BOOK OF ABSTRACTS

13th INTERNATIONAL MODELICA CONFERENCE

March 4–6, 2019
Ostbayerische Technische Hochschule Regensburg, Germany

Editor: Prof. Anton Haumer

OSTBAYERISCHE TECHNISCHE HOCHSCHULE REGENSBURG

MODELICA

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PREFACE

The Modelica Conference is the main event for users, library developers, tool vendors and language designers to share their knowledge and learn about the latest scientific and industrial progress related to Modelica and to the Functional Mockup Interface.

Since the start of the collaborative design work for Modelica in 1996, Modelica has matured from an idea among a small number of dedicated enthusiasts to a widely accepted standard language for the modeling and simulation of cyber-physical systems. In addition, the standardization of the language by the non-profit organization Modelica Association enables Modelica models to be portable between a growing number of tools. Modelica is now used in many industries including automotive, energy and process, aerospace, and industrial equipment. Modelica is the language of choice for model-based systems engineering.

Highlights of the Conference:

- 76 oral presentations and 13 poster presentations, 4 libraries for the Modelica Library Award
- 2 Keynotes
- 7 Tutorials and 2 Industrial User Presentations Sessions
- 14 Vendor Sessions and 17 Sponsors & Exhibitors

Welcome

I warmly welcome you to Regensburg, a city with history going back to Roman times, and to OTH the Technical University of Applied Sciences Regensburg.

Starting with this conference, you will notice some changes:

First, we are going to organize the International Modelica Conference every two years in spring. In the years between International Modelica Conferences, Modelica Conferences are organized on other continents with country specific focus.

Although in 2018 there have been two very successful conferences in Japan and in the United States, we received 101 submissions from authors all over the world which have been thoroughly reviewed.

Second, additional to the tutorials and vendor presentations on the first day of the conference, we are going to have Industrial User Presentations related to the Modelica Association Projects. These presentations are not included in the proceedings, but they should provide a nucleus for discussions and broadening the users groups.

I want to thank the members of the Program Committee for their work during the review process, as well as the members of the Organizing Committee – without their support this conference wouldn't have been a success.

Prof. Anton Haumer
OTH Regensburg
Conference Chair

Modelica News

In the name of the Modelica Association that is co-organizing this event, I also would like to welcome you in

Regensburg. It is now already the 13th conference on Modelica, the Functional Mockup Interface and related technology. Since the number of projects and standards of the Modelica Association is growing, we would like to give you an overview about the current status in the traditional "Modelica Association News" section on Tuesday morning: All the Modelica Association Project leaders will give a short overview about their project and about their future plans.

Prof. Dr. Martin Otter
DRL, Wessling, Germany
Chair of Modelica Association

Keynote: Modelica and virtual education

Dr. Christian Kral
TGM, Vienna, Austria

Good education of engineering students requires theoretical knoweldge and lots of calculation experience to better understand theory and applications. Laboratory courses are offered to better relate theory and practical understanding. Simulations even more improve the linking of theory and practice, as systemic thinking is supported. Students learn to understand the interaction of simple models and more advanced systems.

In the keynote speech two virtual education scenarios in engineering will be presented: First, a workflow of creating and evaluating calculation and simulation examples is proposed. The workflow is based on Modelica and the online tool Letto. Second, virtual lab experiments of electric machines and drives are shown. In the virtual lab Modelica variables are controlled and viszualized by Labview. The presented approaches are possible steps in the direction of virtual education to improve and strengthen the students' expertise and knowledge and with the particular intention to motivate students.

Bio: Christian Kral received the diploma and doctoral degrees from the Vienna University of Technology, Vienna, Austria, in 1997 and 1999, respectively. From 1997 to 2000, he was a Scientific Assistant in the Institute of Electrical Drives and Machines, Vienna University of Technology. Since 2001, he has been with the AIT Austrian Institute of Technology GmbH (the former Arsenal Research) in Vienna. From January 2002 until April 2003, he was a Visiting Professor at the Georgia Institute of Technology, Atlanta. Dr. Kral is teaching electric machines and drives at the higher college of engineering »TGM« in Vienna and the university of applied research, »Technikum Wien« since 2013. His research interests include the modeling and simulation of electrical systems, machines and drives. He is a member of the Austrian Electrotechnical Association (OVE) and the Modelica Association. Dr. Kral published over 150 scientific papers and one book on Modelica and the object oriented modeling of electric machines.

Keynote: Simulation Guided Design for New Automotive Applications

Dr. Gerd Rösel
Continental, Regensburg, Germany

The Automotive Industry has to cope with disruptive technology and business changes within the next decade. Connected vehicles become reality and drive the development to automated driving. New mobility solutions will have to answer shared economy demands. The regulatory requirement on significant reduction of CO2- and pollutant emission leads to fast changing parallel development of additional propulsion systems in the same period. Consequently, the variety of solutions within a vehicle will have to serve a furthermore increasing complexity from embedded-systems to system-of-systems to cyber-physical-systems.

Simulation guided design is the key to handle such complexity in all areas of application for an automotive supplier to keep quality, time to market and costs under control. The speech covers the main directions of disruptive technology changes and examples of dedicated solutions. There will be examples given which cover virtual function development for embedded systems as well as solutions for predictive maintenance and connected energy management as system-of-systems. The focus will be to point out the necessity to design and optimize such systems by simulation.

Bio: Dr. Gerd Rösel is heading the departments Advanced System Engineering for Engine Systems (since 2015) as well as Hybrid Electric Vehicle Business Unit (since 2018) for Continental Powertrain. The application and further development of simulation methodologies is a significant building block in these responsibilities. The variety in simulation technology covers propulsion system simulation as well as specialized simulation in areas like electric machines, mixture formation and NVH.

From 1996 until 2015 he has been responsible in different positions for Gasoline- and Diesel-System-Development for serial and advanced applications. From 1992 to 1997 he was a research associate at Technical University of Dresden and finished with the graduation of Dr.-Ing. in 1997. The Diploma degree in electrical engineering from Technical University of Dresden was achieved in 1992.

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A virtual test-bed for building Model Predictive Control developments

Raymond Sterling[1], Jesús Febres[2], Andrea Costa[3], Adeleh Mohammadi[1], Rafael E. Carrillo[4], Baptiste Schubnel[4], Yves Stauffer[4], Pietro De Cinque[3], Krzysztof Klobut[5], Marcus M. Keane[1]

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INDIGO[1] is a Horizon 2020 EU-funded project carried out by six partners from across Europe that aims to realise more efficient and economic planning, control and management of existing District Cooling (DC) networks. This will be achieved through two specific objectives. The first one is to widen the use of DC systems and motivate the competitiveness of European DC market by the development open-source tools for planning and modelling DC systems (del Hoyo Arce *et al.*, 2018). The second objective is to reduce primary energy consumption via improved DC system management strategies aimed at system efficiency maximisation and cost minimisation.

In this paper we present the results of the work performed to improve the energy consumption of the DC systems across several tasks of the project. This includes modelling and simulation of various buildings and the development and implementation of Model Predictive Controls (MPC) to reduce energy use in buildings.

Modelling and simulation within this paper is presented for the Building models. The geometry, materials, weather, air infiltration and internal gains of the models are developed in EnergyPlus and the model of the energy systems, focusing on the air distribution system while air handling units are built in Modelica.

The aim of the modelling was two-fold. To provide an accurate and validated test-bed for testing the behaviour of the MPC and, at the same time, generate the synthetic data used for the initial development of said controllers.

Model integration across different platforms is performed via Functional Mock-up Interfaces and this article presents the full workflow on the implementation from initial building model development to the generation of results from the MPC.

[1] www.indigo-project.eu

Characterization of Linear Reduced Order Building Models Using Bode Plots

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Simulations of energy supply systems on the urban scale call for dedicated thermal building models with low simulation times and still considering relevant dynamic effects. A common approach for such models are reduced order thermal networks that model heat transfer and storage via thermal resistances and capacitances. To contribute to the open question, how much wall elements should be used in such approaches, this paper characterizes and compares four different model topologies with one, two, three and four wall elements. The characterization using the Linear Analysis toolbox in Modelica and Bode plots in Python reveals a significantly different behavior of the One-Element-Model compared to the higher order models. In consequence, the Two-Elements-Model with comparably low simulation times and a similar behavior as the higher order models qualifies for urban scale simulations.

Reduced order models account for relatively small simulation times by using a small number of state variables, in the case of thermal networks associated solely to thermal capacitances. In this way, they qualify for urban scale simulations, where uncertainties due to unknown boundary conditions and estimated parameters outweigh modeling accuracy. Still, this leads to the question, what the optimal number of capacitances is for the case of urban scale simulations.

To contribute to this question, this paper investigates four different model topologies by lumping either all walls to one element (as for DIN EN ISO 13790), distinguish between external and internal walls (as for VDI 6007-1, Figure 1), further divide between walls exposed to solar radiation and floor plates and finally separate the roof elements as well. The merging or separation of the building elements leads to four different models with the open question, which model considers all dominant dynamics while neglecting all others to have as small simulation times as possible. For this purpose, all four models need to be characterized, e.g. by using Bode plots (Figure 2).

The results show that the behavior of the One-Element-Model significantly differs from the higher order models, for the magnitude as well as the phase shift, when observing the indoor air temperature while exciting outdoor air temperature or internal gains. This originates in neglecting internal masses, what leads to a significantly different transfer function.The Two-, Three- and Four-Elements-Model show slight differences in the Bode plots, what requires further analyses in the time domain. The simulation of one year reveals maximal differences in the free-floating indoor air temperature between Two- and Four-Elements-Model of 0.4 K.

Based on these results, the Two-Elements-Model qualifies for urban scale simulations with low simulation times while keeping a similar behavior compared to higher order models. As the differences partly depend on the insulation and thermal mass level, further research should result in an adaptive method to automatically choose a reduced order modelling approach based on these properties.

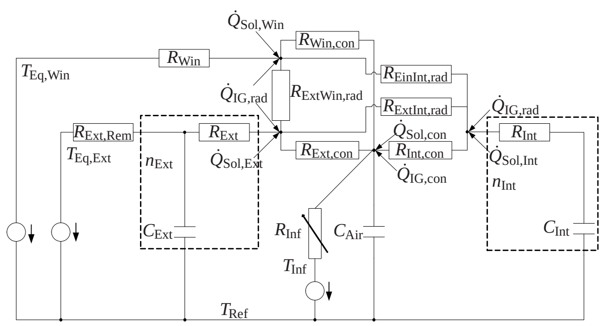

Figure 1. Thermal network of the Two-Elements-Model from `AixLib`.

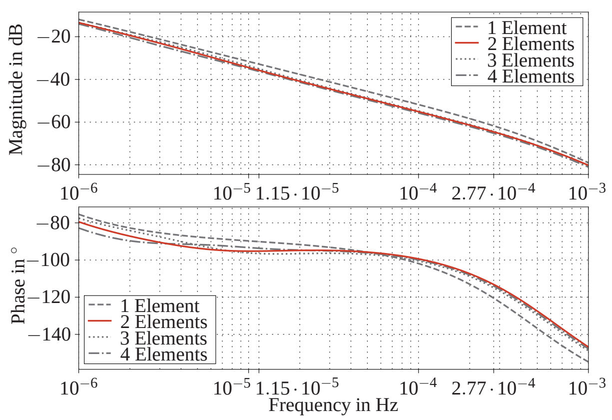

Figure 2. Bode plot for external excitation with heavy-weight setup (EnEV 2009) and indoor temperature as observed output.

BIM2Modelica – An open source toolchain for generating and simulating thermal multi-zone building models by using structured data from BIM models

Christoph Nytsch-Geusen[1] Jörg Rädler[1] Matthis Thorade[2] Carles Ribas Tugores[3]

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This contribution describes an open source toolchain which can transfer BIM models of 3D building constructions from CAAD programs into executable thermal multi-zone buildings models based on Modelica building energy simulation libraries. For this purpose, different open source libraries and tools were integrated into a Python-based software architecture of the toolchain: the IfcOpenShell/OCC libraries as the foundation for the import, analysis, and preparation of the BIM models; CoTeTo as the tool for the template-based code generation of the Modelica building models; the BuildingSystems library as the base for the thermal multi-zone building models; and JModelica as the simulation tool to perform the simulation analyses.

While the first part of the paper describes the general approach and the software architecture of the toolchain, the second part illustrates its application with an example of a real building.

Toolchain

The BIM2Modelica toolchain from the IFC file up to the generated Modelica model includes three serial working Python modules: A module for the BIM data import and analysis, a building data model for storing the analyzed and prepared information for building energy simulation and the CoTeTo tool for generating thermal multi-zone building models based on the BuildingSystems library (http://www.modelica-buildingsystems.de).

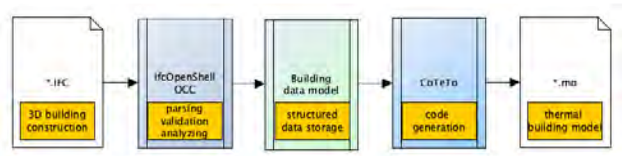

Figure 1. BIM2Modelica software architecture.

Simulation experiment with JModelica

After the multi-zone building model code was generated with CoTeTo, a simulation experiment could be performed with a Modelica tool. Because the objective of the development of the toolchain was a pure open source solution, JModelica was used for this purpose.

