MATLAB/SIMULINK FOR BUILDING AND HVAC SIMULATION - STATE OF THE ART

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ABSTRACT

The use of Matlab, a tool for mathematical programming, is actually increasing in a large number of fields. Together with its dynamic simulation toolbox Simulink, originally developed for control and automation applications, it has become a powerful tool that is suitable for a large number of applications.
In the field of building and HVAC, the number of users of Matlab/Simulink has also been increasing rapidly in the last years. The tool is suitable for many applications in this field as for example the study of energy consumption, control strategies, hydraulic and air flow studies, IAQ, comfort, sizing problems. More and more studies are being published using Matlab/Simulink environment for development of specific tools and for simulations of buildings and technical building services.
This paper gives a synthesis on the use of Matlab/Simulink for the improvement of buildings and HVAC systems. The information has been gathered during two first international workshops on the use of this tool for building simulation. At these two workshops with participation of 10 countries, 33 technical presentations gave an overview on current research and studies using this tool.
Some additional references are also provided in order to include other work that could not have been presented during the workshops.
The paper gives an overview on the topics that are treated using the tool, the related tools that can be used, the modelled phenomena and the issues solved using the tool.

INTRODUCTION

The Matlab/Simulink environment

The use of Matlab (Matlab 2004), a tool for mathematical programming, is actually increasing in a large number of fields. Together with its dynamic simulation toolbox Simulink (Simulink 2004), originally developed for control and automation applications, has become a powerful tool that is suitable for a large number of applications. Many other Matlab toolboxes exist that can be combined (Optimisation toolbox 2004, Control toolbox 2004, Femlab 2004, Identification toolbox 2004, Statistics toolbox 2004, Real-Time-Workshop 2004, Stateflow 2004 etc.). The range of possible applications of the tool is very large and still increases since the tool is used in many fields of dynamic simulation and mathematical programming (cars, engines, etc.).
In the field of building and HVAC, the number of users of Matlab/Simulink has also been increasing rapidly in the last years. The tool is suitable for many applications in this field as for example the study of energy consumption, control strategies, hydraulic and air flow studies, IAQ, comfort, sizing problems. More and more studies are being published using Matlab/Simulink environment for development of specific tools and for simulations of buildings and technical building services.
The tool also allows "hardware in the loop" simulations as shown by Vaezi et al. (1991) and Vaezi et al. (1997), where parts of the system can be real components and others simulated (eg. real controllers can be tested in a virtual system).

Two first workshops on this subject

To date, there is very little exchange of know-how and other information between the users of this tool in order to exchange information about modelling techniques or simulation techniques. Also, in the simulation community, there is very little information available on what can be done with this tool. CSTB has thus organised two first workshops on this subject.
The workshops took place in 2003 (Workshop 2003) and in 2004 (Workshop 2004) on Building and HVAC simulation using the tool Matlab-Simulink and related toolboxes as well as third party software.
43 participants from 7 countries (Belgium, Denmark, France, Germany, Latvia, Netherlands and the UK) attended the first workshop, 29 from 8 countries (Finland, France, Germany, Latvia, Netherlands, Switzerland, UK and USA) the second workshop, both held in Paris. 18 technical presentations were given at the first workshop, 14 at the second.
The presentations, in a certain way representative for the users of the tool, were, summarised over the two workshops, given by 3 manufacturers, 4 consultants and 23 Universities or research centres.

