HVAC system simulation: overview, issues and some solutions

Citation for published version (APA):
Trcka, M., & Hensen, J. L. M. (2011). HVAC system simulation: overview, issues and some solutions. In *23rd IIR International Congres of Refrigeration, Prague* (pp. 4181-4188). (Congres International du Froid-International Congress of Refrigeration). IIR.

Document status and date:
Published: 01/01/2011

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 04. Oct. 2023

Trcka, M. and Hensen, J. L. M., 2011. HVAC system simulation: overview, issues and some solutions. Proceedings of the 23rd IIR International Congress of Refrigeration, Prague , 21-26 August, International Institute of Refrigeration, pp. 8.

ID: 923

HVAC SYSTEM SIMULATION: OVERVIEW, ISSUES AND SOME SOLUTIONS

TRCKA M., HENSEN J.L.M.
Eindhoven University of Technology, Den Dolech 2, PO Box 513, 5600MB, Eindhoven, The Netherlands
m.trcka@tue.nl

ABSTRACT

Integrated performance simulation of buildings' heating, ventilation and air-conditioning (HVAC) systems can help in reducing energy consumption and increasing occupant comfort. Recognizing this fact, in the last forty years many tools have been developed to help achieving this goal. In this paper we introduce a categorization of these tools with respect to which problems they are meant to deal with and summarize current approaches used for modelling (i) HVAC components, (ii) HVAC control and (iii) HVAC systems in general. Further in this paper, we list issues associated with applications of HVAC modelling and simulation. Finally, we present and discuss co-simulation as one of solutions that can alleviate some of the recognized issues.

1. INTRODUCTION

Modern buildings are required to be energy efficient while adhering to the ever increasing demand for better indoor environmental quality. It is a known fact that in developed countries buildings account for 30%-40% of the energy consumed. Depending on the building type, heating, ventilation and air-conditioning (HVAC) systems are responsible for 10%-60% of the total building energy consumption. The long life-cycle of buildings further compounds the importance of architectural and engineering design decisions.

On the one side, challenging goals are set by new initiatives and energy policies. For example, the European Union has defined ambitious goals for reducing emission of CO2 for the industrialized countries. Also, the U.S. Department of Energy and ASHRAE have defined their vision for 2030 [ASHRAE 2008] in a form of net zero energy buildings. On the other side, new buildings consist of numerous dynamically interacting components that are nonlinear, dynamic, and complex. This requires an integrated approach that treats innovative solutions to buildings and the systems that service them as complete entities, not as separately designed subsystems.

To design energy efficient building systems in this complex setting, integrated building performance simulation (BPS) can be used. Experience shows that BPS can indeed result in a significant reduction of emission of greenhouse gases, and give substantial improvements in comfort levels [Hensen et al. 2004]. Forty-year long development of BPS tools resulted in a wide range of currently available products [DOE 2009; Crawley 2005]. These products range (complexity-wise) from spreadsheet tools to more advanced special-purpose simulation tools, and (integration-wise) from tools that handle a single aspect of the building design, to tools that integrate multiple aspects of the building design [Hensen 2009].

Starting from the first generation of BPS tools based on simplified methods found in handbooks, the BPS tools have evolved into fully integrated tools. The number of currently available BPS tools and diversity of aspects taken into account in those tools and modelling approaches used by those tools makes writing a general overview of the field a difficult task. Thus, this paper is restricted to an overview of modelling and simulation developments in one of the more important subsystems in buildings: heating, ventilation and air-conditioning (HVAC) systems.

2. TOOLS FOR HVAC SYSTEM DESIGN AND ANALYSIS

Tools for HVAC design and analysis can be categorized with respect to the problems they are meant to deal with. Although these problems are not mutually exclusive, and some tools can handle several problems, they do tend to be investigated in isolation from each other. The categories are as follows [Trcka and Hensen 2010].