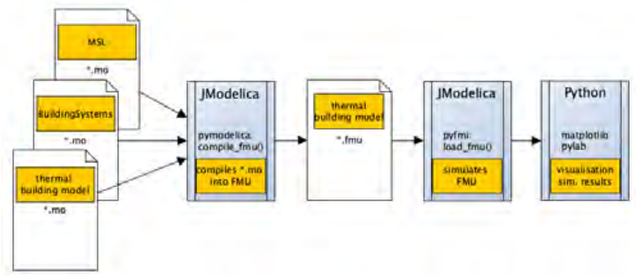

Figure 2. Simulation of building models with JModelica.

Case study

The approach of the toolchain was evaluated with a small residential living unit, the Rooftop building.

Figure 3. BIM model of the Rooftop building.

The generated Modelica model of the Rooftop building was simulated with JModelica for a period of four hot summer days for the location Berlin. In Figure 10, the outside air temperature and the free-floating air temperatures of the four thermal zones are illustrated.

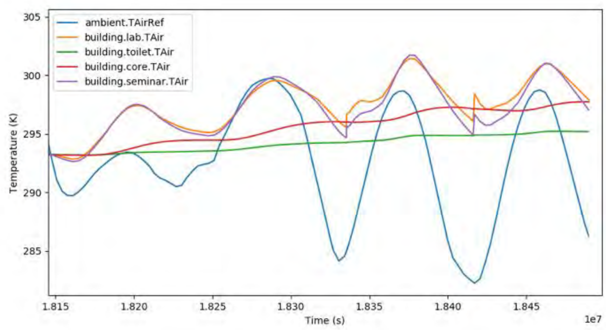

Figure 4. Simulated indoor climate of the Rooftop building during four warm summer days (location Berlin).

Open Source PhotoVoltaics Library for Systemic Investigations

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For the planning of photovoltaic power plants standard software tools are used. Most of these software tools use statistical solar data to determine the overall energy harvest of a photovoltaic plant over one year. The calculations rely on stationary location and ideal boundary conditions, e.g., constant ambient temperature. Even though, for example, shadowing may be considered by standard software, the investigation of untypical configurations and problems cannot be performed by such software, as most configurations cannot be changed by the user.

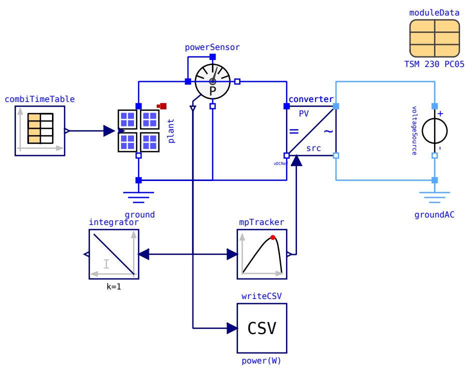
The presented `PhotoVoltaics` library was developed with the intention to provide a flexible framework for standard and non-standard problems. Particularly, the `PhotoVoltaics` library can be coupled with other Modelica libraries to perform systemic investigations.

An application library, `PhotoVoltaics_TGM`, is provided as add-on, where measured data of two photovoltaic pants of the TGM in Vienna can be compared with simulation results. This add-on library serves as validation of the `PhotoVoltaics` library.

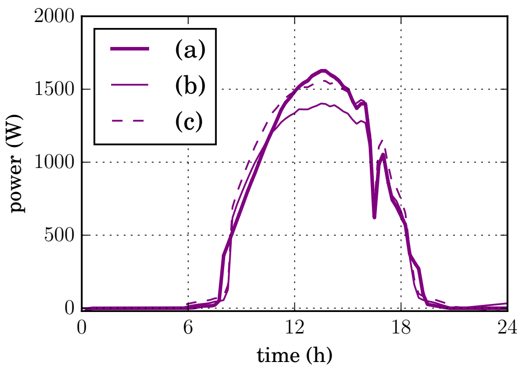
In the `PhotoVoltaics` library the following components are included:

- Photovoltaic (PV) components (cells, modules and plants)
- Converters (DC/DC, quasi static single and three phase, transient three phase)
- Diodes
- Analytic irradiance models (terrestrial, arbitrary sun location)
- Records of selected industrial module data sheets

Typical applications of the PhotoVoltaics library are systemic investigations which include photovoltaics. Since all photovoltaic components are equipped with a thermal heat port, the influence of temperature on the operational behavior may be investigated. Particularly, the library is capable of investigating of the total energy consumption and generation of alternative building concepts including interaction with the power grid.



Simulation model PV plant at TGM in Vienna



(a) simulated DC power, (b) measured AC power and (c) measured DC power of PV plant

The `PhotoVoltaics` library was developed during a Diploma project at the College of Engineering, TGM. The library is available at https://github.com/christiankral/PhotoVoltaics.

Python-Modelica Framework for Automated Simulation and Optimization

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Modeling and simulation are essential for the development of complex engineering systems, such as wind turbines. Thus, Fraunhofer IWES has developed the MoWiT (Modelica for Wind Turbines) library for fully-coupled aero-hydro-servo-elastic simulations of wind turbine systems. To meet the needs for detailed assessment and design development of such sophisticated systems, which imply iterative steps for design optimization, a Python-Modelica framework is set up. By means of this, the simulation of MoWiT models can easily be managed, including redefinition of model parameters, specification of output sensors and simulation settings, integration of optimization algorithms, post-processing of simulation results, as well as parallel execution of several simulations. The application of this Python-Modelica framework is shown based on the example of a design optimization task of a floating wind turbine support structure.

The framework for automated simulation of wind turbine models requires a modeling environment (the MoWiT library); a tool for executing the time-domain simulations (Dymola); and a programming interface (Python) for external and automated control of the simulations. Figure 1 schematically represents the simulation framework and the working levels in Python.

This Python-Modelica framework for automated simulations serves as basis for further applications, such as the realization of optimizations. The pre-processed wind turbine system model, as well as definitions regarding the optimization process, are passed to the main script, by which means finally the execution of the optimization algorithm (Figure 2) is started. Additional information on the optimization is provided by separate classes, clustered into the optimization problem (comprising definitions of design variables, objective functions, as well as constraints), the optimizer, and the optimization algorithm.

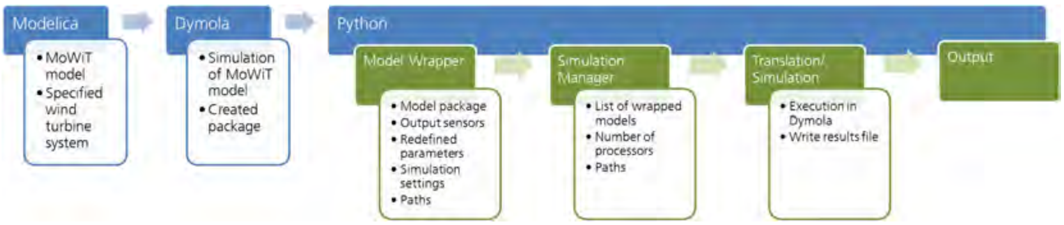

Figure 1. Simulation framework in Python.

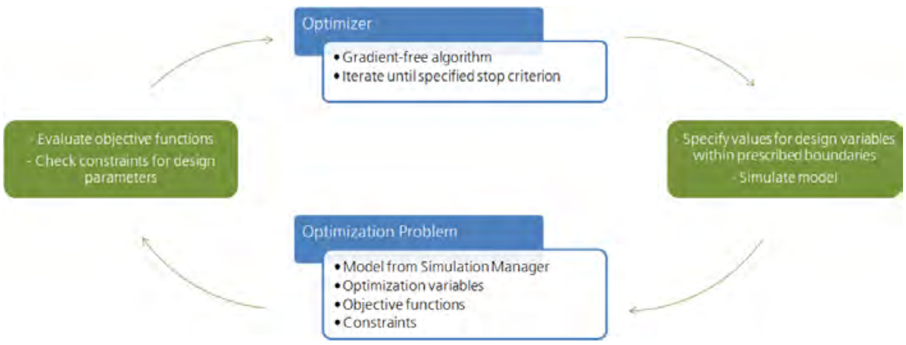

Figure 2. Automated optimization algorithm in Python.

Demand oriented Modelling of coupled Energy Grids

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Abstract

The ongoing integration of renewable energy sources into the different energy grids is one of the major tasks for the next decades. The overall goal behind this integration is the decarbonisation of the energy consumption in the different structural sectors (industrial, service, residential, mobility). Due to the highly volatile and increasing power input of the renewable energy sources, the need for coupled energy grids and flexibilities is rising.

Especially on the distribution level, the question arises how the different grid designs (electricity, gas, heat) will look like and how these networks are going to connect and interact. To find the ecological and technological optimum, different coupled design options have to be analysed.

To address these questions, different libraries and software tools are available. In general, these tools share one common philosophy. A fixed grid structure is given and forms the basis of the model to which the consumers are connected.

The natural process in the development of cities and districts is that the demand structure is defined by the urban framework and its developing demand and decentralised production. The energy grids have to develop towards these needs and therefore the grid design, connections and interactions are the variables of this adjustment process. The given or designed spatial structure of the settlement delivers the loss relevant lengths between the consumers, producers and the demand density, which are needed for the sizing of pipes, cables and the design of the resulting networks.

The future energy grid will undergo considerable changes through decentralisation, an increasing share of renewable energy supply and sector coupling technologies. In order to investigate the potentials of these technologies and other feasible innovations in grid design, the modelling of energy grids needs to be able to map the existing structure as well as future options. Thus, a modelling philosophy for energy grids should be based upon flexibility to allow the research of multiple configurations of technologies, types of energy supply and grid structures.

In case of energy grids, the network structure, as in routing and connections of pipes and cables to consumers, is not fixed and can change depending on the energy supply strategy and time. For example, it might happen that an energy concept for a district based entirely on decentralised oil heating systems is converted to an energy supply via district heating, PtH or gas heating. In this case the overall grid structures are changed and extended, but the demand structure, as in the distances between consumers and their location, stays constant. Based upon this, the modelling of energy grids only from a standpoint of grid structure with fixed types of pipes and cables, which are derived from the given technologies, is no optimal solution to target research projects regarding the development of future energy grids. The use of such models would make simulations with changing technologies difficult since changes in energy generation can involve a change in grid structure. Instead, modelling based on demand structure is more feasible, since it will usually not undergo modifications with changed technologies or grid structure.

This paper describes the development of a modular approach for modelling and simulation of coupled energy grids within different kinds of settlement structures. One presented thesis is that the spatial distribution of the demand structure is given by the urban framework and should be the origin of the modelling of coupled energy grids on the distribution level. Thus, the logic is that the grid is developing towards the given and developing demand structure and not vice versa.

Following these assumptions, a modular approach was realised by creating a so-called *GridConstructor*. This constructor allows it to easily build user defined urban frameworks and combine them with a single grid or multiple grids (electricity, gas, heat). These grids can be coupled via different systems. In conclusion, first results of coupled grid simulations are presented.

Keywords:

Thermodynamic and energy systems applications, Large-scale system modelling

OMSimulator – Integrated FMI and TLM-based Co-simulation with Composite Model Editing and SSP

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Abstract

OMSimulator is an FMI-based co-simulation tool and recent addition to the OpenModelica tool suite. It supports large-scale simulation and virtual prototyping using models from multiple sources utilizing the FMI standard. It is integrated into OpenModelica but also available stand-alone, i.e., without dependencies to Modelica-specific models or technology. OMSimulator provides an industrial-strength open-source FMI-based modelling and simulation tool. Input/output ports of FMUs can be connected, ports can be grouped to buses, FMUs can be parameterized and composed, and composite models can be exported according to the (preliminary) SSP (System Structure and Parameterization) standard. Efficient FMI-based simulation is provided for both model-exchange and co-simulation. TLM-based tool connection is provided for a range of applications, e.g., Adams, Simulink, Beast, Dymola, and OpenModelica. Moreover, optional TLM (Transmission Line Modelling) domain-specific connectors are also supported, providing additional numerical stability to co-simulation. An external API is available for use from other tools and scripting languages such as Python and Lua. The paper gives an overview of the tool functionality, compares with related work, and presents experience from industrial usage.
Keywords: FMI, FMU, SSP, modelling, simulation, co-simulation, composite

FMU-proxy: A Framework for Distributed Access to Functional Mock-up Units

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Abstract

The main goal of the Functional Mock-up Interface (FMI) standard is to allow simulation models to be shared across tools. To accomplish this, FMI relies on a combination of XML-files and compiled C-code packaged in a zip archive. This archive is called an Functional Mock-up Unit (FMU) and uses the extension *.fmu*. In theory, an FMU can support multiple platforms, however this is not always the case and depends on the type of binaries the exporting tool was able to provide. Furthermore, a library providing FMI support may not be available in a particular language, and/or it may not support the whole standard. Another issue is related to the protection of Intellectual Property (IP). While an FMU is free to only provide the C-code in binary form, other resources shipped with the FMU may be unprotected.

