systems engineering (SE) principles in the analysis and design of integrated control solutions for building performance applications by run-time coupling. Although these solutions are based on the use of SE practice and corresponding standards, the development lifecycle of control systems are covered ranging from the operational needs to implementation, operation and disposal. As all these achievements are a key step towards using computer simulations to evaluate the impact of advanced control systems on buildings operation and energy use, this paper also describes a distributed simulation mechanism that was developed and implemented between different simulation tools such as ESP-r and Matlab/Simulink.

Keywords: systems engineering; distributed simulation; control systems; building performance simulation

1. INTRODUCTION

With today's environment changing concerns, advanced control systems must be applied to buildings Heating, Ventilation, Air-Conditioning and Refrigeration (HVAC&R) equipment and lighting components in order to achieve occupants' well being and comfort aspects while at the same time reducing energy use and greenhouses gas emissions. Such developments need to be designed, implemented and deployed rapidly in order to reduce time involved in improving building HVAC&R equipment and lighting components for new deployments. In addition, it has been previously indicated by Yahiaoui (2008) that building performance applications are substantially influenced by the quality of automation and control systems provided in it. Therefore, the application of advanced control systems in building performance operations has for objective to promote sustainable buildings as well as the development and the next generation issues of economic strategies. Hence, sustainable buildings or "high-performance buildings", also called green buildings are buildings with complex systems, which must have minimum impacts on the built and natural environment. One of the major challenges today is the protection of the ecosystem. Although the building is designed and constructed for a long period, its life cycle can vary from some months to hundreds of years. During the period of its usage, the building can progressively consume significant amounts of natural resources, produce large quantities of gas emissions and affect the ecosystem in many different ways. As a result, there is a need to apply advanced control systems in order to make buildings more sustainable and efficient while at the same time improving occupants' well-being and indoor performance operations as well as reducing their impacts on local and global environmental quality.

The dwelling aspects concerned with sustainable buildings are comfort, well-being and energy efficient of occupants. The history shows that the protection of human health, in which the ecosystem protection is associated with, is much more closely related to comfort problems (thermal and visual comfort and indoor air quality). For this reason, this paper presents a framework for the application of SE concept to the design of control systems for building indoor processes and plant components by run-time coupling. While recognizing that there are many other aspects involved in achieving lower energy consumption, greater satisfaction and higher productivity of the occupants, the work described in this paper, focuses on modeling and simulation for better control design of the indoor environment in buildings.

The benefits of integrating advanced control systems in building performance applications would consist of offering an enhanced functionality of building indoor operations and of building HAVC&R equipment and lighting components resulting in better buildings performance, as well as an improved reliability with further reduction in energy costs. To well-establish such a vast diversity of control functions for all the building HVAC&R equipment and lighting components that operates within the building environmental performance, it is necessary to take into account several factors, which may particularly include indoor environment processes, occupants' requirements, and economic parameters in the form of microeconomic and macroeconomic levels. It is then important to mention that such sophisticated improvements would occur as a result of automated building HVAC&R equipment and lighting components (or more precisely, as the art of automating buildings). Therefore, automated building refers to the automation and control of building HVAC&R equipment and lighting components, which have been the subject of Building Automation and Control Systems (BACS) or Building Automation Systems (BAS) since last century.

However, a variety of simulation tools for building performance and energy analysis have been developed, ranging from the simple and estimated to the difficult and detailed use. Among them, a small number of programs have given up because they became either useless or too restricted. Even it is complicated to categorize the existing simulation tools since some of them integrate particular components while others incorporate other different components. Another issue is concerned with the building design, as many buildings gave up or demolished since their performances in energy use turned into disastrous. In (EERE 2010), it is pointed out that the energy consumption of new buildings can be reduced by as much as 50% with little or no impact on the cost of ownership through the use of SE concept. Therefore, the use of SE concept in the building domain would certainly offer a systematic approach to properly adapt procedures, tools, and standards toward an information-oriented problem in order to analyze, to design, to develop, to manage and to finally implement an effective and a pragmatic integrated solution, as shown in Figure 1. Detailed specifications are translated into test and integration procedures, design, and user documentation.