- **Tools for pipe/duct sizing** are system design tools that consider flow distribution and sizing of liquid/air distribution system (e.g. AFT Fathom, DOLPHIN, DUCTSIZE, Pipe-Flo, PYTHON).
- **Tools for equipment sizing and selection** offer automatic HVAC equipment sizing (e.g. Carrier HAP, Trane, TRACE 700, EnergyPlus).
- **Tools for energy performance analysis** are designed to predict the annual energy consumption of an HVAC system. Based on a system of equations that define thermal performance of buildings and systems, and with given boundary conditions, operation strategy and controls, these tools perform (hourly or sub-hourly) simulations (e.g. EnergyPlus, ESP-r, IDA ICE, TRNSYS, VA114, SIMBAD). These tools are typically used to calculate and analyze the full- and part-load performance, to analyze system operation strategy, to compare different design alternatives, etc. [e.g. Jokisalo et al. 2009, Stadler et al. 2006]
- **Tools for system optimization** are used in conjunction with tools for energy performance analysis. In multiple simulation runs, a set of parameters is optimized according to a given objective function. An example is the generic optimization tool GenOpt [Wetter 2001].
- **Tools for control analysis and control optimization**. The level of HVAC system control modelling and simulation in the available tools varies:
    - Controllers can be associated with high abstraction system models, such as in ESP-r.
    - Controllers can be represented explicitly either
        - as models of supervisory control, such as in EnergyPlus, or
        - as simple models of local control, such as in ESP-r and TRNSYS.
    - More advanced representation of controllers, such as fuzzy logic, are available in e.g. MATLAB based tools (SIMBAD), Dymola and tools coupled to MATLAB (ESP-r [Yahiaoui et al. 2003], TRNSYS [CSTB 2003]). These tools are efficient for design and more comprehensive testing of controllers in a simulation setting [Jreijiry et al. 2003], as well as for testing and validation of controller design in real time [Riederer 2005].
- **Simulation tools for real-time performance optimization.** Benefits of using simulation tools in the building operational stage are still insufficiently explored. Simulation tools could be used for:
    - Commissioning diagnostics (initial commissioning): i.e. to verify the performance of the whole building, its subsystems and components [IEA-ANNEX40 2004];
    - Monitoring diagnostics (continuous commissioning) and fault detection diagnostics: i.e. to detect, analyze, locate and/or predict problems with systems and equipment occurring during everyday operation [e.g. Hyvikinen 1996, Haves et al. 1998, 2001].
    - Emulating a building and its HVAC systems: i.e. simulating the response of a building and its HVAC systems to building energy management system (BEMS) commands. Emulators can also be used for control product development, training of BEMS operators, tuning of control equipment and imitating fault situations to see how the BEMS would cope [Clarke et al. 2002];
    - Simulation assisted control: i.e. to execute a simulation model (encapsulated within the BEMS) as part of the control task in order to evaluate several possible control scenarios and make a choice in terms of some relevant criteria [Clarke et al. 2002].

  The system simulation models that belong to this category are expected to predict system performance accurately. Thus, they need to be able to treat the departures from ideal behaviour that occur in real systems and to realistically model controls and HVAC system dynamics. The tools for energy performance analysis can be used as tools for real-time optimization of system performance [Zheng and Pan 2007], but models of a building and its systems need to be well calibrated [Reddy 2007a]. In general, well calibrated first-principle models can be used [Reddy 2007b], but simpler and precise empirical models can be used as well.

3. MODELLING APPROACHES

3.1. Modelling approaches for HVAC components

According to Zeigler [1976], the majority of models (some exceptions exist) in building and system performance simulation are continuous in state, discrete in time, deterministic, time varying, both steady state and dynamic. There exist both forward and backward models. The former are used to predict the response of output variables based on a known structure and known parameters when subjected to input and forcing variables. The latter tend to be much simpler but are relevant only for cases when system-specific and accurate models of specific building components are required, e.g. for fault detection and diagnosis [Hyvikinen 1996].

There is a distinction between primary and secondary HVAC system components. The former are sometimes referred to as plant, and the latter are referred to as system. A primary system converts fuel and electricity and delivers heating and cooling to a building through secondary systems. In both primary and secondary systems there are two types of components: distribution components and heat and mass balance components.