In order to overcome these challenges, this paper presents FMU-proxy, an open-source framework for accessing FMUs across languages and platforms. This is done by wrapping one or more FMUs behind a server program supporting multiple language independent Remote Procedure Call (RPC) technologies over several network protocols. Currently, Apache Thrift (TCP/IP, HTTP), gRPC (HTTP/2) and JSON-RPC (HTTP, WebSockets, TPC/IP, ZeroMQ) are supported. Together, they allow FMUs to be invoked from virtually any language on any platform. As users don't have direct access to the FMU or the resources within it, IP is more effectively protected.

The software architecture is shown in Fig. 1 and consists of three main parts:

1. *Discovery service(s)* - Provides users with the required information needed to connect to a remote FMU. Available FMUs can be listed through a web page or be querying it through HTTP.

2. *Server(s)* - Exposes locally available FMUs through one or more RPCs, possibly over several network protocols. Optionally, publishes information to a discovery service, making the server *discoverable*.

3. *Clients* - Interacts with the remote FMU(s), and may be implementing in virtually any language.

Some features of FMU-proxy include:

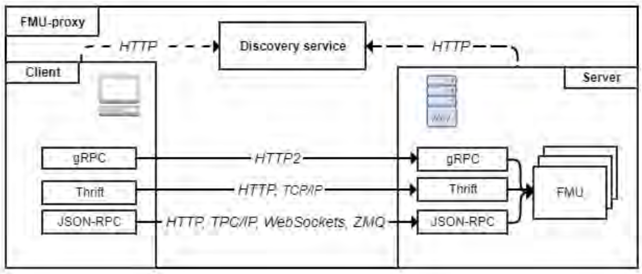

Figure 1. Software Architecture

- Brings FMI capabilities to previously unsupported languages and otherwise incompatible platforms.

- By implementing the RPC functions directly, FMI compliant models can be implemented without having to package them into FMUs.

- Allows re-use of code between software projects that requires distributed execution of FMUs, independent of implementation language.

- Enables companies to securely share FMUs. By hosting their own proxy server and directory service, neither the FMUs nor the knowledge about them leaves the company controlled servers.

Server implementations exists for C++ and the JVM, while client implementations exists for JavaScript, Python, C++ and the JVM. Due to the language independent nature of the RPC frameworks and protocols used, and especially the code-generation feature of selected RPC frameworks, client implementations in other languages require little effort.

FMU-proxy is available from GitHub at `https://github.com/NTNU-IHB/FMU-proxy`. Here, pre-built server executables can be obtained. Client libraries for Java are available through *maven* at `https://jitpack.io/#NTNU-IHB/FMU-proxy`, while client libraries for C++ will be available through *vcpkg*.

Keywords: RPC, FMI, Co-simulation, Model Exchange

Standardized Integration of Real-Time and Non-Real-Time Systems: The Distributed Co-Simulation Protocol

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Extended Abstract

Modeling and simulation represent key methods for successful development of cyber-physical systems. With the introduction of co-simulation methodologies, holistic cross-domain or system simulations became possible. This enabled exchange and integration of simulation models, tools, and solvers from different sources. The automotive industry is characterized by a multi-tiered organization. A deep hierarchy of suppliers performs distributed development and integration of automotive components, parts, and systems, that in the end are manufactured to complete vehicles. Depending on the stage of development, simulation models or real prototypes are available. The advantage of simulation models is that they can be tested in terms of software. Software tests are comparably cheap. However, they typically do not consider timing aspects or uncertainties of measured quantities. On the other hand, prototypes are advantageous when it comes to product validation. A prototype shows real-world behaviour and interacts with the environment. The disadvantages are that prototypes are usually very expensive and safety critical. For these reasons it seems advantageous to combine simulation and real-world prototype based testing approaches. This especially includes the field of automated driving (Doms et al., 2018). Testing efficiency is key to successful product development. Interoperability of simulation tools and test infrastructure contributes to testing efficiency. Therefore the use of standards is essential.

The DCP (Distributed Co-Simulation Protocol) was developed in the ACOSAR project (Krammer et al., 2016). ACOSAR stands for "Advanced Co-Simulation Open System Architecture". ACOSAR was an ITEA 3[1] project. Three original equipment manufacturers (OEM), 9 companies from the automotive supply chain, including simulation tool vendors, system and component providers, as well as 4 partners from research and academia cooperated. Their main goals were (1) the specification and demonstration of the DCP, and (2) preparation of standardization of the DCP with a recognized standardization body in order to promote it as the next co-simulation standard. The DCP is introduced in (Krammer et al., 2018). It was granted as a Modelica[2] Association Project (MAP) in 2018[3].

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[2]http://www.modelica.org
[3]http://www.dcp-standard.org

Anti-Roll Bar Modeling for NVH and Vehicle Dynamics Analyses

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Abstract

In the automotive field of application, the anti-roll bar is a suspension component tailored to influence the dynamical roll motion characteristics of the vehicle independently from the layout of the vertical suspension. It is designed in a way to connect suspensions on the right and the left side of the vehicle's axle by a cranked bar that acts as a torsional spring, see Figure 1. Since it is additionally attached to the vehicle body and due to the available space at the underfloor, it's design often results in a geometrical complex structural element that is prone for dynamical vibrations.

The given background motivates the introduction of a new modeling capability called *AntiRollBar* into the *DLR FlexibleBodies* Library. In the present paper, a principle of the flexible body modeling and of the beam theory behind the *AntiRollBar* model is given. Additionally, its application for particular automotive-related purposes of NVH and vehicle dynamics as well as a simple simulation experiment are presented.
Keywords: anti-roll bar, vehicle chassis, flexible body, beam model, finite element

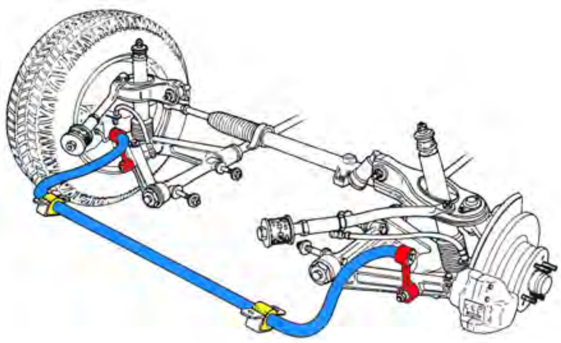

Figure 1. Vehicle axle with an anti-roll bar (color emphasized, courtesy of Wikimedia Commons).

System level heat pump model for investigations into thermal management of electric vehicles at low temperatures.

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With the growth and spread of electric vehicles there has been increasing concern regarding their operation at low temperatures. At low temperatures batteries suffer from reduced capacity which limits range, leading to the requirement of battery heating. Additionally the cabin needs sufficient heat to satisfy occupants. Due to the heat wasted by engines in internal combustion vehicles, the cabin heating demand was previously met with ease. This new demand has resulted in a growth in heat pump related research. With this growth, a selection of different proposed vehicle architectures have arisen.

This paper describes a model which allows for the creation and comparison of many different theoretical vehicle architectures. The model allows for the motor, transmission, cabin exhaust, thermal storage unit and electric battery to be dynamically connected and disconnected from coolant circuits of the heat pump. The paper describes each of the relevant sub-models, how they are linked through coolant circuits and the control system for the heat pump. The control system has been designed to be robust to unseen potential vehicle architectures.

Two test cases are used to test that the model is capable of fulfilling the following four objectives:

1. The ability to dynamically connect and disconnect components from the thermal management system.

2. The ability to arbitrarily request heat flows between components (e.g. request 5kW for cabin heating), while being physically limited by sensibly sized heat exchangers.

3. Contain a control system for the heat pump which self regulates compressor speed regardless of vehicle configuration.

4. Run quickly enough to be useful for performing parameter sweeps and optimisations in suitable time frames.

The test cases selected are used to answer two proposed questions; can the battery be used as a thermal heat source at low temperatures, and is the transmission a useful source of heat to the heat pump. These questions

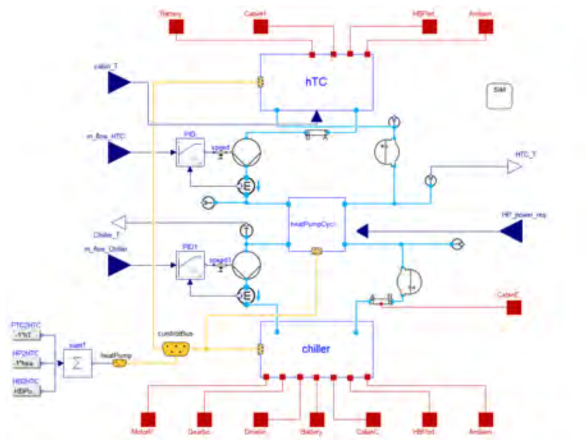

Figure 1. Heat pump capable of taking heat from multiple sources and distributing it to the cabin, battery or both.

demonstrate the flexibility of this model, but are also pertinent to the research area.

The first objective, regarding dynamic connections, has been shown using the first test case. When the battery was heated the system successfully disconnected the battery from the thermal management system when its temperature became too high. To demonstrate the second objective, a heat demand of 5kW was requested for cabin heating which was successfully sustained when the heat pump was producing sufficient heat. Objective 3 was demonstrated by completing all the scenarios tested without the model failing due to coolant fluids, refrigerants etc. going beyond their operational limits. Finally simulation time for each of the cases is presented, confirming that the model is executed in sensible time, with regards to objective 4.

Two cases have been presented, with some interesting results, which both demonstrate the flexibility and robustness of the model presented. Given the breadth of thermal management opportunities that are arising in the heat pump research area, architectures similar to this could be used as an early tool in identifying which options show potential.

Diesel Cooling System Modeling for Electrification Potential

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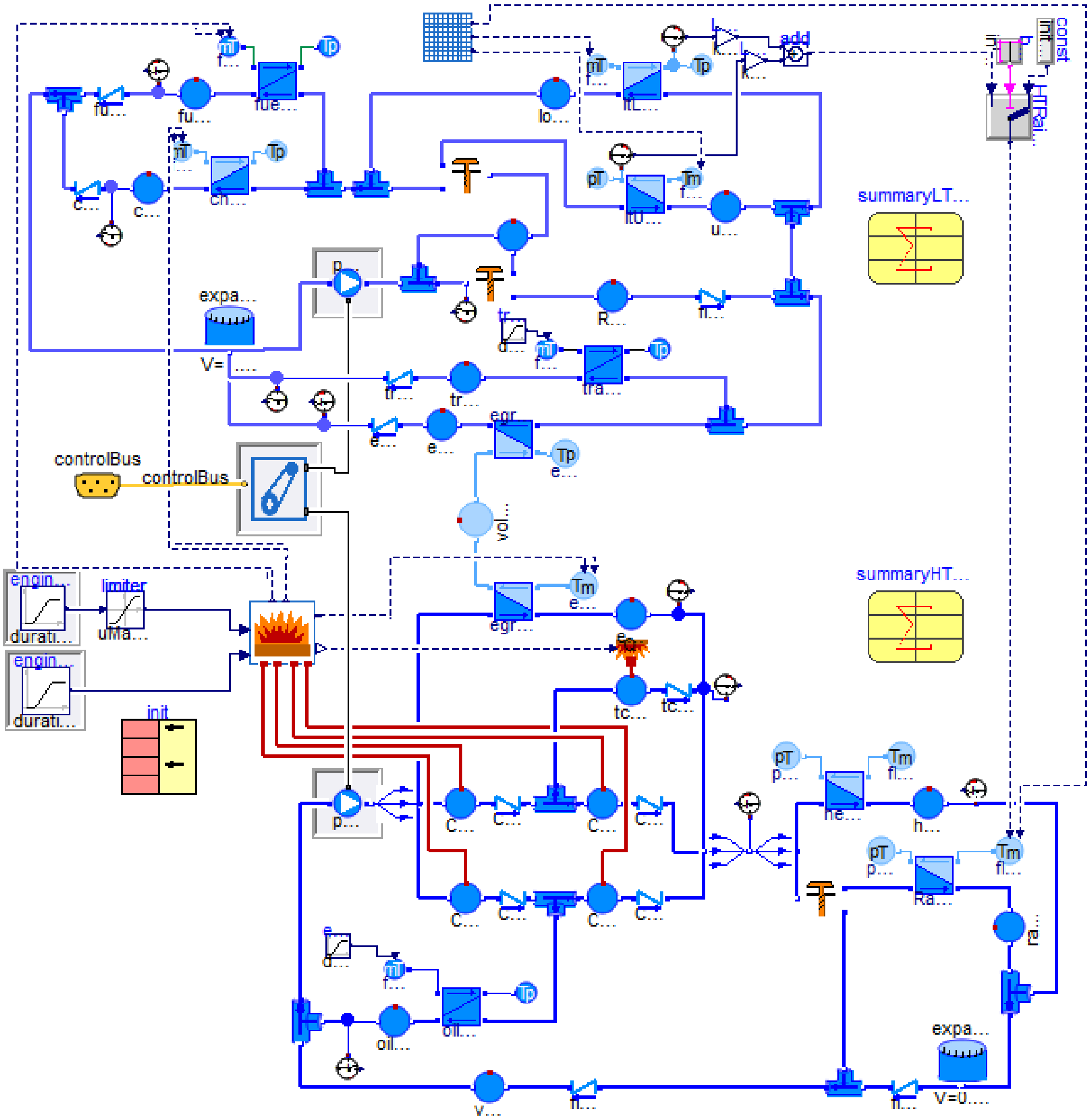
Electrification of automotive systems presents significant opportunities for improvements in cooling system efficiency and performance. This paper describes an effort to develop an analytic platform for Hanon Systems to evaluate the electrification potential for powertrain cooling systems. The paper describes the development of a baseline diesel cooling system model based on the Ford 6.7L Power Stroke diesel. A variant of the system with electric pumps is also modeled. Performance of the baseline conventional and electric pump system are compared on a typical automotive drive cycle to quantify potential benefits of the electric pump system and advanced controls.