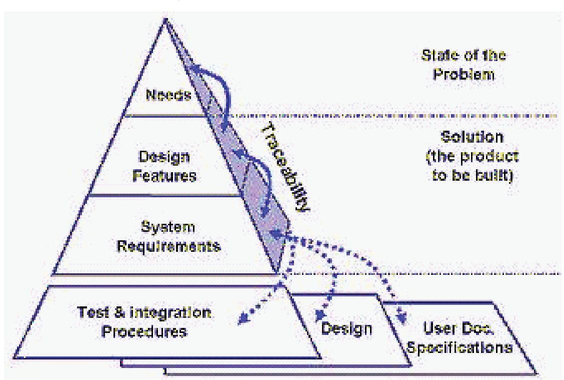

Figure 1: Approach based on managing the integration of advanced control systems in building performance applications.

The remainder of this paper is organized as follows: the next section presents a brief description of context, problematic and state of the art. Then it follows with the essential of SE concepts and design methodology process towards establishing a comprehensive framework. The third part concentrates on the development and implementation issues. This is followed by a building control application. The last part finishes with conclusions and perspectives for future work.

2. CONTEXT, PROBLEMATIC AND STATE OF THE ART

2.1 Context and Application

The context in this work is related to the development and design of advanced control systems in buildings, especially in building environmental performance. The integration of building science engineering, architecture, construction management and risk assessment for new construction projects and existing buildings becomes a must. Building control and performance applications require a lifecycle of development as shown in Figure 2.

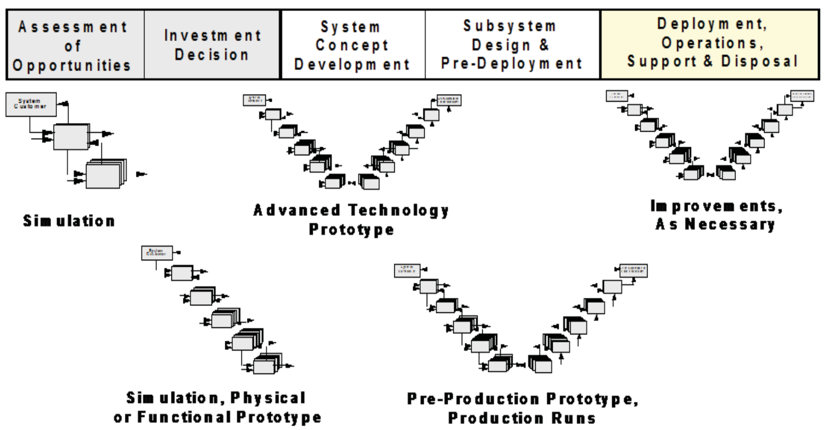

Figure 2: Enterprise-based life cycle phases

In this context, this study is concerned from the systems development (including subsystems design and deployment operation) to the deployment operations concerning the multiple development and implementation of the initial systems as a final system or a prototype.

2.2 Problem Statement

There are numerous approaches to the integration of new technologies in the buildings domain. However, a comprehensive framework where a building is seen as a system is not yet industrialized. Such developments using SE practices require to define requirements ranging from users/stakeholders needs to institutions, standards, local, national regulations, etc, where the limit of such integration cannot be defined if a global approach is not used. For this reason, this work has focused on the problematic of integrating advanced control systems in building performance applications by using information technology (IT) tools to assist an optimal solution design.

2.3 State of The Art

Up to our knowledge, there are not yet establishment mythologies and approaches linking SE practices with the appropriate use of building HVAC&R (equipment lighting components. However, some energy research departments in America, such as EERE (2010) use SE concepts to home buildings as advanced framing and insulation methods to increase efficiency and comfort while decreasing construction and energy costs.

3. SYSTEMS ENGINEERING AND DESIGN METHODOLOGY PROCESS

3.1 Systems Engineering Process

SE practice is not new, but the discipline is. It started with large-scale programs in USA, mainly in aeronautics (Mathers and Simpson 2000), in space (Shishko 1995), and particularly in defense (DSMC 1990) and (Hoang et al. 1996). Furthermore, it is getting popular in country having a well-established aeronautic and military industries; it has been since the 1990’s deployed in manufacturing, automotive (Loureiro et al. 1999) and recently in Society of Manufacturing Engineers (SME) (INCOSE 2010). As a simple definition: SE is an interdisciplinary approach encompassing the entire technical effort to evolve and verify an integrated and life cycle balanced set of system people, product, and process solutions that satisfy customer needs. SE includes:

- the technical efforts related to the development, manufacturing, verification, deployment, operations, support, disposal of, and user training for system products and processes;
- the definition and management of the system configuration;
- the translation of the system definition into work breakdown structures; and
- development of information for management decision making.