The distribution components models should satisfy energy and mass balance equations. Most of the simulation tools model distribution components in a simplified way [ASHRAE 2009], which eliminates the need to calculate the pressure drop through distribution system at off-design conditions. In general, this approach is sufficiently accurate for studying temperatures in the system. For detailed analysis of e.g. fan/pump control loops and for answering questions related to the placement of the return/exhaust fan, type and size of dampers/pipes, flow and pressure balancing between the components is necessary [Haves et al. 1998].

The above heat and mass transfer components of secondary systems are usually described by forward modelling using fundamental engineering principles. The components of primary systems, due to their complexity, are described by empirically obtained equations, i.e. by using regression analysis of design data published by a manufacturer, or by simply specifying look-up tables.

3.2. Modelling approaches for HVAC control

HVAC controllers can be divided into two categories: local controllers and supervisory controllers. The former are low level controllers that allow HVAC systems to operate properly and to provide adequate services and the latter are high level controllers that allow complete consideration of the system level characteristics and interactions among all components and their associated variables. From a modelling point of view, controllers are represented by equations that must be satisfied in every simulation step. The controllers direct the interaction between building and system as well as interactions between components within the system. In reality, the closed-loop local-process control includes a sensor that samples a real world (measurable) variable. The controller, based on the set point value and measured value, and according to the controller-specific control algorithm, calculates the control signal that feeds the real world actuator. However, in the simulation tool the user can address variables that can not be sensed or actuated in reality, as well as apply control algorithms that do not exist in reality. For example, a modeller can directly actuate the heat flux in a model where in reality this could only be done indirectly by changing a valve/damper position.

Furthermore, due to the accessibility of many variables not directly known in the real world, such as the zone cooling/heating load, in simulation the concept of 'ideal' (local process) control becomes feasible. An 'ideal' local process controller means that the actuated variable will be adjusted to satisfy the set point requirements for the controlled variable, without specifying the explicit control algorithm and by numerically inverting the (forward) simulation models (from the required output calculate the input needed to satisfy this).

Possibilities to simulate different (advanced) controllers in state-of-the-art BPS tools are limited. Some tools offer predefined control strategies, some offer flexibility in specifying only supervisory controllers (EnergyPlus) and some even in specifying local controllers (TRNSYS, ESP-r). The domain-independent environments, such as MATLAB and Dymola, are efficient tools for designing and testing of controllers in a simulation setting, but lack the models of all other physical phenomena in buildings.

3.3. Modelling approaches for HVAC systems

Hensen [1996] defines four categories of HVAC system representation in BPS tools, ranging from purely conceptual towards more explicit. Pure conceptual system modelling approach represents the case where only room processes are considered, while all other processes in primary and secondary systems are idealized, with a possibility to impose a capacity limitation upon them. An example application is to use the predicted room cooling/heating peak loads to determine the required HVAC system size. Most state-of-the-art BPS tools can be used to model systems using this approach.

System-based modelling approach represents the case with preconfigured common system types, such as variable air volume system and constant-volume variable-temperature system. The user has flexibility in specifying capacities, system flow rates, efficiencies and off-design system component characteristics, but is restricted to the system configurations and control strategies that are predefined in the tool. This modelling approach is implemented in e.g. DOE-2, eQUEST, and DesignBuilder.

Component-based system modelling approach represents the case where a system is specified by (a) network(s) of interconnected component models. This approach is more flexible in terms of possible system configurations and control strategies compared to the previous approach.

Component-based multi-domain system modelling approach represents the case where component representation is further partitioned into multiple interrelated balance concepts, e.g. fluid flow, heat and electrical power balance concepts. Each balance concept is then solved simultaneously for the whole system.

As an addition to the above four categories defined by Hensen [1996], Trcka and Hensen [2010] lists a fifth category: the equation-based system modelling approach. This modelling approach represents the case where a system is represented by a basic modelling unit that is physically 'smaller' than a component and that is in the form of an equation or a low-level physical process model. It has evolved from the need to improve the BPS tools that had been based on technology available in the early seventies [Sahlin et al. 2003]. Examples of equation-based tools are: SPARK (Simulation Problem Analysis and Research Kernel) [LBNL 2003], NMF (Neutral model format), IDA [Sahlin 2004], and Modelica [Tiller 2001].