Dynamic Simulation of Residential Buildings Supporting the Development of Flexible Control in District Heating Systems

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Abstract

Load shifting, peak shaving and night-time setback are key demand-side management measures to make the operation of District Heating Systems (DHSs) more flexible and efficient. These goals can be achieved through appropriate control strategies exploiting the building's and space heating system's thermal inertia. To ease the development of such an advanced controller, we programmed a detailed dynamic Modelica simulator representative of French multi-stories radiator-heated residential buildings. We parametrized the simulator to vary the factors influencing the flexibility potential of a building (e.g. envelope properties, additional internal mass such as partition walls and furniture, the heating system…). This helped us designing a reduced-order building model relevant to our application and setting up a robust identification method for its parameters. We finally used the detailed simulator to test an optimal space-heating controller, thereby allowing many incremental improvements without jeopardizing end-users thermal comfort. This simulation work paves the way to considering the actual implementation of our advanced controller on a real building.

Keywords: District Heating System, Optimal Control, Building Simulation, Reduced-order building model

Integrated Modelica Model and Model Predictive Control of a Terraced House Using IDEAS

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Abstract

Modelica has been used extensively within the Thermal System Simulation (The SySi) research group at KU Leuven to simulate and optimize the control and design of building energy systems. Within this scope, the open source Modelica library IDEAS has been developed (Jorissen et al., 2018c) and papers have been published that explain how IDEAS can be used to develop fast simulation models and MPC. Jorissen et al. (2018a) describe the detailed Modelica model of an office building and a comparison with measured data. An MPC has been developed for this model using TACO, an MPC framework that is tailored to buildings (Jorissen et al., 2018b). In simulations the operational cost of the building was reduced by more than 50 %, however thermal depletion of the ground by passive cooling was not accounted for.

The presented approach for speeding up models was thus far demonstrated in papers but open-source practical examples of reasonable size are not yet available, which makes it harder for Modelica users to learn from these guidelines. Therefore, this paper presents an open-source simulation model of a 9 zones terraced house for which these earlier presented guidelines are applied and for which MPC results are made available. A heating system, ventilation system and controller are included in the model. A full-year simulation of the nine-zones model takes four minutes and energy savings of 12.8 % are reported compared to a current-practice rule-based controller, although MPC has thermal comfort violations of up to 0.4 K.

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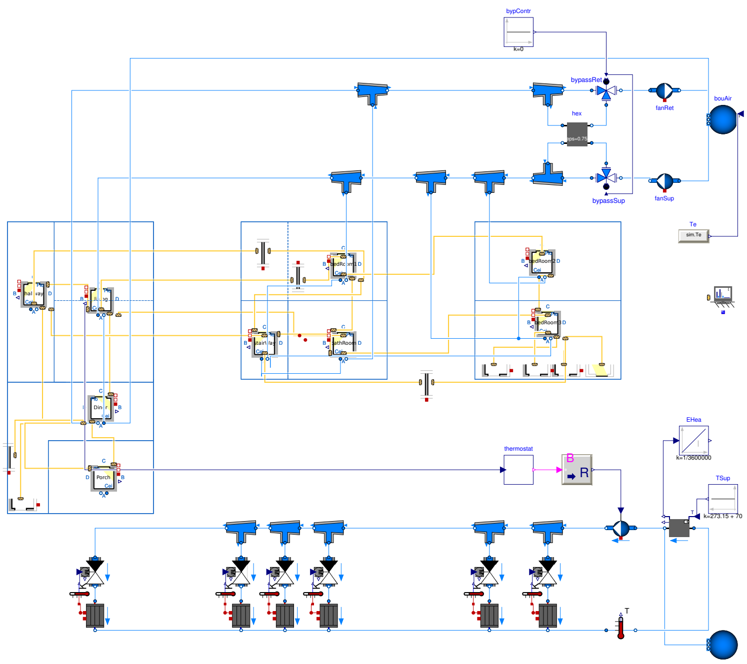

An Extended Luenberger Observer for HVAC Application using FMI

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Abstract

State estimation is one of the important use cases for the Functional Mockup Interface (FMI). For example, states of a nonlinear continuous-time model can be estimated from discrete-time measurements of the input and output of a plant using a continuous-discrete Extended Kalman Filter (EKF), realized using the co-simulation form of a Functional Mockup Unit (FMU) of the plant. Fundamentally, the EKF, and its various extensions estimate the state in a two-step process. In the prediction step, the EKF computes the predicted state estimate using a discretized plant model. Then in the correction step, the covariance and gain are computed as a function of the predicted state estimate, and the predicted state estimate state is corrected. The discrete-time prediction model is then initialized using the corrected state, and the process is repeated.

An *observer* is an alternative technology for estimation of the plant states and parameters. An observer is a deterministic, continuous-time dynamical system that takes as input the measured input and measured output of the plant, and produces as its output an estimate of the state of the plant. It is similar to the Kalman filter, but based on deterministic assumptions and mathematics. Fundamentally, the concept of *output injection* is used to stabilize the observer error dynamics, which govern the difference between the estimated state and the plant state. Output Injection means that a signal is injected (added) to the derivative of the observer state vector as stabilizing feedback. Because of this, it is the continuous-time dynamics of the plant *with* output injection that needs to be simulated as a continuous-time feedback system. There are not separate, algorithmic prediction and correction steps.

In this paper we show how an instantiation of a model-exchange type of FMU can be used with the Dymola tool to realize output injection, enabling design and implementation of linear and nonlinear state observers and specifically the Extended Luenberger Observer (ELO). Our specific interest is to estimate unmeasured performance variables of a building and HVAC system as a part of a building “digital twin.” Toward this end we have considered several alternative methods to estimate the performance variables, including various flavors of the EKF. However, these may prove too computationally burdensome for our application because the number of states can be large (hundreds), the number of measurements can be large (tens to hundreds), and the EKF can be computationally challenging because of the covariance update, although there are many techniques such as model reduction and square root filtering that are available to improve its computational efficiency. More importantly, an EKF can fail to converge, or in some cases, cause the model to fail at run time, at least for our building HVAC applications. Convergence failures are caused by some of the characteristics of the model that we consider in this paper, which are not unusual for this field of application. The model is stiff (with time constants ranging from milliseconds to several weeks — eight orders of magnitude), and is numerically ill-conditioned (with states varying 8-9 orders of magnitude because of the choice of units). Thus the Jacobian may not accurately predict the state over the fixed and usually large EKF sample time, causing it to diverge. Moreover, the model itself contains state constraints, such as a non-negative limit on mass concentrations, which can be violated at run time because of the EKF correction step, causing a run-time error.

On the other hand, the ELO is relatively simple and light-weight computationally. In its simplest form, it uses a constant feedback gain matrix that is computed at design time from the steady-state solution of a Ricatti equation, and therefore avoids the real-time covariance update and computation of the system Jacobian that is necessary for the EKF. Further, it may offer improved stability and performance advantages over the EKF (and similar filters) for certain applications because it makes use of implicit variable-step solvers for the continuous-time model.

We present the design steps required to compute the feedback gain from a linearization of the model. The key step is to compute a sequence of model order reductions which remove weakly observable and controllable modes from the model. We show how the feedback is realized in a Modelica model that uses an FMU for model exchange. We close by making several remarks concerning the design of discrete-time state estimators and some of the needs for dynamic analysis of building models.

Keywords: Estimation, Buildings, HVAC, FMI, FMU

A Modelica-Based Framework for District Heating Grid Simulation

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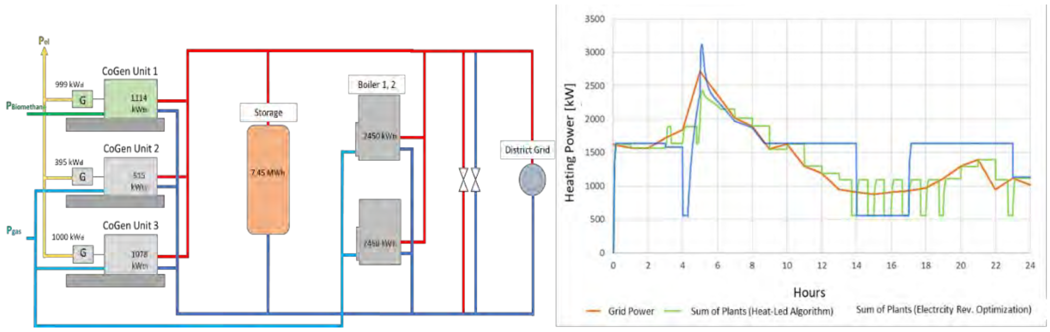
The interdisciplinary modelling language Modelica is increasingly used in the design and evaluation of energy systems. Heat supply represents a considerable share of the global energy supply. Especially in European cities, district heating grids are often used and implemented for heat coverage. The increasing integration of renewable energies and the extension of existing grids require engineers to be able to analyze and evaluate the behavior of such grids, not only statically in certain operating conditions, but also dynamically to enable the representation of complex system interaction.



This paper shows and describes a new approach as to how Modelica models can be used to evaluate the dynamic behavior of district heating grids. It furthermore introduces a consistent framework to parameterize these models with GIS-data via the COM interface. The advantages of the shown approach compared to previously used static methods are shown with specific case studies.

Optimization of District Heating Systems: European Energy Exchange Price-Driven Control Strategy for Optimal Operation of Heating Plants

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Abstract

District heating (DH) systems are often seen as a good practical approach to meet the local heat demand of districts, especially CHP-based DH systems and, therefore, these CHPs are frequently heat driven. Consequently, CHP's electricity is fed into the grid at a variable or fixed tariff, which leads to some additional profits. Yet, under today's regulations to renovate buildings on high efficiency standards, the local heat demand is decreasing. This demand profile and the national electricity demand fluctuate seasonally and hourly with asynchronous patterns, thus this might lead to less profit for the operators of DH systems. Therefore, it is important to guarantee an optimal-operation of the heating plants coupled to the DH networks. Thus, the operators strive for an optimal operation at which the heat demand is met and the profits are maximized. In this work, a control strategy for optimal operation of a combined heat and power (CHP) based DH is presented. The proposed control strategy couples the operation of CHPs to the European energy exchange (EEX) price by implementing different operation constraints. To test this strategy, a validated power-based model of a DH system is used. This model shows the amount of energy flows between the different parts of the DH system (supply side, transmission network and demand side). Moreover, this configuration is accompanied with another, which is the installation of additional storage volume. Thereby it is held to provide the optimal operation for the plant technically and economically.

Automated model generation and simplification for district heating and cooling networks

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Abstract

The current operation of district heating networks often relies on static analyses and control parameters. In the future, possible integration of renewable energy sources like solar or geothermal energy are getting more and more important. To investigate the impact of these new energy sources in combination with new control strategies, dynamic simulation models for district heating and cooling systems are getting more important. However, these models are often large and therefore have large computation times and require manual effort to create and optimize them. Thus, this paper investigates in the simulation of a large and meshed district heating network, presenting a workflow for automated generation and model simplification of simulation models based on GIS data. Therefore, we use Modelica models from the *modelica- ibpsa* (van der Heijde et al., 2017) library as well as the *AixLib* (Müller et al., 2016). The validity of the model simplification is proven and the usability of the model is demonstrated by a Use Case with two different control strategies.

Starting with a GIS dataset, the graph framework for urban energy systems *uesgraphs* (Fuchs et al., 2016) is used to transfer the GIS data into a graph for more efficient data handling. This graph is used to store additional information about the district heating and cooling system, like pipe diameters and insulation thicknesses. These information are used to automatically generate a simulation model in Modelica, taking all available information regarding the thermo-hydraulic network behavior into account. Tackling the problem of large DHC networks and their huge complexity as a simulation model, the presented paper describes two steps to reduce the DHC network for a more efficient simulation.

The first step is a complexity reduction regarding the network layout. Therefore, *uesgraphs* is able to simplify the graph network to contain less pipe network representations by nodes and edges. This is mainly done by a weighted reduction of the existing pipes between nodes which represent junctions, substations or supplies. Figure 1 shows an exemplary cutout of the presented use case before the simplification process.

The second step is a simulation model reduction by replacing the used plug-flow pipe model with a static pipe model for short pipe segments. This leads to a reduction in simulation times by 45 % and a more stable simulation in terms of *bad allocation errors*.

Concluding, the presented paper shows the usability of the modeling language Modelica for DHC applications. Future work will include a comparison of the used models with even more simplified models to elaborate which model detail is necessary for the evaluation of top level control strategies. Nevertheless, the paper present possible network simplifications and their results of an Modelica user oriented view.