3.2 Define Systems of Systems

The deployment of SE product can be carried out in a comprehensive approach by separating the final product (i.e., building) from the enabling product (i.e., control systems, HVAC&R equipment and lighting components, etc.) and development product (simulation tools, etc.) this can be best illustrated by the following Figure 3.

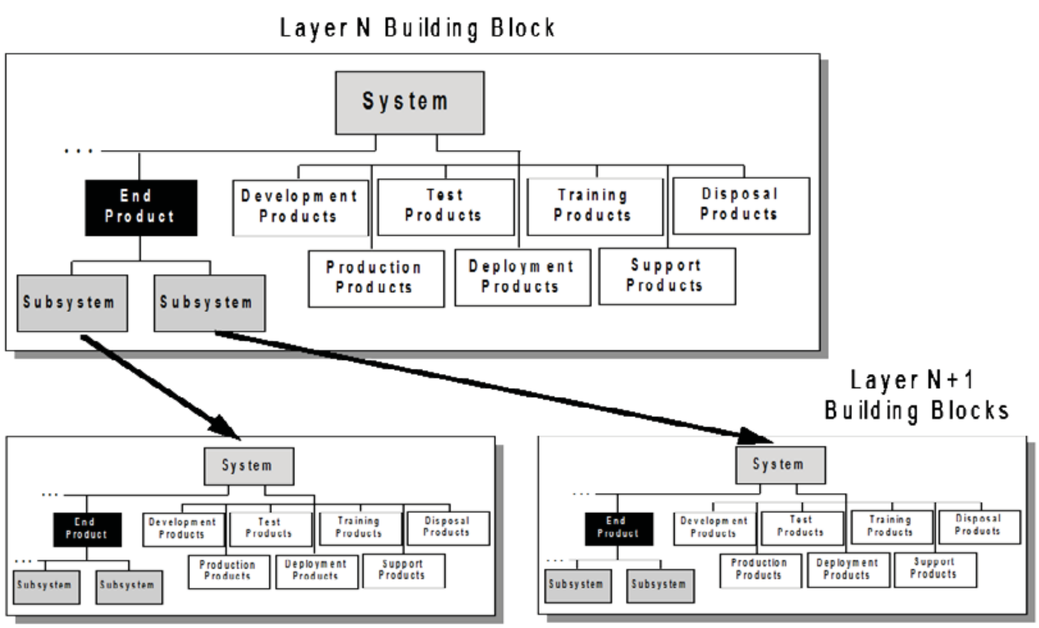

Figure 3: Hierarchy of building blocks

A single block will define the complete solution to a complex problem more typical of the design project. When an end product sub-system requires further development it will have its own subordinate building block. Once the descriptions of the end product of the initial building block are completed, and preliminary descriptions of the end product subsystems are defined, the development of the next lower layer of building block can be initiated.

3.3 Systems Engineering Deployment and Standard

In order to deploy SE for a specific building application, it requires first to identify all subsystems contained in the final product (the building model) and subsystems that are part of enabling product for integrating building HVAC equipment and lighting components and their control systems. Although HVAC equipment, lighting components, elevators and/or escalators, and fire as well as security equipment are essentially integrated in automated buildings, the simulation and modeling tools used, in this context can play a principal role in enabling the current building model as a final product.

SE concept is a diagram that includes the known processes that are daily in use. However, there are many models of popular SE standards, such as: ISO-15288, ANSI/EIA-632, IEEE-1220, SP-6105, ECSS-E-10A, but certain phases of these diagrams are frequently similar to each other (Sheard and Lake 1998). Although the objective of this research is to apply the deployment strategy to a building control application, the EIA standard (EIA-632 1998) is applied to the concerned levels. While recognizing that the EIA-632 standard is applied in diverse industries with success, it is certainly well suited for developing strategies such as simulation, prototyping, and benchmarking for resolving uncertainties and optimization issues in the analysis of automated buildings.