Objectives of the paper

This paper analyses mainly the given presentations under different aspects such as fields of application,

simulated phenomena, issues to be solved and the use of this tool in combination with other building simulation tools.
In addition, other references, not complete, are given in order to describe activities using this environment.
The presentation is grouped into:

- Matlab toolboxes and development of related tools
- Control: Design, test, demonstration and training
- Modelling and simulation of physical phenomena and systems
- Commissioning, fault detection, diagnosis and visualisation
- Coupling with other tools outside Matlab environment

MATLAB TOOLBOXES AND RELATED TOOLS:

The Mathworks provides a large number of tools and toolboxes - see Mathworks (2004) for a complete list. Here are selected tools:

- Matlab (Matlab 2004): Matlab is a matrix oriented tool for mathematical programming. It includes several toolboxes (Optimisation toolbox, 2004), (Identification Toolbox 2004) or others.
- Simulink (Simulink 2004): Simulink is a graphical environment for the simulation of dynamic systems. It is a generic environment that can be used for any system with a selection of ode solvers.
- Stateflow: This toolbox allows the ease development of complex, event driven control strategies (Stateflow 2004).
- Real Time Workshop (Real Time Workshop 2004) allows the user to compile Simulink simulation models to create executables.
- Femlab (Femlab 2004): Femlab is a toolbox based on Matlab for the modelling and simulation of 2D or 3D heat transfer problems.
- Dedicated Building and HVAC toolboxes.
  There exist, on the one hand, commercial or free toolboxes such as Carnot Toolbox (Carnot 2005), International Building Physics Toolbox (Weitzmann et al. 2003), (Modelbook 2004), Simbad Toolbox (Simbad 2005), Wavo (de Witt et al., 2001), or ASTECCA (Mendes et al., 2003). Some manufacturers, universities or organisations dispose of their own toolboxes (Eftaxias et al. 1999, CEA 2001, Thermosys Toolbox 2003). The latter cover for example photovoltaics or refrigeration-specific toolboxes.
  These toolboxes allow the user the simulation of buildings and their technical systems (mainly HVAC and renewables or lighting). A more complete list of toolboxes based on Matlab can be found on (Mathworks Connections Programme 2005). By combining several of these toolboxes the user will obtain a very powerful tool for any kind of studies on the building field.
  Due to the large number of models or toolboxes there is still some work or coordination to be done to ensure compatibility between the tools available, especially for dedicated building and HVAC toolboxes. Inputs and outputs of different models are to date defined by each modeller, a connection between models from two different toolboxes can thus take some time. This should be normalised in the future in order to allow a fast integration of new models from other toolboxes.

CONTROL

Controller design

Matlab/Simulink environment allows to simulate and optimize controller design, to detect and correct errors in the design cycle and finally to test and validate controller design in Real Time (Mathworks 2003, Huyge 2003 and Huyge 2004). The tool has been applied to different systems.
Control algorithms for innovative systems have been developed, on the basis of the Simbad and Stateflow toolbox, for a desiccant cooling system by Ginestet et al. (2003). Liekens (2003) presented an optimisation of control parameters of mico-CHP systems.
Fuzzy techniques or neural networks have been developed and tested by different authors. A quasi-adaptive fuzzy controller for space heating in solar buildings has been presented by Underwood et al. (2003). An artificial neural network has been used to predict comfort conditions in a space one hour ahead and the output from this is used as one of several fuzzy input variables to a fuzzy heating controller. For these developments a variety of Matlab toolboxes can be used.
Strategies for hybrid ventilation have been presented combining Simbad toolbox and the Stateflow toolbox by Jreijiry et al. (2004).
Start stop optimisers, night ventilation strategies or sunblind control algorithms have been developed by Bakker et al. (2003) or Lahrech et al. (1999).
The tool has also been used for integrated control of buildings optimising the joint management of heating/air condition, lighting and blinds or of other components (Yu 2003, Visier 2001).
The control strategy should meet two main conditions, to minimise the thermal energy and electricity consumption (these can also be expressed in terms of emissions or costs) while maintaining the wished indoor set point temperature. Optimisation toolboxes (cf. section related toolboxes) can therefore be used to optimise a control strategy related to environmental or economic criteria.

Controller test and real time simulation

The tool, due to its capabilities of real time simulation, is more and more used for the test of controllers. In the frame of a European research project SIMTEST (Lahrech et al. 2002) and in close collaboration with the CEN technical committee TC 247, a test bench for HVAC terminal controllers has been presented (Riederer 2003). This test bench is now being integrated in a european certification programme for controllers.