Keywords: District Heating and Cooling Networks, Model Simplification, Control Strategies

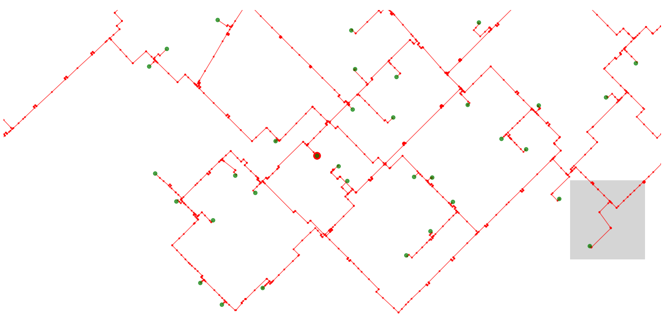

Figure 1. Original model cutout of an exemplary district heating grid

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Non Linear Dimension Reduction of Dynamic Model Output

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Modelica models are more often than not dynamic. However, most advanced mathematical methods for the analysis of numerical models cannot cope with functional outputs. There is therefore a need for efficient dimension reduction of dynamic outputs.

Principal component analysis is a well established method, and can be used to tackle this issue. To do so, the functional output is discretised, and its value at each time step is considered as a random variable. Principal component analysis performs dimension reduction while considering only a given number of new high-variability variables, called *component*. The method however relies on a linear hypothesis that limits its applicability.

The non linear method of auto-associative model overcomes this shortcoming thanks to a different projection index and nonlinear regression functions. Similarly to Principal Component Analysis, only a given number of the new variables formed is selected as "meaningful".

We illustrate both methods on a case study, the well-known bouncing ball. We found out that the auto-associative model requires a lower number of variables than principal component analysis to replicate the behaviour of the model with a low error. Moreover, the variables issued of auto-associative model somehow decomposes the inputs effects. It thus provides physically interpretable data representations.

Keywords: dimension reduction, functional data analysis, FMI, OtFMI, principal component analysis, auto-associative model, sensitivity analysis.

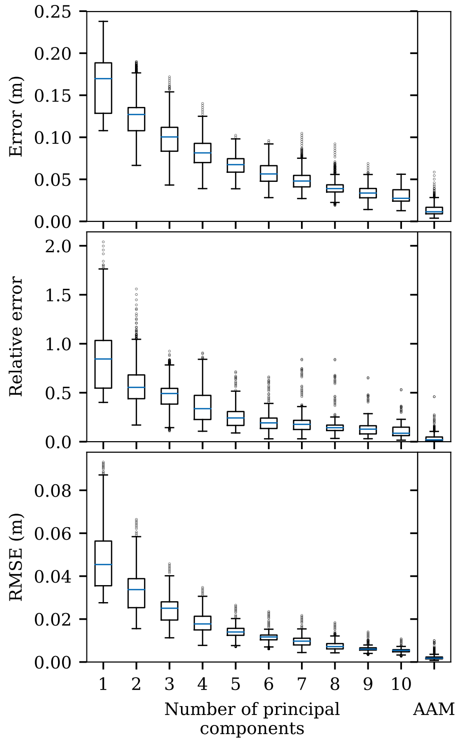

Figure 1. Comparison of the boxplots issued of Principal Component Analysis, with a number of components up to 10, and of Auto-Associative Model, with 1 component.

Relative Consistency and Robust Stability Measures for Sequential Co-simulation

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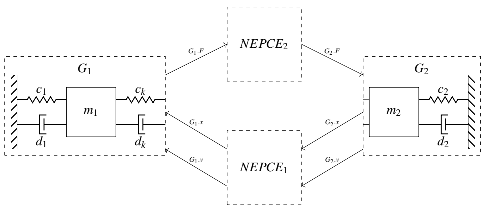
The paper introduces a matrix co-simulation model for the purpose of evaluating co-simulation masters. It assumes that co-simulation slaves solve a linear time invariant differential equations using general linear methods. Any non-linear systems providing the Jacobian matrix are covered by presented methods. The co-simulation is orchestrated by a sequential master with linear extrapolation elements. An example of such a system is illustrated in Figure 1.



$$\sigma_{12}(r) = \begin{cases} 1, & r = 1 \\ 2, & r = 2 \end{cases}$$

$$\sigma_{21}(r) = \begin{cases} 2, & r = 1 \\ 1, & r = 2 \end{cases}$$

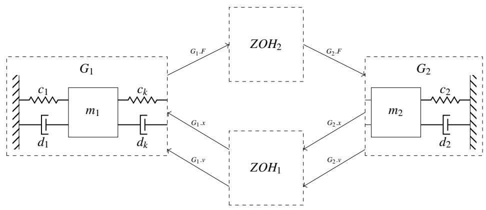


Figure 1. The paper presents the example of tuning the co-simulation master for a simple two-mass oscillator system. There is a choice between two extrapolation methods, namely *NEPCE* and *ZOH*, and two different calling sequences of co-simulation slaves.

The developed co-simulation model is used for the calculation of relative consistency and robust stability. A co-simulation master with a better consistency is shown to have a smaller co-simulation error. In addition, it is shown how a robust stability measurement based on spectral radius can be used to measure robustness to slave parameter changes. In order to utilize the calculation both objectives can be plotted with respect to the co-simulation step size (Figure 2). The plot allows a visual comparison of co-simulation masters. The paper proposes multi-objective optimization in order to automate the manual work. Such a procedure enables the choice of a co-simulation master prior to the co-simulation run.

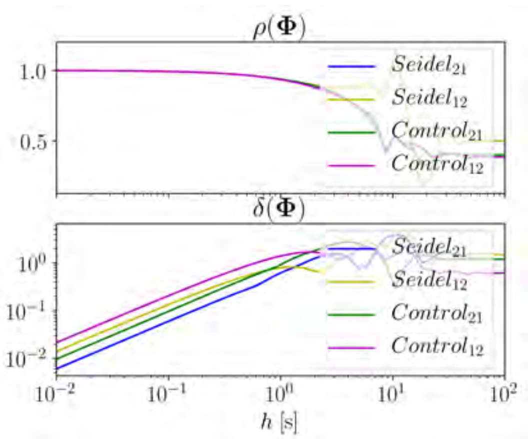


Figure 2. The relative consistency and the robust stability calculation can be used to evaluate the co-simulation step size.

Energy balance based Verification for Model Based Development

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This paper focuses on a new model verification method for Model-based development (MBD) using cross-sectional tools. GAIO technology Co. Ltd. (GAIO) have pushed Model-Centered Development (MCD) which targets tool developments and services for MATLAB based MBD and UML based MDD (Model Driven Development) so far. Especially, MCD ver.1.0 concentrates on the controller models whose code is mainly described by MATLAB/Simulink. The next generation, MCD ver.2 targets not only the controller models but also the plant models. For example, MCD ver.2 targets co-simulation based on the plant model composed of various simulation models such as MATLAB/Simulink, Mathematica, Maple/MapleSim, IMG-CarMaker and so on. This results in the expansion of test area not only unit tests of Function Mockup Unit (FMU) but also integration tests of Functional Mockup Interface (FMI). So, GAIO needs to enter a new stage of model verification and have to introduce new test insights.

The accuracy of MBD depends on the accuracy of the model. Typically, the accuracy of the model is categorized by two. The first is the correctness of the program code which realizes model. The second is the correctness of the law of physics which is realized by model. The former has been checked by a typical program verification method including unit tests and integration tests. The latter focuses on that ideal simulation models realize some physical laws. “The energy balanced verification” method proposed by Miyamoto et al. 2014 checks the energy balance of the model according to the fact that the energy conservation laws hold for no error models. That is, if the no error model has no internal loss energy, the total energy difference between the inputs and outputs will match the stored energy. Otherwise, the conservation law does not hold. Even if the hybridization and electrification of automobiles make system structure complexity, the energy conservation laws do not change. This paper introduces the energy balance based verification as a new model test concept for MCD ver.2.

This paper introduces a prototype system that streamlines the workflow of the energy balance verification method. The method checks on the input-output relation of each module consisting the model to calculate energy quantity. In other words, the model expression considering the energy relation leads to efficient energy balance check of the model. Then, this paper proposes a hierarchical diagram and an energy flow diagram of the model. The former categorizes modules of the model according to energy conservation laws. The latter expresses the energy flow relationship between modules. The prototype system supports the energy balance verification based on the two diagram. To verify the validity of the proposed system, we consider the mild hybrid electric vehicle (MHEV) composed of MATLAB/Simulink, MapleSim, and IMG-CarMaker as shown in Fig. 1.

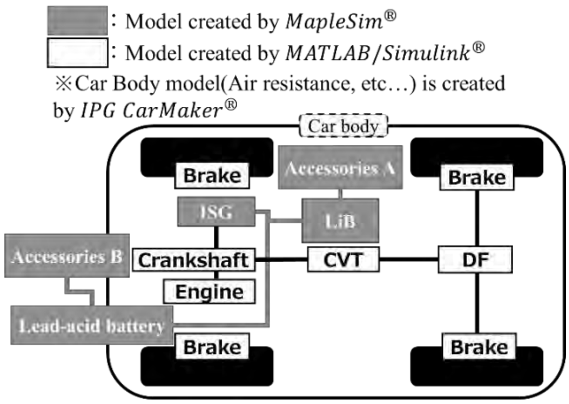

Figure 1. MHEV model.

The verification procedure is as follows:

I. Construct the hierarchical diagram of the model.
II. Energy calculation via the simulation.
III. Construct the EF diagram.
IV. Construct the energy balance checking equation and the loss energy checking equation.
V. Carry out the unit and integration tests.

We developed the prototype system carries out from Step III to V: Tool α and Tool β in Fig. 2.

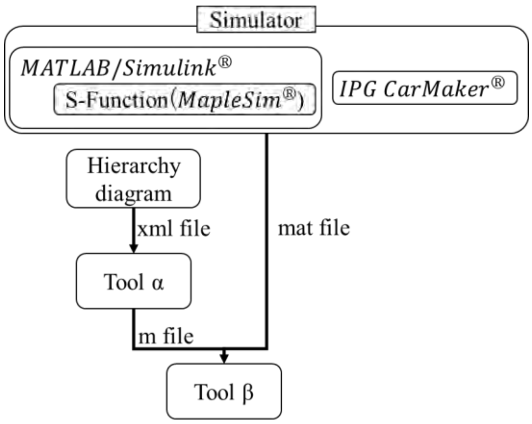

Figure 2. Data flow between tools.

Parameterization Of A Simplified Physical Battery Model

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Abstract

The importance of batteries is increasing, especially in the field of the high power requirement systems like electric driven vehicles. Mobile energy storage makes it possible to accelerate with incredible torque, without any accruing air pollution. Due to the high costs of real components, it is of great use to simulate battery driven systems before building them. Transient processes within a cell are highly dependent on the operating point of the complete system, which makes it difficult to create equations and model parameterizations. This paper shows which data is important for cell modeling and how to parameterize simplified physical cell models.
Keywords: simplified battery model, battery parameterization, physical battery model

1 Introduction

The main target of the master student's project was to get a method to generate a simplified model of a lithium ion cell. In general the physical models of batteries are generated with electronic elements like resistors, capacitors, or inductances.
The complexity of battery models can go up to infinity, so it is necessary to simplify the structure as much as possible. The simpler models contain a resistor, which represents the inner resistance of the cell and a resistor connected in parallel with a capacitor, which represents the capacitive behavior. Because of that, this model can only recreate the real battery behavior in a few situations and is also the least accurate one. To generate a more precise simulation, it is necessary to use more RC-elements (resistance connected in parallel with a capacitance). With more of these elements, it is possible to fit the Nyquist plot of batteries much more accurately.

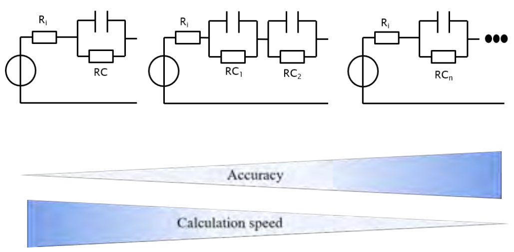

Figure 1. Rising calculation speed versus higher complexity

For high frequencies the impedance goes even inductive, so therefore a inductance should also be considered. The disadvantage of more elements in the equivalent circuit is that more information about the cell is needed for parameterization and the CPU time for calculations is increased.
The most accurate models are completely numeric models in which all Elements are parametrized with interpolated tables, which are depending on temperature, SOC (state of charge) and flowing current. These models need much more measurement data than the ones with simple concentrated elements. All the parameters have to be recalculated in every state of the battery, which causes an extreme rise of the calculation time for the simulation. The measurements are very time consuming and expensive, so not many institutions have access to the necessary information and data for this kind of simulation models. That is the reason why in this paper no such model is discussed and presented.