3.4. Solution techniques for HVAC system simulation models

The differences in solution techniques employed by different simulation tools are based on the distinction in the way the integrator is employed [Hillestad and Hertzberg 1988].

- **Simultaneous modular solution**, where the various components are integrated simultaneously by a common integrator. In general, the tools that employ this solution technique use model equations that are based on first principles [Hillestad and Hertzberg 1988].
- **Independent modular solution**, where each module is provided with individual integrator routines. The component's modules encapsulate all information relevant to the component's simulation model setting and execution. In general, the tools that employ this solution technique use model equations that can be based on first principles but can also be empirical input/output correlations [Hillestad and Hertzberg 1988]. Each component is executed sequentially and the system solver iterates until a convergent solution has been found.
- **Equation-based solution using formula manipulation**, which has emerged in recent years with the developments of equation-based tools. Models composed with these tools cannot be executed directly. To be executed, a model needs to be transferred into a programming language that can be compiled [Sowell and Haves 1999].

4. INTEGRATION OF BUILDING AND HVAC SYSTEM MODELS

The integration of building and HVAC system models is accomplished at different levels. The models can be (i) sequentially coupled (e.g. BLAST, DOE-2) – without system model feedback to the building model or (ii) fully integrated (e.g. ESP-r, EnergyPlus, IDA ICE, TRNSYS) - allowing the system deficiencies to be taken into account when calculating the building thermal conditions. Levels of detail of both building and system models can vary from simple (e.g. the bin method and pure conceptual representation for system model) to complex (numerical model of physical processes).

5. ISSUES IN MODELLING AND SIMULATION OF HVAC SYSTEMS

Even though the available tools for HVAC system design and analysis cover a wide range of design and operational problems, there is still an enormous amount of work to be done in this area. Some requirements for further research and development are:

- Buildings are complex systems of which the real performance usually deviates from the performance predicted in the design stage. Recent studies, e.g. [Elkhuizen and Rooijakkers 2008], show that the difference between the predicted and real energy consumption can be up to 40%. For crude analysis, including the relative comparison of the design alternatives, this may not be a problem. However, to be able to correctly base design decisions on predictions, there is a need to understand where the above discrepancies come from and to include the uncertainties in the system model.
- Although some design problems immediately exclude the use of some tools, the user is still free to choose between a large numbers of available tools for a particular case. So far, there is no comprehensive guideline on how to make this choice relative to the required accuracy of the predictions based on the model.

- Simulation tools have been seen as promising tools for establishing the baseline performance prediction which can be used during building operation to monitor the performance and/or to detect and identify abnormalities in the system behaviour. However, the research is still in its early phases.
- The capability of most of the tools is limited to a set of predefined system configurations. To successfully continue the development of BPS tools the focus should be on supporting flexible modelling environments that allow analyzing building systems which are not yet covered in current BPS tools.

In the following section we continue by presenting co-simulation as a promising approach to alleviate at least the last barrier from the above list.

6. CO-SIMULATION

To successfully continue the development of the BPS tools that accelerates innovation of building technologies that help in mitigating climate change, a focus should be on supporting a flexible modelling environment that allows analyzing building systems that have not yet been implemented by the program developers. A way forward would be to provide a facility to combine features from different tools, sharing developments and reusing component models. A tool should be coupled with a complementary tool in such a way that the integrated result provides more value to the end user than the individual tool does itself. This can be achieved by integration of physical process models by linking applications at run-time. The strategy is known as process model cooperation [Hensen et al. 2004], external coupling [Djunaedy 2005], or co-simulation [Wetter and Haves 2008; Trcka 2008]. Co-simulation is a case of simulation scenario where at least two simulation tools solve coupled differential-algebraic systems of equations and exchange data during the time integration in order to couple these equations. In general, compared to the traditional, monolithic approach, co-simulation has several advantages:

- It facilitates reuse of state of the art BPS tools by taking advantages of existing models;
- It allows combining heterogeneous solvers and modelling environments of specialized tools;
- It enables fast model prototyping of new technologies;
- It facilitates collaborative model design and development process;
- It makes immediate access to new model developments;
- It permits information hiding, i.e., use of proprietary tools.