3.4 Development and implementation issues

For the analysis and design of integrated control systems for building performance applications, a number of issues can be addressed, among them are the followings: 1) Although most building HVAC&R equipment and lighting components have been developed with an idea of improved performance, their developed control systems that regulate their capacities in buildings are basic and not established properly. As a result, it requires developing a systematic knowledge to make best use of their potential benefits through appropriate control systems of their performance characteristics under transient climatic conditions and occupants needs. 2) When building HVAC&R equipment and lighting components are used in a building, the simple addition of individual best performances does not warrant the best performance of the entire building. As a result, it is necessary to develop control systems through integrated SE concept in order to provide the maximum benefits to buildings. 3) When requiring simulating a building performance application and its control system is that frequently certain building equipment and/or components can be modeled in one simulation software while some models are only available in other simulation environment. Hence, there is on the one hand domain specific building performance simulation, which is usually relatively basic in terms of control modeling and simulation capabilities (e.g. ESP-r). On the other hand, there exists a domain dependant control modeling environments, which is very advanced in control modeling and simulation features (e.g. Matlab/Simulink), but still limited in building simulation. Marrying the two approaches by run-time coupling would potentially enable building performance assessments by predicting the overall effects of innovative control systems in building indoor environment (Yahiaoui et al. 2003).

3.4.1 Development lifecycle

The development lifecycle, in this study, includes several phases during which utilized software tools for BPS and CME must work together separately. In sub-system level, the last phase occurs when the study of the building model or the control system is disposed of and the task performed is either eliminated or transferred to the system level. The tasks and work activities for each phase are described below. The integrated control systems for building performance applications require that the phases of both the building model and its remote control system should be sequentially executed. However, the lifecycle diagrams concerned with both the building model and its remote control system are interdependent in which their phases may be combined and overlapped.

The SE concept, which specifies functions, sequence and the interrelationships between various phases of both the building model and its remote control system, is extremely imperative so that their integration into the same entity will be successful. Although, there exists several lifecycle diagrams (such as spiral, waterfall, V, etc.), the V diagram is used for the application of SE concepts to the development of complex projects because of its emerging proprieties. The V diagram is based on the interactions that take place between the links of decomposition or analysis (\) and construction, which means physical integration, or synthesis (/) of the design project (Yahiaoui et al. 2006b). When the cycle V is applied and contains all the components of the project, as shown in figure 4, the number of loops can be easily deduced by decomposing and reconstructing the design concept.

As indicated by (Blanchard 1991), SE introduces the notion of top-down design, which involves viewing an entire system comprised of its components as a whole functioning unit. This starts by identifying the sub-systems and then components of the system, decomposing them into low-level sub-systems and then lower-level components and iterating until the desired level of detail is achieved. By considering this notion of top-down design, the integration of control systems together with building performance applications can viewed as the whole functioning unit of a building operation that is actually represented in the form of V diagram (so to the entire design process of the building operation). The SE concept to the analysis and synthesis of structural V diagrams focuses on the scope of the building operation along with a set of identified requirements engineering, especially functional requirements. SE concept can go one step further to establish further functions that are critical to successfully design a proper control system for building performance application.