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Modeling of transformer-rectifier sets for the energization of electrostatic precipitators using Modelica

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Abstract

Many industrial plants need to satisfy low and strict emission levels of pollutants in the emitted flue gases. One method to reduce the emission of solid pollutants suspended in gas streams is the use of electrostatic precipitators (ESPs). In ESPs, the particles of pollutants are electrically charged and pass through a strong electric field. The charged particles moving within the gas stream are thus deflected towards collecting plates, to which they stick. To create the ions that are required to charge the particles and to sustain the required strong electric field, high-voltage power supplies are required. ESPs are normally internally subdivided in electrically isolated sections which are independently energized and controlled. Different topologies of power supplies which can be used to energize ESPs exist. One of them, also the most traditional, is called transformer/rectifier (T/R) set. T/R sets can be single phase or three phase: because of the different output voltage they generate, their usage depends on the particular process of which the ESP is part. The basic diagram of a three-phase T/R set is shown as an example in Fig. 1. The aim of this paper is to model open-loop controlled, single- and three-phase T/R sets coupled to ESPs. After introducing the main components of single- and three-phase T/R sets, the Modelica models which have been built are described. The Modelica Standard Library and the OpenModelica Connection Editor (OMEdit) have been used to model both single- and three phase T/R sets. The availability of interfaces between different physical domains makes Modelica ideal for modeling multiphysical systems like ESPs. For this work, the following physical domains have been used: *electrical*, for the power electronics stage; *blocks*, for the open-loop control of the power electronics stage; *thermal*, for the calculation of the losses. The simulation results and field measurements are presented and compared. The models have been validated with measurements from existing plants and an example for three-phase T/R sets is given in Fig. 2. Further work will be required, like the derivation of the models of the ESP, of closed-loop controllers and of other topologies of power supplies. The derivation of a complete thermal model for these power supplies is planned.

Keywords: Modelica, power supply, electrostatic precipitator, ESP

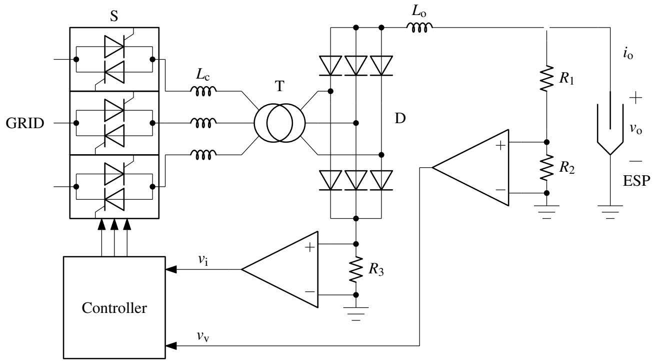

Figure 1. Schematic and block diagram of a three-phase T/R set connected to an electrostatic precipitator (ESP)

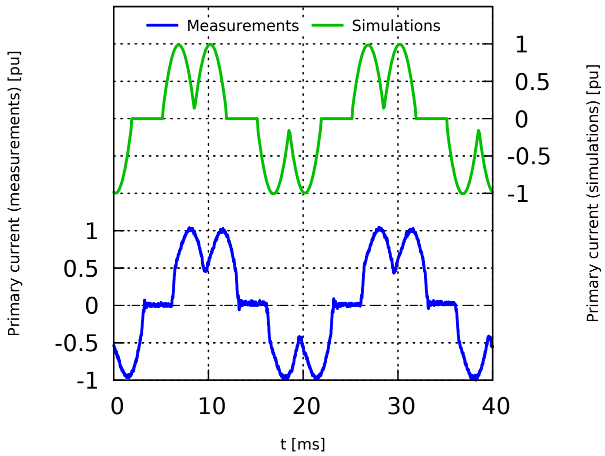

Figure 2. Measured and simulated normalized primary current for two different three-phase T/R sets

A Model Predictive Control Application for a Constrained Fast Charge of Lithium-ion Batteries

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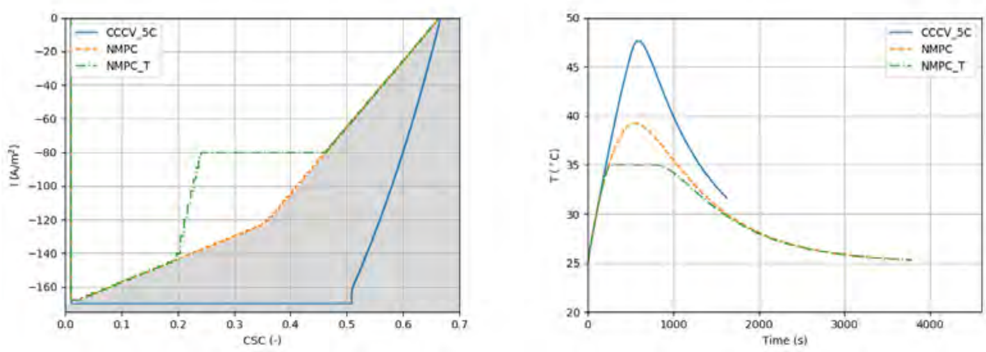
The spread of electrical storage devices continues to be underpinned by the limited charging currents that can be applied. The limitation arises from the lack of sufficient high power charging stations, either at home or along roads and highways, and from the maximum admissible current that can be applied to the battery before undesirable degradation mechanisms are triggered. Accordingly, traditional charging protocols limit the charging current as a function of the standing state of charge of the battery. An example of these is the widespread constant-current-constant-voltage (CCCV) protocol. Protocols like this are designed empirically and restrict the potential benefit in charging time of more flexible charging options. However, the alternative to traditional protocols must rely on a more precise knowledge of the operating constraints and on advanced control techniques to compute online the best operating plan.

This work presents a non-linear model predictive control (NMPC) application to minimize the charging time of a lithium-ion battery subject to electrochemical and thermal constraints. The satisfaction of these constraints (Fig. 1) ensures that the battery degradation is minimized, or at least mitigated. The programming language Modelica and the optimization and simulation framework JModelica.org is used in combination with Python language to assess the implementation time and potential use of NMPC in commercial batteries to extend their operational life.



(a) (b)

Figure 1. Comparison of a traditional charge protocol (CCCV) with non-linear constrained control without (NMPC) and with (NMPC_T) temperature constraint ($T_{\max} = 35°C$). Left: Current (I) and Critical Surface Concentration (CSC) phase plot (in grey the unfeasible region); right: temperature profiles

Modeling Heat Pump Recharge of a Personal Conditioning System with Latent Heat Storage

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Abstract

Roving Comforter provides personal cooling in the range of 150 W using vapor compression cycle (VCC) up to 4 hours. During this operation, the condenser heat is stored in a latent heat storage made of phase change material (PCM). This heat needs to be discharged before next cooling operation. A heat pump mode is considered and analyzed for this heat discharge in the present article. The cycle is modeled using `CEEEModelicaLibrary`, which is a commercial package for complex vapor compression systems. Equations and assumptions involved in modeling some of the components is presented. Programming and modeling decisions for PCM modeling are discussed in detail. A parametric study is conducted with the heat pump system model to identify merits and demerits of operating heat pump cycle at various compressor RPM's.

Real-time optimization of intermediate temperature for a cascade heat pump via extreme seeking

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Abstract

Improving the energy efficiency of air-source heat pump (ASHP) has been a critical issue for heating operation in cold climates. The cascade heat pump system has been developed as a more advantageous solution over the single-stage heat pump. However, the increased complexity of cascade heat pump systems has presented great challenge for online optimization for the energy efficiency, as model based control/optimization methods incur costly modeling and calibration under different operation and equipment conditions. We propose to use the extremum seeking control as a model-free real-time optimization strategy for efficient operation of cascaded heat pump. The intermediate temperature setpoint is used as the manipulated input for minimizing the system efficiency while satisfying the heating load demand. A Modelica model of an R134a/410a cascade heat pump is developed, and control simulations are conducted for validating the system performance under different ambient conditions.

Tube-fin Heat Exchanger Circuitry Optimization For Improved Performance Under Frosting Conditions

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Abstract

Frost accumulation on tube-fin heat exchanger leads to reduction in evaporator capacity and deteriorates cycle efficiency. The conventional counter-flow heat exchanger circuitry has the disadvantage that more frost tends to accumulate in the first few banks exposed to the incoming air. This frost concentration makes the air side flow resistance increase rapidly, thus reduces the air flow rate and evaporator capacity under constant fan power. In this paper, a novel integer permutation based Genetic Algorithm is used to obtain optimal circuitry design with improved HX performance under frosting conditions. A dynamic HX model with the capability to account for non-uniform frost growth on a fan-supplied coil is used to assess the performance of optimal circuitry. The case study shows that the proposed circuitry design approach yields better circuitry with larger HX capacity, more uniform frost distribution, less air flow path blockage, and therefore longer evaporator operation time between defrost operations.

Keywords: Heat Exchanger, Frost Growth, Circuitry Optimization, Genetic Algorithm

Coupled Simulation of a Room Air-conditioner with CFD Models for Indoor Environment

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Abstract

The assessment of closed-loop performance of HVAC systems often requires an integrated approach that couples the dynamic models of HAVC system with building energy simulation programs. Most of these building simulation programs assume that indoor air is well mixed in order to simplify the computation. However, this prevailing assumption fails to simulate the distribution of temperature, pressure, concentration in buildings with large space and high heat gain. As a result, these programs cannot accurately predict building energy consumption and the closed-loop performance of HVAC system. In addition, they cannot satisfy advanced design requirements, such as personal cooling/heating and optimal sensor placement, due to lack of local thermal comfort information.

In contrast with the well-mixed assumption, computational fluid dynamics (CFD) divides fluid domain into a large number of small volumes such that a detailed prediction of airflow and temperature distributions, thermal comfort and indoor air quality can be obtained. Coupling building energy simulation programs with CFD can be effective to overcome the deficiencies of stand-alone programs and achieve better results. Consequently, building simulations can provide dynamic boundary conditions to CFD, whereas CFD simulates the airflow dynamics based on these boundary conditions and then can send the average airflow and temperature information back to building simulations such that the closed-loop performance of HVAC system can be evaluated.

Comprehensive review of the literature indicates that coupled simulation of building energy systems (BES) and CFD often focuses on the integration of air handlers with indoor environment, and does not incorporate vapor compression systems into the analysis, yielding inaccurate prediction of building energy consumption. Meanwhile, the reported coupled simulations are all based on the commercial CFD programs rather than open-source code. To bridge the research gap, this paper attempts to couple the dynamic models of a room air-conditioner with detailed CFD model for indoor environment to explore the pull-down performance of the system with different vane angles and airflow modes. The dynamic models of the air-conditioner are constructed in Modelica, whereas the indoor environment is simulated in OpenFOAM. The use of coupled simulation facilitates more accurate exploration of system dynamics than using the well-mixed air model due to the inherent non-uniform air flow and temperature distributions in buildings.

Keywords: Modelica, OpenFOAM, co-simulation, building energy simulation, vapor compression system

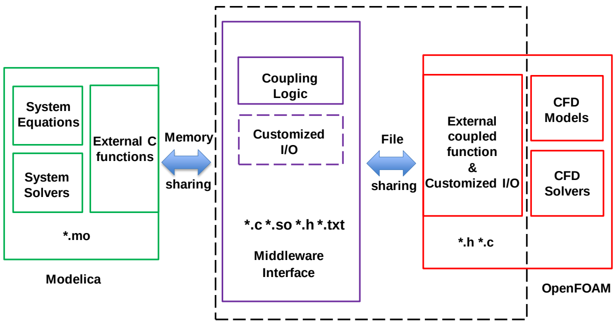

Figure 1. Coupling between Modelica and OpenFOAM.

Modelica language extensions for practical non-monotonic modelling: on the need for *selective* model extension

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Abstract

A Modelica language extension for structural non-monotonic model variation is presented. It enables *selective* model extension: the well-defined refinement of models by deselecting components and connections not of interest or inappropriate for a new design. The need for such variations is explained by the example of Modelica Synchronous, whose adaptation is suffering from crosscutting synchronous decompositions that cannot be *anticipated* when continuous models are designed; instead, contradicting model structure has to be removed when an *actual* sampling is desired. Besides synchronous, further applications for selective model extension are investigated using our prototype implementation in Dymola.

Keywords: Modelica, model variation, synchronous

1 Introduction

Of key importance for Modelica is model variation support, enabling simulation of design alternatives and their step-wise refinement from idealistic prototypes to physically-detailed solutions. To that end, Modelica provides many different abstraction and variation techniques, like model extension, replaceable components, parameters and component modifications.

Having a strong heritage from object-oriented programming however, Modelica's model variation constructs are monotonic with respect to model structure because components, connections or equations can only be added but not removed when extending models. An unfortunately overlooked consequence of flatting is however, that such a structural-monotonic type-strictness, as known from class inheritance in traditional strongly typed object-oriented programming languages like Java or C++, is not required in Modelica. In Modelica, models are flattened before simulation. Flattening essentially reduces the design space of a set of models to a fixed number of instances according to a given parameterization and replaces the resulting instances with their corresponding fixed equation system. The difference to traditional strongly typed object-oriented programming is striking: all instances are known before runtime, such that they can be statically constructed. There exists no *runtime* control-flow in Modelica that may cause different instantiations of entities; dynamic dispatch is not required, ultimately neglecting object-oriented polymorphism and the type-system restrictions that typically come with it[1]. As a consequence, Modelica's current restriction that sub-models must inherit all components and connections of their base-models when extending – that model extension must be monotonic with respect to model structure – can be dropped.

Leveraging on this observation, the paper presents a new Modelica-language extension for non-monotonic modelling: *selective model extension*. Selective model extension can be used to exclude components and connections in a *well-defined* way from inheritance when extending models. Its semantic can be fully understood in terms of model-diagram edits, such that tools can support a convenient graphical user interface for structure-wise non-preserving model variation. The main contribution of selective model extension therefore is to enable unforeseen structural variability without requiring deliberately prepared base-models.