However, these flexibilities can pose numerical challenges, and to scale the use of co-simulation to a large community of building designers requires more research and development. Co-simulation has been successfully applied in different fields, such as aerospace and automotive [ADI 2010], high performance computing, defence and internet gaming [Fujimoto 2003], chemistry [Hillestad and Hertzberg 1988] and aerodynamics, structural mechanics, heat transfer and combustion [Follen et al. 2001; Sang et al. 2002].

In the field of BPS, considerable effort has been made in integrating coupled physical phenomena into the individual BPS tools (e.g., ESP-r, EnergyPlus, IES VE, IDA ICE, TRNSYS). Some of the integrated BPS tools integrate process models by converting models available in other tools into their own subroutines. Examples of such integrations are the coupling between ESP-r and TRNSYS [Hensen 1991; Wang and Beausoleil-Morrison 2009], COMIS and EnergyPlus [Huang et al. 1999], COMIS and TRNSYS [McDowell et al. 2003], EnergyPlus and MIT-CFD [Zhai 2003], EnergyPlus and Delight [Carroll and Hitchcock 2005], and EnergyPlus and SPARK [LBNL 2003].

However, only a limited amount of work has been done in process model co-operation (co-simulation). Examples of such integration include the integration of high-resolution light simulation (Radiance) with building energy simulation (ESP-r) [Janak 1999], the integration of computational fluid dynamics simulation (FLUENT) with building energy simulation (ESP-r) [Djunaedy 2005], which was extended to include moisture by Mirsadeghi et al. [2009], and the integration of heat air and moisture envelope simulation with building energy simulation (ESP-r) [Costola et al. 2009]. In the domain of HVAC simulation tools examples include integration of TRNSYS with several other programs, such as MATLAB [CSTB 2003] and EES [Keilholz 2002]. The recent work [Trcka et al. 2010] illustrates more comprehensive co-simulation framework which has been proven to be stable, consistent and thus convergent. The framework has been implemented using EnergPylus and TRNSYS. Similar architecture has been implemented in the Building Controls Virtual Test Bed (BCVTB) [Wetter and Haves 2008].

The co-simulation strategy in comparison with other strategies that enable sharing of developments and reusing existing component models [Hensen et al. 2004] is presented in Figure 1. The coupled models are independently created and the results are analyzed separately, while the simulators are coupled at run-time, exchanging data in a predefined manner. In comparison to process model interoperation, co-simulation enables immediate use of the component models developed in different tools (providing that the tools are open for communication). Once developed and implemented the general co-simulation interface between the simulators can be used without any code adaptation, which is necessary in any other tool integration strategy. Using co-simulation for BPS can be beneficial since:

- There is no single tool that can be used to solve all simulation analysis problems encountered by designers.
- Each tool can benefit from future simulation model developments of emerging technologies as soon as they become available.
- Rapid prototyping of new technologies, which is difficult in the state of the art domain tools, could be done using an equation-based simulation tool. When used in co-operation with whole building energy analysis programs, it would assure the integrated approach to building and systems simulation.
- Multi-scale modelling and simulation can be done by combining various building and system models, developed by different parties, to simulate scenarios on the scale of a town or even regions.