The tool has also been used for the evaluation of BEM systems by Visier et al. (1994) and Vaezi et al. (1991).

Virtual laboratories for the assessment of ventilation control strategies or hydronic systems are in development (Husaunndee et al. 2003, Couillaud et al. 2004) or already developed (da Silva et al. 2003).

Lindeloef (2004) presented a Matlab-based tool for the control of a real building via internet.

General studies on run time coupling of controllers to building simulation programs has been shown by Yahiaoui et al. (2003).

Demonstration and training

Tools for demonstration and training purposes have for example been presented in the frame of the European project Simtrain (Arditi 1998) aimed in a training tool for terminal controllers.

Other selected studies on system control are listed in the references.

MODELLING AND SIMULATION OF PHYSICAL PHENOMENA AND SYSTEMS

Matlab/Simulink is a generic simulation environment. Underwood et al. (2004) described in a generic way the modelling of phenomena including different approaches such as discrete or continuous modelling.

In parallel to the available Simulink toolboxes, other studies presented the implementation of models into Matlab/Simulink environment, but are not all publicly available. The following list gives a selection of studies or grouped by phenomena or system:

- Multizone building models have been developed by different authors. These are based either on heat and moisture (de Wit et al. 2001) or on heat (El Khoury et al. 2004), the latter providing a graphical user-interface for the building description. Specific work has been carried out on conduction in walls (Déqué et al. 2001) and their mathematical reduction (Palomo et al. 1997).
- Room modelling has been described either on perfectly mixed air (Riederer et al. 2000) or on air distribution in rooms. These can be based on the zonal modelling approach (Ghiaus 2003, Peng 1996, Peng et al. 1997 or Riederer et al. 2001) or on CFD modelling (Sormunen 2004). van Schijndel et al. (2003) also coupled the CFD approach with HVAC system models.
- Ventilation, air flow and air quality has been studied by Jreijiry et al. (2004) by integrating multizone air flow modelling in Simulink environment. This work includes the modelling of moisture phenomena and pollutant transport (CO2 etc.).
- Hydronic networks have been modelled and simulated by Hegetschweiler (2004), Riederer (2003) or Couillaud et al. (2004) in order to study water networks and the control of variable speed pumps in heating or cooling systems.
- Active or smart façades have been modelled including their control algorithms by Park et al. (2003) and Stec et al. (2003).
- General HVAC components such as coils have been implemented by Yu et al. (2003) and Husaunndee et al. (1998).
- Heat generation by solar, CHP or heat pumps: Hedström et al. (2004) developed models for a combined solar–hydrogen–biogas-fuel cell system, Liao et al. (2003) implemented boiler models including sequencing control. A CHP plant has been simulated by Petruzzi et al. (2003). de Jong et al. (2000), Underwood et al. (2001) implemented heat pump models into Simulink environment.
- Some work has also been carried out on heat storage, from water storage by Harunori et al. (2001), Yoshihito et al. (1999) to thermochemical seasonal heat storage (Visscher 2004).
- Lighting and blinds: Models for lighting and blinds have been implemented by Husaunndee et al. (2001).
- Renewable systems: Ginestet et al. (2003) developed models for desiccant cooling systems. Ground coupled heat exchangers have been integrated by Jain (2003) or Kumara (2003). Finally, wind turbines coupled with fuel cell systems have been developed by Iqbal (2003) or Surgevil et al. (2005).

This list of developed models is not complete. It shall only give an idea on which area work has been carried out. A list of available models will be prepared during the next workshops in order to organise the developments in this environment.

As mentioned previously, some work to normalise model development would be helpful to obtain a better compatibility between the models.

COMMISSIONING, FAULT DETECTION, DIAGNOSIS AND VISUALISATION

Matlab/Simulink is a useful tool for commissioning and fault detection due to several toolboxes and its data analysis capabilities. Different studies have been presented. An existing, combined solar/CHP/boiler system for example has been simulated in order to improve the management of the three heat sources which had caused problems in the real building (Liekens 2003).