The paper starts with an evaluation on the need for non-monotonic model variation in Modelica (Section 2). To that end, the application of Modelica Synchronous to refine continuous models for discrete use-cases is chosen which requires non-monotonic modeling to handle the crosscutting clock-partitions of different synchronous designs. Based on the non-monotonic modeling requirements elaborated throughout that discussion, an exact syntax and semantic for selective model extension is presented (Section 3). A demonstration of general practical modelling-benefits, not only for Modelica Synchronous, follows (Section 4). A prototype implementation in Dymola is used on a sophisticated example taken from the Modelica Standard Library to show how selective model extension enables model-development along the lines of real engineering processes – i.e., in terms of step-wise model variation and adaptation – avoiding model variation inconsistencies and artificial intermediate models without physical meaning.

[1]Object-oriented languages typically require monotony of inheritance to ensure the functionality of entities is well-defined for all usage-contexts, independent of control-flows determining instantiation. If sub-classes could drop base-class functionality – i.e., inheritance could be non-monotonic – runtime errors are possible whenever base-class functionality is called on sub-class objects. Static type-systems enforce monotonic inheritance to avoid such errors in the first place.

MetaModelica – A Symbolic-Numeric Modelica Language and Comparison to Julia

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Abstract

The need for integrating system modeling with advanced tool capabilities is becoming increasingly pronounced. For example, a set of simulation experiments may give rise to new data that are used to systematically construct a series of new models, e.g. for further simulation and design optimization. Such combined symbolic-numeric capabilities have been pioneered by dynamically typed interpreted languages such as Lisp and Mathematica. Such capabilities are also relevant for advanced modeling and simulation applications but lacking in the standard Modelica language. Therefore, this is a topic of long-running design discussions in the Modelica Design group. One contribution in this direction is MetaModelica, that has been developed to extend Modelica with symbolic operations and advanced data structures, while preserving safe engineering practices through static type checking and a compilation-based efficient implementation. Another recent effort is Modia, implemented using the Julia macro mechanism, making it dynamically typed but also adding new capabilities. The Julia language has appeared rather recently and has expanded into a large and fast-growing ecosystem. It is dynamically typed, provides both symbolic and numeric operations, advanced data structures, and has a just-in-time compilation-based efficient implementation. Despite independent developments there are surprisingly many similarities between Julia and MetaModelica. This paper presents MetaModelica and its environment as a large case study, together with a short comparison to Julia. Since Julia may be important for the future Modelica, some integration options between Modelica tools and Julia are also discussed, including a possible approach for implementing MetaModelica (and OpenModelica) in Julia.

Keywords: Modelica, MetaModelica, symbolic, Julia, meta-programming, language, compilation

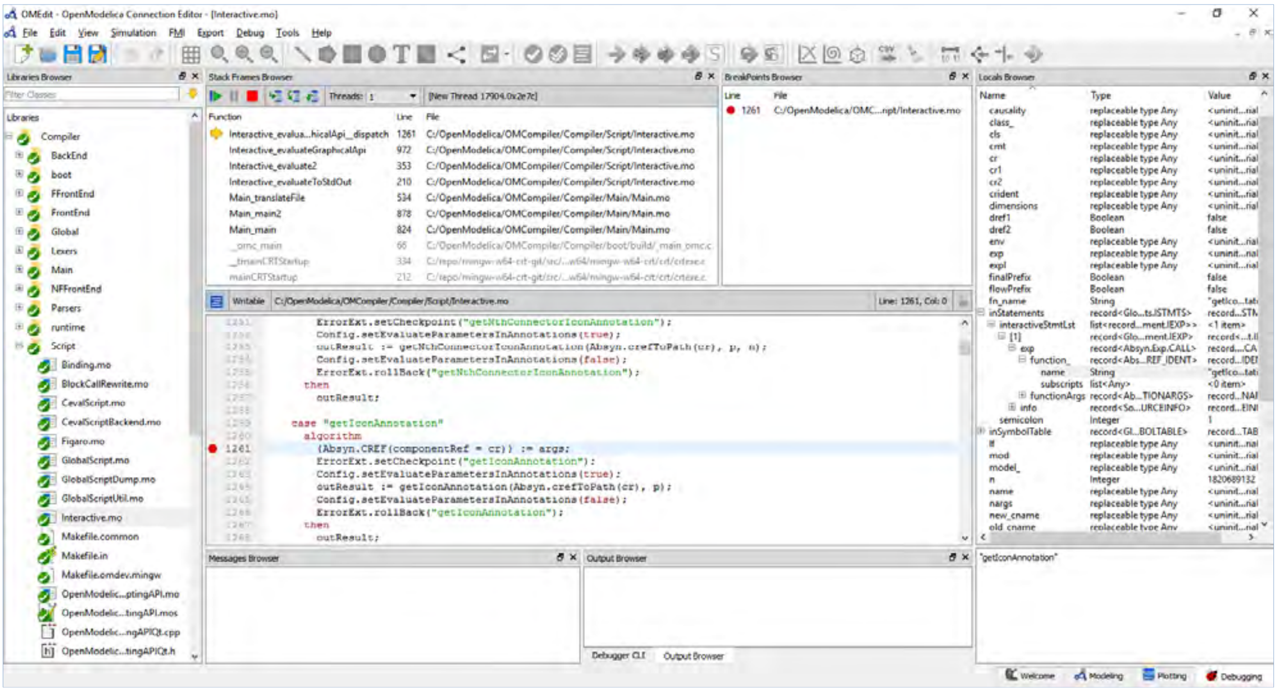

Figure 1. The integrated MetaModelica OMEdit-based development environment in debugging mode. *Left*: the package browser. *Top*: the active stack frames (including C routines) and breakpoints. *Middle*: text editing and breakpoint setting. *Right*: the local variables browser. The user can switch to modeling mode which has both textual and graphical editing.

Controller Design for a Magnetic Levitation Kit using OpenModelica's Integration with the Julia Language

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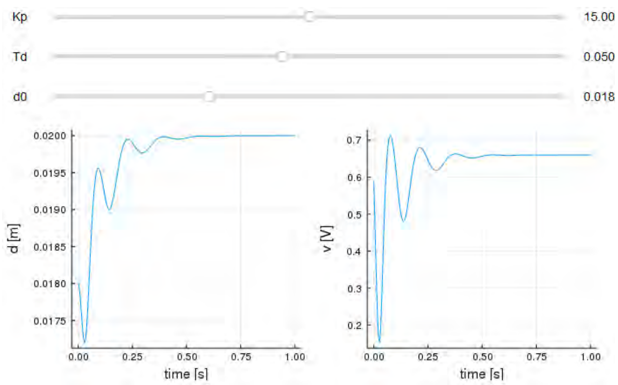
Abstract

This paper presents a practical application of computer aided control systems design using a new OpenModelica API (OMJulia) which allows to conveniently operate on Modelica models from the Julia language. Julia is a rather young language (Julia 1.0 was released in August 2018) designed to address the needs of numerical analysis and computational science, in particular it already has decent support for the control community. The magnetic levitation application at hand demonstrates how control system design can benefit from a suitable integration between Julia and Modelica. It is based on a commercially available control education kit in which the original controller is replaced by our own digital controller developed in this work. There exists an accompanying but independent paper which introduces the complete OMJulia API. Figure 1a depicts a simple web technology based GUI created in a few lines of Julia code which allows interactive experimentation with a closed-loop nonlinear magnetic levitation Modelica model using the OMJulia interface. Figure 1b shows the magnetic levitation system which uses the Arduino Uno as electronics prototyping platform for the presented digital controller.
Keywords: OpenModelica, OMJulia, control, magnetic levitation, Arduino, Julia, Modelica



(a) Simple interactive GUI with sliders for setting parameters of the closed-loop nonlinear magnetic levitation Modelica model using the OMJulia interface. Changing a slider will immediately trigger a new simulation and update the plots.

(b) Arduino controlled electromagnetic levitation system.

Figure 1. Magnetic levitation control design case study leveraging the OMJulia bridge to OpenModelica.

Towards a High-Performance Modelica Compiler

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Introduction

Large-scale models are becoming increasingly common in a variety of relevant application fields: *smart grids*, *detailed thermal simulations* and *coarse-scale fluid dynamics* are just some examples.

Mainstream Modelica toolchains, however, scale poorly for systems approaching or exceeding the one-million equation target. The code generation time is unacceptably large. The memory footprint of the generated simulation code is another scalability concern, as it has an impact on simulation speed due to CPU cache misses. Although the need to extend existing Modelica implementations to support large models is recognized by the Modelica community (Frenkel et al., 2011; Casella, 2015), significant effort is still required to effectively support large-scale systems.

Even considering the recent introduction of sparse solvers (Braun et al., 2017), existing Modelica toolchains perform heavy structural analysis optimization passes that scale poorly for large-scale system, and lose structural information during the flattening phase, such as arrays and looping constructs. As a consequence the generated C code does not exploit CPU architectures effectively. Furthermore, the C code generation phase does not take into account architectural optimizations, and simply generates unoptimized C code. This approach passes the burden of optimization to the C compiler, to the detriment to the overall translation efficiency and runtime performance.

New approach to Modelica compilation

In this paper we argue that significant performance improvements of Modelica toolchains could be achieved if an integrated approach is adopted, where high-level information from the Modelica source, instead of being transferred to an imperative language compiler, is used directly to produce architecture-optimized machine code. To scale the Modelica language to large-scale problems, a change of perspective is thus required, where a Modelica *compiler* – not just a translator – can perform model-specific and architectural-specific optimizations in an integrated way.

Our proposal aims at improving the code generation process without any impact on the Modelica syntax and semantics, thus being fully compatible with existing Modelica models and libraries.

A high-performance Modelica compiler needs to preserve arrays, `for` loops, and in general the object-oriented structure of the models as much as possible, in order to factor out common behaviour (= equations) in large-scale models. Thus it is possible to achieve much faster code generation, a much smaller memory fooprint, and hence much faster code execution thanks to the vastly reduced chances of cache misses.

The modularization of *flow* variables in connection sets and improvements to structual analysis for the compilation of systems of index greater than one are also areas of future research to achieve our goal.

We argue that to achieve this result in a cost-effective way, said Modelica compiler has to be integrated in an existing compiler framework.

For this reason, we propose to design a Modelica compiler integrated in LLVM (Lattner and Adve, 2004), which is a state of the art compiler framework, designed with the explicit goals of modularity and extensibility.

The authors form an inter-disciplinary research group within the Dipartimento di Elettronica, Informazione e Bioingegneria of Politecnico di Milano, which includes strong competences in the areas of Modelica and object-oriented modelling and simulation, Computer Architectures and Compiler Design.

This on-going work is today at a very early stage of development. The main goal of this paper is thus to present this group's vision and roadmap, as well as to present some initial results of a very early prototype.

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Overview of the DLR RailwayDynamics Library

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Christoph Schwarz[1]

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Keywords: railway vehicle dynamics, wheel-rail contact, multi-domain vehicle modeling

Background and Motivation

Railway vehicles are complex multibody systems running at high speed along a given track. The particular contact between steel wheels and rails carries the payload, provides lateral guidance and submits traction forces. The running gears and their suspensions ensure track-holding and control the vibration comfort, which the passengers perceive.

However, railway vehicles also employ multiphysical subsystems such as pneumatic friction brakes and air suspensions, electrical engines to provide propulsion and to regenerate energy, Diesel-electric or Diesel-hydraulic drive trains and so on.

With this background, the newly released commercial DLR RailwayDynamics Library is supposed to support holistic system design, optimization and hardware or software in-the-loop testing by provision of vehicle dynamics models. Since these models may be scaled and adapted with respect to the required modeling level, the library proposes a sound modeling framework to support multidisciplinary engineering tasks.

Railway Modeling Particularities

Besides library structure and templates to assemble vehicle models from substructures, the paper presents some modeling particularities that are tailored for railway dynamics simulations:

- the track, which is the path as a function of the path length parameter s, i.e. the 3D curve $\boldsymbol{r} = \boldsymbol{r}(s)$, the vehicle is intended to move along,
- the track joint that defines one mechanical degree of freedom and presents the capability to move along the 3D path $\boldsymbol{r}$,
- the track panel, which is used to introduce the flexibility of the rail and the subgrade structure,
- the wheelset, that reproduces inertia properties and contains two translatoric and three revolute degrees of freedom of the wheels in addition to the longitudinal motion already presented by a track joint,
- and the wheel-rail contact model, which includes the consideration of non-linearities in normal and in tangential direction in view of the wheel and rail profile geometry.

Example Applications

The paper contains elaborate example applications, which in parts are shown in Fig. 1:

- Traction analysis investigates in-train forces as well as longitudinal oscillations of coupled vehicles during acceleration and braking maneuvers.
- Comfort studies examine and assess the level of vibrations that the passengers perceive and which are initiated by track lay-out and irregularities.
- Roller rig models reproduce the capabilities of test rigs that are used for research and development in industry and research institutes.

Conclusions and Outlook

The consideration of vehicle dynamics issues in multidomain engineering tasks is a specific focus of the RailwayDynamics Library. Therefore, the paper also includes two proposals in order to organize multidomain modeling, on which the authors intend to initiate a discussion. Additional future applications of the library concern the synthesis of advanced observer and control lay-outs and refined assessment scenarios for crosswind stability of railway vehicles.