7. IN CONCLUSION

This paper presents an overview of available tools for HVAC system design and analysis, modelling approaches and simulation techniques. The numerous available tools range from simple spreadsheet tools to more advanced simulation tools. Even though they cover a wide range of design and operational problems, there is still an enormous amount of work to be done in this area. We identified some requirements for further research and development and presented co-simulation as one approach that ca alleviate some of the recognized issues. A benefit of a co-simulation environment is that domain-specific tools can be coupled for an integrated simulation while preserving their individual features. It therefore enables the following:

1. Use of disparate tools that support individual domains. For example, the EnergyPlus building model may be used as it allows modelling daylight availability in rooms, while TRNSYS may be used as it allows a graphical, flexible modelling of the mechanical system;
2. Development of control algorithms in tools like MATLAB/Simulink or LabVIEW, which provide toolboxes for designing controllers, as well as code generation capabilities to translate a simulation model to C code that can be uploaded to control hardware;
3. Development of control algorithms in tools that allow a richer semantics for expressing models compared to what can be found in typical building simulation programs. For example, the complexity of large control systems can be managed using a hierarchical composition in which finite state machines define the states and their transition at the supervisory control level, and each state may have a refinement that defines how set points are tracked within the active state Lee and Varaiya [2002]. Tools that allow such formulations include MATLAB/Simulink, LabVIEW and Ptolemy II [Brooks et al. 2007].

While technically not belonging to co-simulation, a co-simulation framework also allows replacing one of the simulators with an interface to control systems, thereby enabling the use of hardware in the loop in which controls may be realized in actual hardware while the building system is emulated in simulation.

8. REFERENCES

ADI 2010, Applied Dynamics International, Available at: http://www.adi.com [Accessed: December, 2010].

ASHRAE 1008 *ASHRAE 2020 Vision, Position, Strategies, Actions*, Technical report, The American Society of Heating, Refrigerating and Air-Conditioning Engineers Available at: http://www.ashrae.org [Accessed: April, 2008].

ASHRAE 2009, *ASHRAE Handbook, Fundamentals,* American society for heating, refrigerating and air-conditioning engineers.

Brooks, C., et al. 2007, *Ptolemy II: Heterogeneous Concurrent Modelling and Design in Java.* Technical report No. UCB/EECS-2007-7, University of California at Berkeley, Berkeley, CA.

Carroll, W.L. and Hitchcock, R.J. 2005, DELIGHT2 daylighting analysis in EnergyPlus: Integration and preliminary user results. *Proceedings of 9th International IBPSA Conference* Montreal, Canada: International Building Performance Simulation Association.

Clarke J.A., Cockroft J., Conner S., Hand J. W., Kelly N. J., Moore R., O'Brien T., Strachan P. 2002, Simulation-assisted control in building energy management systems, *Energy and buildings* 34, 933-940.

Crawley D. B., Hand J. W., Kummert M., Griffith B. T. 2005, Contrasting the capabilities of building energy performance simulation programs, *Proceedings of 9th International IBPSA Conference*, International Building Performance Simulation Association, Montréal, Canada, 2005, 231-238.

Costola, D., Blocken, B., Hensen, J.L.M. 2009, External coupling between BES and HAM programs for whole-building simulation, *Proceedings of the 11th IBPSA Building Simulation Conference*, 27-30 July, International Building Performance Simulation Association, Glasgow, 316-323.

CSTB 2003, Type 155 - A new TRNSYS type for coupling TRNSYS and Matlab, online presentation available at: http://software.cstb.fr/articles/18.ppt [Accessed: December, 2003].

Djunaedy, E., 2005. E*xternal coupling between building energy simulation and computational fluid dynamics*. Thesis (PhD). Technische Universiteit Eindhoven.

DOE 2009, Building energy software tools directory, U.S. Department of energy, Available at: http://www.eere.energy.gov/ [Accessed: August, 2009].

Elkhuizen B., Rooijakkers E. 2008, Visie op ontwikkelingen gebouwbeheersystemen, Verwarming Ventilatie Plus 336-339.

Follen, G., et al., 2001. A CORBA-based development environment for wrapping and coupling legacy scientific codes. *Proceedings of 10th IEEE International Symposium on High Performance Distributed Computing* San Francisco, CA, USA: The Institute of Electrical and Electronics Engineers (IEEE), 22-31.

Fujimoto, R.M., 2003. Distributed simulation systems. *Proceedings of 2003 Winter simulation conference* New Orleans, Louisiana, USA: The Institute of Electrical and Electronics Engineers (IEEE).