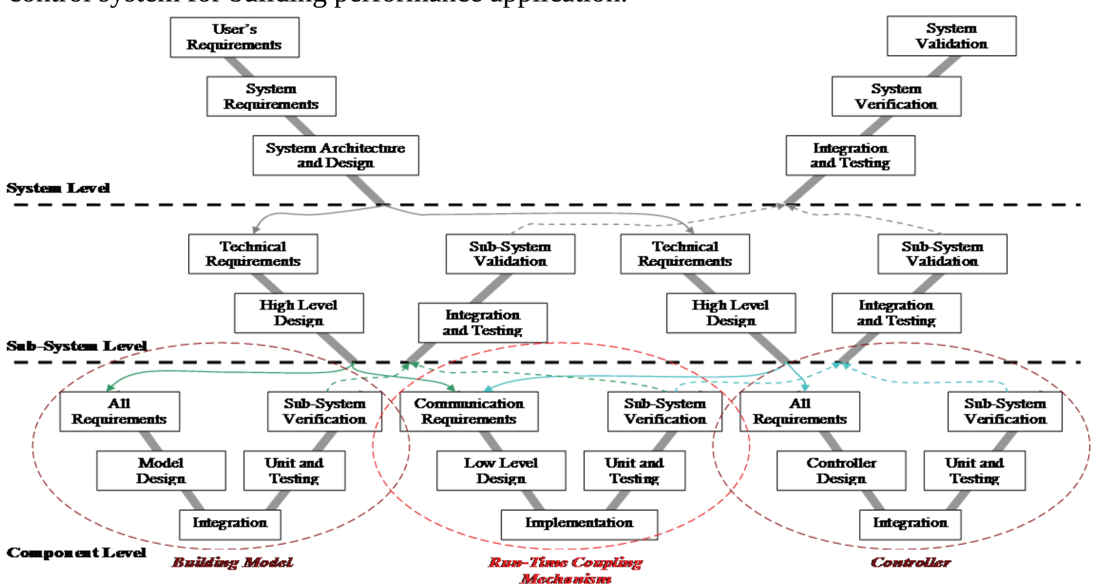

Figure 4: Development lifecycle model

At top level, the building is represented in the total form of the V diagram, in which at low level this building consists of two sub-systems that stand for the building model and its remote control system, which at lower level are represented separately to work together by run-time coupling. As in BACS architecture, building HVAC&R equipment and lighting components are located in the field level and their control systems are located in the automation level, and they exchange data through a network. By similarity to BACS architecture, a distributed dynamic simulation mechanism was developed and implemented between BPS and CME in order to simulate building control applications, as happen in a real situation (Yahiaoui et al. 2006a). While building models (including zones, HVAC&R equipment and lighting components) are built on ESP-r, their remote control systems are modelled on Matlab/Simulink. Both PBS and CME can run either on the same computer or on different computers connected by a network. In addition, both software environments should exchange data by run time coupling in order to obtain simulation results as accurate as possible. In consequence, there are three V diagrams at component level, as shown in figure 4, where the V diagram in between concerns run time coupling between a building model and its control system (Yahiaoui et al. 2006b).

3.4.2 Distributed Dynamic Simulation Mechanism

The most critical issues facing the design of run-time coupling between Matlab/Simulink and ESP-r include heterogeneity, interoperability, and parallelism. In previous works (Yahiaoui et al. 2003, Yahiaoui et al. 2004, Yahiaoui et al. 2005), it has been shown that the appropriate way of developing run-time coupling between ESP-r and Matlab/simulink is to use an Inter-process Communication (IPC) mechanism based on Internet sockets. This performs a distributed simulation using network protocols including transmission control protocol (TCP) and user datagram protocol (UDP) by exchanging data between building models and their control systems, as occurs in BACS architecture. Both a building model built on ESP-r and its remote control system modelled on Matlab/Simulink that are separated and work together by run-time coupling can be located on either the same host or different kinds of hosts to speed the simulation Therefore, one of the main objectives of this distributed dynamic simulation mechanism is not only to enable the integration of (advanced) control systems in building performance simulation by run-time coupling but also to be able to simulate building environmental applications that had been previously infeasible (i.e., yet impossible).

During simulation, commands and data are exchanged between a building model built on ESP-r and its remote control system modelled on Matlab/Simulink at every time step. When a building model has to send the current measured data to its control system using TCP/IP-suite, a method is first called to encode data to exchange to network format. When a control system has to receive this current measured data from its building model, another method is also called to decode from network format to data received. The same procedures are executed when a control system has to send back the actuated data to its building model, and when a building model has to receive the actuated data from its control system. Therefore, both a building model built on ESP-r and its remote control system modelled on Matlab/Simulink running either on the same computer or on different computers (i.e., machines with different operating systems such as Windows and Unix) connected to the network exchange data at every time step using the same procedures. Furthermore, the iteration continues with the same way until the simulation is completed. Figure 5 shows how a distributed simulation is performed between ESP-r and Matlab/Simulink over a network.

In addition, this dynamic mechanism of distributed building control and performance simulation is also implemented to support data exchange in ASCII, binary, and XML formats as well as synchronous, partially synchronous and asynchronous communications modes.

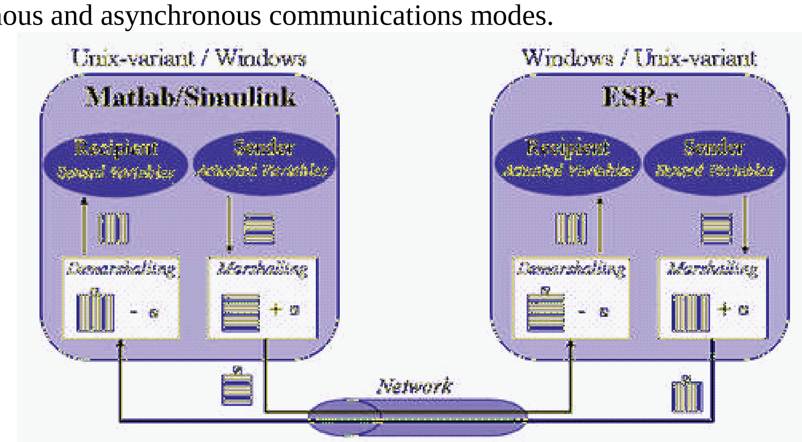

Figure 5: A distributed dynamic mechanism for building control and performance simulation