Model-based fault detection and diagnosis on the building installations have also been presented by different authors such as Yu (2003), Morisot et al. (1999), Li et al. (1997) or Salsbury (1999).

Knabe et al. (2003) and Vaezi-Nejad et al. (2003) developed methods for commissiong of HVAC plants, both based on Matlab/Simulink models.

Baumann (2003) and (2004) demonstrated interesting tools for the diagnosis of buildings and HVAC systems, based on Matlab-based visualisation tools and models that could be applied either to simulated or real buildings.

Finally, Yu et al. (2003) presented building energy diagnosis based on fuzzy techniques.

COUPLING WITH OTHER TOOLS OUTSIDE OF MATLAB ENVIRONMENT:

In spite of a growing number of available models, it is essential to develop the link to other existent building simulation tools. This allows to take profit of the advantages of these tools in both senses: use the powerful toolboxes such as control or optimisation for the simulation in other environments as TRNSYS (Knabe et al. 2003), couple a Simulink plant model to the powerful TRNSYS type 56 multizone model (Gaehler et al. 2004 and Keilholz et al. 2003). The “commander” of the simulation can then either be Matlab/Simulink or the other simulation environment. The link in both directions has been shown, but has to be improved in order to be more generic.

Strategies on the link to other tools have been presented by Yahiaoui et al. (2003).

Another approach consists in a coupling of tools by data models, presented by Keilholz et al. (2004). Common data bases for model parameters would then be used. Contrarily to the IFC approach these data models would be reduced to energy simulation in order to keep the level of detail on an acceptable level.

CONCLUSION

General

This paper presented a summary of ongoing modelling and simulation activities in the field of building and HVAC systems.

It has been shown that, recently, the amount of studies using Matlab/Simulink environment has been grown rapidly. More and more papers have been presented on conferences or in scientific journals.

The success of this tool is probably due to the multidisciplinarity in a single environment. The coupling of a large number of fields is achieved without any effort.

Also the common opinion that building modelling is restricted to monozone buildings and only useful for restricted studies is proved to be false. New multizone building models have been implemented into toolboxes. Buildings with a large number of zones or even several buildings can be simulated using these models. The aim in these multizone studies can either be focussed on control with small time steps (El Khoury et al. 2004) or energy studies with hourly time step (de Wit et al. 2001).

Feedback of the workshop and future perspectives

As shown, two first workshops have been organised in order to initiate more exchange between the users of the large number of Matlab-related toolboxes. The presentations on these workshops were mainly focussed on building operation, control strategies, the impact of the control strategy on whole system behaviour and the commissioning of controllers and of the whole system.

All participants agreed that they got a lot of interesting information during the workshop. It has therefore been decided to continue the workshop on a yearly basis and including more demo and tutorial sessions. The workshops should deal with two main aspects: why and how do we use Matlab/Simulink.

A usergroup has recently been created in order to increase the exchange between users (Simubuild 2004) in terms of information or models. An up-and download page has been integrated into the homepage. This could especially be interesting to share public domains models from universities.

Manufacturers on the other hand can probably not contribute by sharing models. Their assistance would be helpful by giving specifications or feedback to the model developpers (eg. which existing interfaces to use, how to document the validations, parameters of the models which are really available to make the models “usable”).

An advantage of the usergroup shall also be a data base of existing models that are available in order to know who is working on which kind of models or phenomena.

Since several toolboxes are being developed in parallel, more effort has to be spent on model interchangeability between libraries and models. The usergroup should thus define rules which will enable a common approach to these toolboxes (eg. standard connections for models).

The Mathworks or Femlab as software developers expressed their interest to obtain needs of the usergroup. The user group could then submit needs for future developments in the basic Matlab/Simulink environment.

Since a large number of other simulation environments exist, the link to other groups such as Trnsys could be interesting and avoid redundancy. In this case the efforts should probably be more concentrated on coupling methods than on re-development of component models.

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