Haves P., Salsbury T., Claridge C., Liu M. 2001, Use of whole building simulation in on-line performance assessment: Modelling and implementation issues, *Proceedings of 7th International IBPSA Conference,* International Building Performance Simulation Association, Rio de Jeneiro, Brazil, 335-342.

Haves P., Norford L. K., DeSimone M. 1998, A standard simulation test bed for evaluation of control algorithms and strategies, *ASHRAE transactions* 104 (1).

Hensen, J.L.M. 1991, *On the thermal interaction of building structure and heating and ventilating system.* Thesis (PhD). Eindhoven University of Technology.

Hensen J.L.M. 1996, Application of modelling and simulation to HVAC systems, *Proceedings of 30th Int. Conf. MOSIS '96*, Krnov, Technical University of Ostrava, CZ.

Hensen, J.L.M., Djunaedy, E., Radosevic, M., and Yahiaoui, A., 2004. Building performance simulation for better design: Some issues and solutions. *Proceedings of 21st Conference on Passive and Low Energy Architecture*, Technische Universiteit Eindhoven, The Netherlands.

Hensen J.L.M. 2011. Simulation tools for energy e-cient building design, Available at: http://www.bwk.tue.nl/bps/hensen/courseware [Accessed: August, 2011].

Huang, J., et al. 1999. Linking the COMIS multi-zone air°ow model with the EnergyPlus Building Energy Simulation Program. *Proceedings of 6th International IBPSA Conference* Kyoto, Japan: International Building Performance Simulation Association.

Hillestad M., Hertzberg T. 1988, Convergence and stability of the sequential modular approach to dynamic process simulation, *Computers & Chemical Engineering* 12 (5): 407-414.

Hyvikinen J. 1996, *Real time simulation of HVAC systems for building optimization, in: Fault detection and diagnosis technical papers of IEA Annex 25*, Finland, Technical Research Centre of Finland, VTT Building Technology.

IEA-ANNEX40, 2004, *Commissioning tools for improved energy performance*, Tech. rep., Program of the International Energy Agency, Available at: http://www.commissioning-HVAC.org [Accessed: August, 2005]

Janak, M. 1999, Coupling building energy and lighting simulation. *Proceedings of 5th International IBPSA Conference*, Vol. 2 Kyoto, Japan: International Building Performance Simulation Association, 307-312.

Jokisalo J., Kurnitski J., Korpi M., Kalamees T., Vinha J. 2009, Building leakage, infiltration and energy performance analyses for Finnish detached houses, *Building and environment* 44 (2): 377-387.

Jreijiry D., Husaunndee A., Inard C., Villenave J. G. 2003, Control of ventilation in buildings using simbad building and HVAC toolbox, *Proceedings of 8th International IBPSA Conference*, International Building Performance Simulation Association, Eindhoven, The Netherlands, 661-667.

LBNL 2003, *SPARK 2.0 Reference manual simulation problem analysis and research kernel*, Tech. rep., Lawrence Berkeley National Laboratory.

Lee, E.A. and Varaiya, P.P. 2002, *Structure and Interpretation of Signals and Systems*. Addison Wesley.

Keilholz, W., 2002. TRNSYS World-wide. The journal of the international building performance simulation association, *ibpsaNEWS*, 12 (1).

c, T.P., Emmerich, S., Thornton, J.W., and Walton, G., 2003. Integration of Airflow and Energy Simulation Using CONTAM and TRNSYS. *ASHRAE Transactions, 109 (1).*

Mirsadeghi, M., Blocken, B., Hensen, J.L.M. 2009, Application of externally-coupled BES-CFD in HAM engineering of the indoor environment, *Proceedings of the 11th IBPSA Building Simulation Conference*, 27-30 July, International Building Performance Simulation Association, Glasgow, 324-331.

Reddy T., Maor I., Panjapornpon C., 2007, Calibrating detailed building energy simulation programs with measured data - part ii: General methodology (RP-1051), *AHVAC&R research journal 13 (2)*: 221-241.