3.4.3 SE Practices in Design of Advanced Control Systems for Building Performance Applications

A very structured way of designing advanced control systems for building performance applications by run-time coupling between ESP-r and Matlab/Simulink is by involving SE practices in order to translate the occupant requirements (or need) into a control system specification and realization that most efficiently meets these needs. Figure 6 shows how to develop and design an advanced control system through a simple V-diagram while applying SE principles.

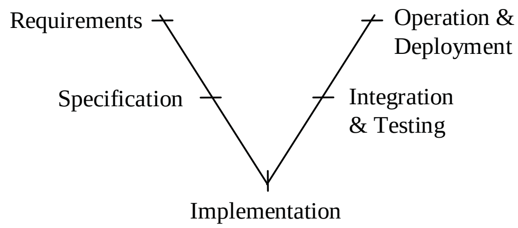

Figure 6: A well-established way of designing advanced control systems

As shown in Figure 6, the V-diagram is simple because it consists of a small number of phases ranged from requirements to specification, implementation, integration and testing, and operation and deployment. The requirements phase defines the occupant needs and determines the building processes and/or dynamical models of plants to control and to be used for instance to derive requirements of the subsystem level of abstraction from requirements of the system level of abstraction. The specification phase identifies the goals and functionalities of the control systems, along with their inputs and outputs that must be selected to be run-time coupled with ESP-r. The implementation phase takes needs and goals of the pervious phases and implements them using appropriate control systems. The integration and testing phase consists of integrating building and/or plant models built on ESP-r with their remote control systems modeled on Matlab/Simulink by run-time coupling and then testing if their inputs and outputs are connected correctly. The operation and deployment phase consists of calibrating the necessary control parameters to meet requirements (i.e., needs) and then running simulations.

4. BUILDING CONTROL APPLICATION

A simple exemplar building model from ESP-r is used for the application of an advanced control system using a distributed dynamic mechanism between ESP-r and Matlab/Simulink by run-time coupling, as shown in Figure 7. A requirements document for building heating process is well documented and described in (Booch 1991) and (Hatley and Pirbhai 1988). With the modeling approach proposed in this paper, it demonstrates that the use of a system-level architectural design provides numerous advantages over traditional design methods. A number of limitations and/or shortcomings presented in traditional design methods using classical or conventional control systems can therefore be avoided. By using system-level considerations, control systems can be designed following the SE concept through various abstraction levels. In this consequence, it requires using a sequence diagram expressing all feasible interaction among objects describing the behavioral and operations of the heating process in a building model.

The hybrid control system is designed in such a way as to set by default the heating plant to the position "Off", but once detect that the air-temperature in the building space is lower than the air-temperature set-point , it immediately switches the heating plant to "On". When the heating plant is on the amount of heat supplied to the space is calculated depending on an approximate amount of the heat loss from the space plus inside and outside air-temperature. For this reason, StateCharts, developed by Harel (1987), are used as a visual modeling formalism for the specification and modeling of complex systems. Because the modeling of building performance operations remains complex, StateCharts are used to model the functioning of heating process in the test-cell. The Stateflow of Matlab/Simulink is thus used to simulate the StateChart model. In this application, the outside air-temperature is not included as it has no large disturbances on the indoor air-temperature during the simulation period, as illustrated in Figure 8.

Figure 8 shows the simulation results obtained by run-time coupling between a building model built on ESP-r and its control system modeled on Matlab/Simulink, as shown in Figure 7. This control system was designed to automatically adjust the heating supply into the building space in order to maintain the indoor air-temperature as comfortable as possible (i.e., at the desired set-point) between 7:00 to 18:00 o'clock. The simulated results shows that there are small variations in the control response and these are due to the discrete states of the hybrid control system, or rather embedded control system. It is important to note that these obtained results can still be improved by combining artificial and hybrid control systems.

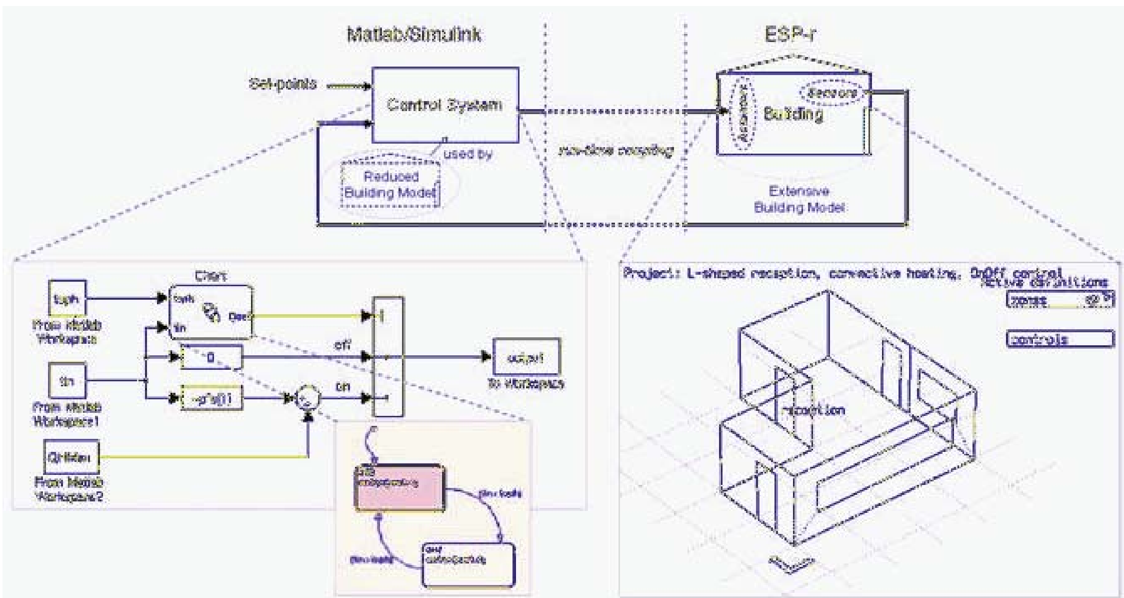

Figure 7: A building control application: control system (left) and building model (right)

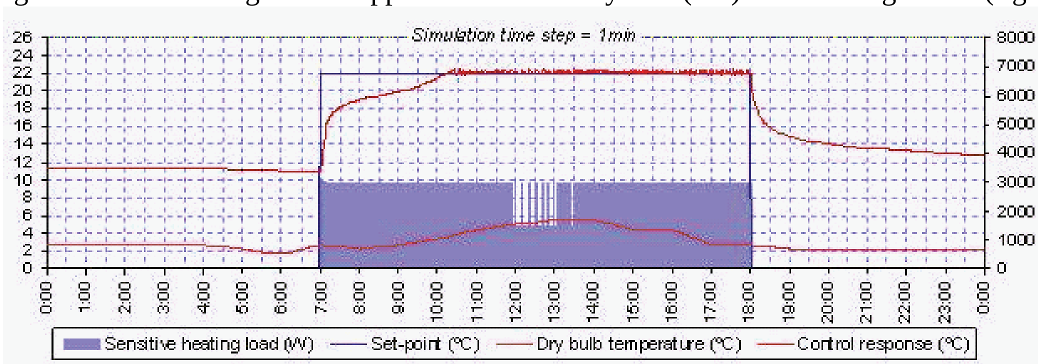

Figure 8: Simulation results

5. CONCLUSION AND PERSPECTIVES

A system-level design of an advanced control system for a building performance application is presented and tested using a distributed dynamic simulation between ESP-r and Matlab/Simulink by run-time coupling. One of the main objectives of this study is the use of SE methodology to facilitate the development and implementation of a distributed dynamic simulation between Matlab/Simulink and one or multiple ESP-r(s) by run-time coupling to use as a practical solution for developing and implementing new automated building applications as well as improving existing building control applications in the quest to satisfy occupants requirements while reducing energy use and greenhouse gas emissions. Finally, it can be concluded that corresponding practical solutions are possible to be integrated for such purpose.

Based on the perspective that designing a distributed simulation for control and building performance application is a complex system, the use of the SE methodology is needed to define all operational needs and required functionalities in the development, implementation, validation, and operation of run-time coupling early in the development life-cycle within the V diagram. Among other perspectives, future work envisage to analyze and simulate building control applications involving the utilization of distributed dynamic simulation between multi ESP-r(s) and Matlab/Simulink by run-time coupling using different communication modes including synchronous, asynchronous and partially asynchronous.

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