Reddy T., Maor I., Panjapornpon C., 2007, Calibrating detailed building energy simulation programs with measured data - Part II: Application to three case study office buildings (RP-1051), AHVAC&R research journal 13 (2): 243-265.

Riederer P. 2005, Matlab/Simulink for building and HVAC simulation- State of the art, *Proceedings of 9th International IBPSA Conference,* International Building Performance Simulation Association, Montréal, Canada, 2005, 1019-1026.

Sang, J.C., Follen, G., Kim, C., and Lopez, I., 2002. Development of CORBA-based engineering applications from legacy Fortran programs. Information and Software Technology, 44 (3): 175-184.

Sahlin P., Eriksson L, Grozman P., Johnsson H., Shapovalov A., Vuolle M. 2003, Will equation-based building simulation make it? - Experiences from the introduction of IDA indoor climate and energy, in: Proceedings of 8th International IBPSA Conference, International Building Performance Simulation Association, Eindhoven, The Netherlands, 1147-1154.

Sahlin P., Eriksson L., Grozman P., Johnsson H., Shapovalov A., Vuolle M. 2003, Whole-building simulation with symbolic DAE equations and general purpose solvers, *Building and Environment* 39: 949-958.

Stadler M., Firestone R., Curtil D., Marnay C. 2006, On-site generation simulation with energyplus for commercial buildings, in: *ACEEE Summer Study on Energy Efficiency in Buildings*, PANEL 3 - Commercial Buildings: Technologies, Design, Performance Analysis, & Industrial Trends, Pacific Grove, California.

Tiller M. M. 2001, *Introduction to Physical Modelling with Modelica*, Norwel, Mass.: Kluwer Academic Publisher.

Sowell E. F., Haves P. 1999, Numerical performance of the SPARK graphtheoretic simulation program, *Proceedings of 6th International IBPSA Conference*, International Building Performance Simulation Association, Kyoto, Japan.

Trcka, M. 2008, *Co-simulation for Performance Prediction of Innovative Integrated Mechanical Energy Systems in Buildings*. Thesis (PhD). Eindhoven University of Technology, Eindhoven, The Netherlands.

Trcka, M., Hensen, J.L.M., Wetter, M. 2010, Co-simulation for performance prediction of integrated building and HVAC systems - An analysis of solution characteristics using a two-body system. *Simulation Practice and Theory*, 18(7): 957-970.

Trcka, M., Hensen, J.L.M. 2010, Overview of HVAC system simulation. Automation in Construction, 19(2), 93-99.

Wang, W. and Beausoleil-Morrison, I. 2009, Integrated simulation through the source-code coupling of component models from a modular simulation environment into a comprehensive building performance simulation tool. *Journal of Building Performance Simulation,* 2(2): 115 – 126.

Wetter M. 2001, GenOpt - A generic optimization program, *Proceedings of 7th International IBPSA Conference*, International Building Performance Simulation Association, Rio de Jeneiro, Brazil, 601-608.

Wetter, M. and Haves, P., 2008. A modular building controls virtual test bed for the integration of heterogeneous systems. *Proceedings of SimBuild, 3rd National Conference of IBPSA-USA* Bekeley, CA, USA: International Building Performance Simulation Association, USA chapter.

Yahiaoui A., Hensen J. L. M., Soethout L. 2003, Integration of control and building performance simulation software by run-time coupling, *Proceedings of 8th International IBPSA Conference*, International Building Performance Simulation Association, Eindhoven, The Netherlands, 1435-1442.

Zeigler B.P., *Theory of modelling and simulation*, John Wiley & Sons, Canada, 1976.

Zhai, Z. 2003. *Developing an Integrated Building Design Tool by Coupling Building Energy Simulation and Computational Fluid Dynamics Programs*. Thesis (PhD). Massachusetts Institute of Technology, USA.

Zheng M., Pan S. 2007, *Application of various hvac simulation programs and visual tools to commissioning,* Tech. rep., Texas A&M University, Available at: http://hdl.handle.net/1969. 1/6212 [Accessed: June, 2009].