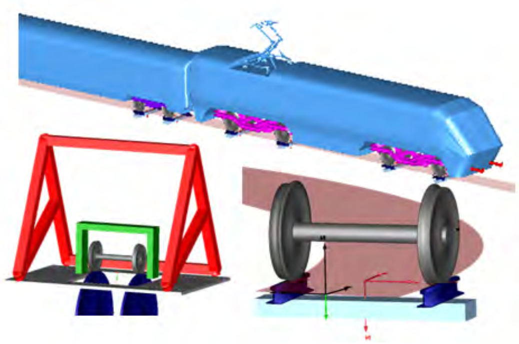

Figure 1. Animations from example applications of the DLR RailwayDynamics Library

Using Baumgarte's Method for Index Reduction in Modelica

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Abstract

Modeling and simulation of some types of constrained mechanical systems, such as closed kinematic chains, can be challenging in the Modelica language. One reason is because component-oriented modeling for such systems results in a set of high-index nonlinear differential algebraic equations (DAEs). Modelica compliers, such as Dymola, use the method of "dummy derivatives" to reduce the index automatically, for very good and fundamental reasons. However, for closed chains it has some disadvantages, and there are other methods which have advantages especially for consistent initialization and use cases beside simulation, such as control system design.

In this paper we show by example how Baumgarte's method of index reduction can be used in Modelica to reduce the index of a constrained mechanical system *prior* to compilation. The method is applied at modeling time, and results in a model that is of lower index to begin with, so that the compiler does not have to reduce further the index. We begin by showing Baumgarte's method for the simple pendulum. The method and its properties can be understood from this example. But our primary target is a delta robot, for which we derive a singularity-free, index 1 differential-algebraic equation model. No automatic index reduction is done at compile time, and no dynamic state selection is required at simulation time. We find that the method is amenable to Modelica's object oriented modeling paradigm, and results in simulation code that can be, at least anecdotally, faster. We construct several components of a feedback controller directly from the index-1 system model, and show how consistent initial conditions can be computed in this formulation.

We provide a third example, elevator cable sway, in which the method is vital to simulation and feedback control system design. Indeed we have failed to construct a model of this system using the Modelica Standard Library and Dymola's built-in index reduction algorithms. However using Baumgarte's method to essentially pre-reduce the index results in a simple model. We have developed several feedback control strategies for reducing cable sway that occurs during events such as earthquakes.

The method can be extended to model some situations in which constraints are time-varying, such as in loss-of-contact or constraint-breaking problems. More generally, we believe the method may find successful application in other domains, particularly for problems in which consistent initial conditions are difficult to compute.

Keywords: DAE, index reduction, robotics, control

Modeling of Rotating Shaft with Partial Rubbing

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Abstract

The rubbing phenomenon is one of the main malfunctions in rotating machines and causes the breakdown of machines. The rub-impacting vibration of a rotor system shows a very complicated phenomenon including not only the periodic motion but also the quasi-periodic and chaotic motions. When the rub-impact happens, the partial rub arises at first. During a whole period, the rub and impact interactions occur between rotors and stators (i.e. casings) once or fewer times. Gradual deterioration of the partial rub will lead to the full rub, and then the vibration will affect the normal operation of the machines negatively.

Because of serious damage of rubbing, many researchers have studied this problem from different aspects. Much attention has been given to the nonlinear dynamics of the rub-impacting rotor system. A contact force of rubbing between a rotor and a casing has been modeled as a piecewise linear spring and damper model. The relationship between the contact configurations and the generation of various kinds of vibration, such as "collision type synchronous vibration", "sub harmonic vibration", etc. has been studied, both theoretically and experimentally (Watanabe *et al*, 2005).

We have created the rotating machinery library by transfer matrix method in Modelica (Ishibashi *et al*, 2017). By transfer matrix method, the rotating shaft is decomposed into rotors, shafts, journals, couplings, housings and supports. The 5 DOF rotor dynamics model components have common faults of rotating machinery systems such as static and dynamic unbalance, shaft bending, and faulty bearing. The objective of creating this library is to carry out analytical investigations in order to gain some insight into the diagnostics of rotating machinery.

In this paper, rubbing components for partial rub are implemented in our rotating machinery library. Rubbing components in the one side contact case and the annular contact case are created for analyzing the several contact configurations respectively (Figure 1).

In the analysis of rubbing, models in which the rotor come into contact with the casing due to unbalance or models in which rotor is already contacting with the casing at rest are usually analyzed. However, in this research, the model in which the rotor come into contact from a non-contact state by an external force due to earth quake or flow-induced vibration is analyzed. The relationship between the contact configurations and the generation of various kinds of vibration is investigated (Figure 2). We validated the rubbing model in one side contact case with a rotor kit. By simulation, we reproduced the time history, the orbit and the full spectrum characteristics of the rotating shaft measured by the experiment precisely.

Keywords: Rotor Dynamics, Rubbing, Contact, Friction, Subharmonics

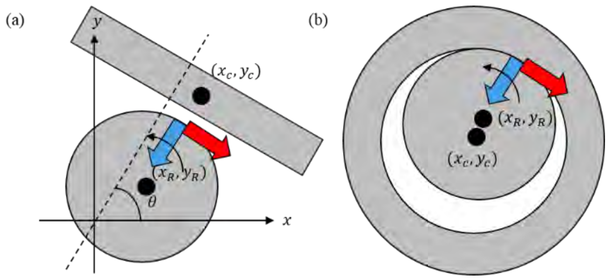

Figure 1. Type of Rubbing. (a) One side contact case. (b) Annular contact case.

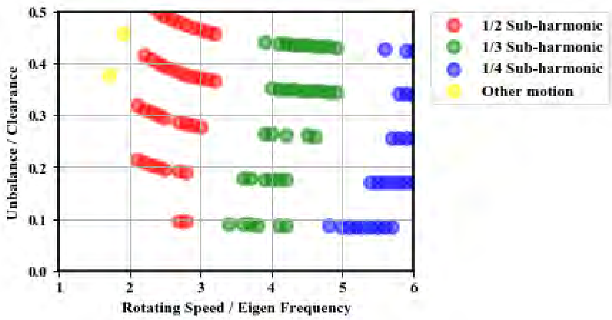

Figure 2. The domain of the rubbing vibration occurrence in the one side contact case.

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Aspects of Train Systems Simulation

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Abstract

This paper present needs and implementations for system modeling of high speed trains with focus on the Beijing-Zhangjiakou Intercity Railway.

Typical scenarios which are relevant in systems design are

- Vehicle energy consumption estimation for systems and supply network optimization
- Electric grid harmonic estimation for topology and filter selection
- Traction system thermal capacity estimation for cooling system layout and control of power reduction
- Driven cars stability estimation

The implementation of the library with Modelica is discussed and demonstrated for the rail-wheel contact and mechanical, logical, electrical and thermal systems, with special attention to the rail-wheel contact and electrical power off-take.

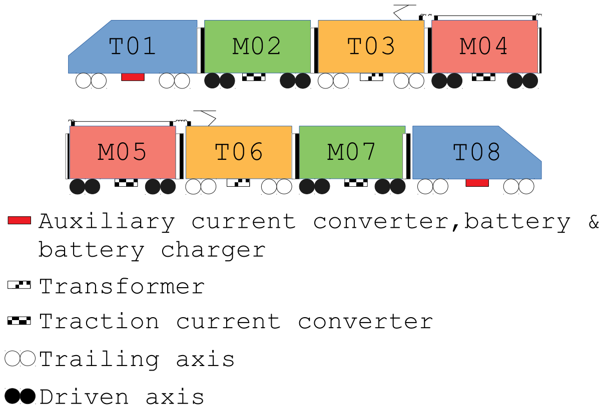

Figure 1. Schematic diagram of traction system.

Modeling Supply and Demand in Modelica

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Abstract

This paper demonstrates using component oriented modeling and acausal semantics to create a basic library of behavioral components to model supply and demand. The models presented are each steady state models. While some examples include shifting economic conditions that cause the equilibrium points to change during the simulation, none of the models feature dynamic states. The main purpose of this paper is to demonstrate to people unfamiliar with Modelica (Modelica Association 2017) how Modelica can be used to model non-engineering systems and how it makes such modeling faster, easier and less error-prone compared to other approaches (*e.g.,* using spreadsheets).

Modelica Modelling of an Ammonia Stripper

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This work presents a Modelica model for an ammonia stripper that is used to process waste (digestate) from a biogas production unit.

Figure 1 shows the basic configuration of the simplified stripper along with the inputs, outputs and the processes under consideration. Digestate enters the stripper with a given flowrate and initial composition. Air is added at the base of the stripper with a given temperature and relative humidity. At the top, the result is a stripped gas containing air, water and ammonia. The liquid output is the digestate with reduced TAN (total ammonia nitrogen). Heat is lost from the liquid through warming of the gas and the liquid to gas water mass transfer (evaporation). Hence, heating is required to maintain the digestate at the correct temperature an ts of the stripper

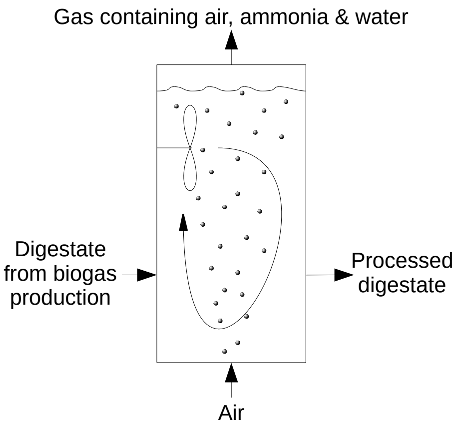

Figure 1. Stripping column exchanges.

The model includes the chemical balance equations between species in the liquid and gas, and includes the exchanges between both phases and the energy consumption of the unit. In Figure 2 the model inputs are in red and the outputs are in blue. The internal processes are in green, where the mass balances include $NH_{3(aq)}$, NH_4^+ , HCO_3^- , CO_3^{2-} , $CO_{2(aq)}$, N_{org} , H_2O , H^+ and OH^- species for the liquid phase, NH_3, $CO_2$and H_2O species in the gas phase. The energy balance includes water vaporisation and air heating. In order to model this process we must consider the chemical equilibrium between the TAN and DIC (dissolved inorganic carbon) species, the mass transfer of NH_3, $CO_2$and H_2O between liquid and gas, and an energy balance. The dynamics in the column depend on time lumn heigh g column l

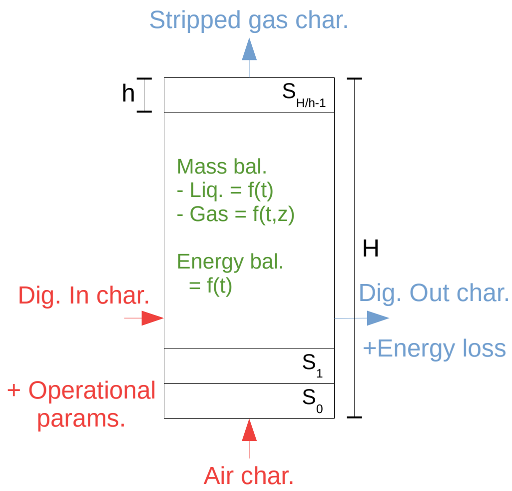

Figure 2. Stripping column schematic.

Results show the expected behaviour with an increasing pH with time (Figure 3), with further validation and calibration being necessary once experimental results are available. This is a novel use of Modelica designed to expand the library of processes that are simulated using this approach.

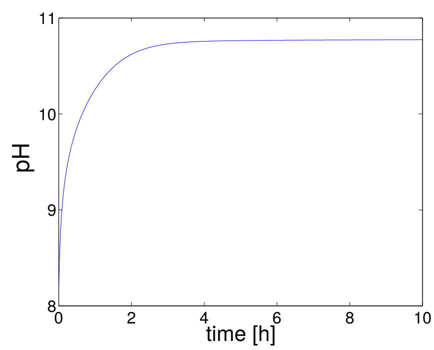

Figure 3. Change in pH with time.

Keywords: nutrients recovery, chemical reactions, process engineering, environment

Algorithms for Component-Based 3D Modeling

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The experimental, open source modeling environment *Modia3D*[1] is used to test and evaluate ideas to model and simulate larger and more complex 3-dimensional systems than it is possible with a pure equation-based modeling system such as current Modelica. Modia3D models 3D mechanical systems and utilizes ideas of multi-body programs and game engines. It is implemented with the powerful *Julia programming language*[2], which supports multiple dispatch, metaprogramming, and has excellent performance benchmarks compared to C. The basic idea is to combine 3D modeling techniques closely with equation-based modeling à la Modelica within one high level programming environment. *Modia*[3] is used for the equation-based modeling and is implemented with Julia's metaprogramming features.

The user's view of Modia3D was introduced in (Neumayr and Otter, 2018) to show the very flexible definition of 3D systems and to start an approach to cope with the underlying inherent Modelica issues. In this article, several key algorithms are discussed which have been developed for the Modia3D prototype. One of the algorithm groups Object3Ds, depending on their properties, into rigidly attached super-objects (Figure 1).

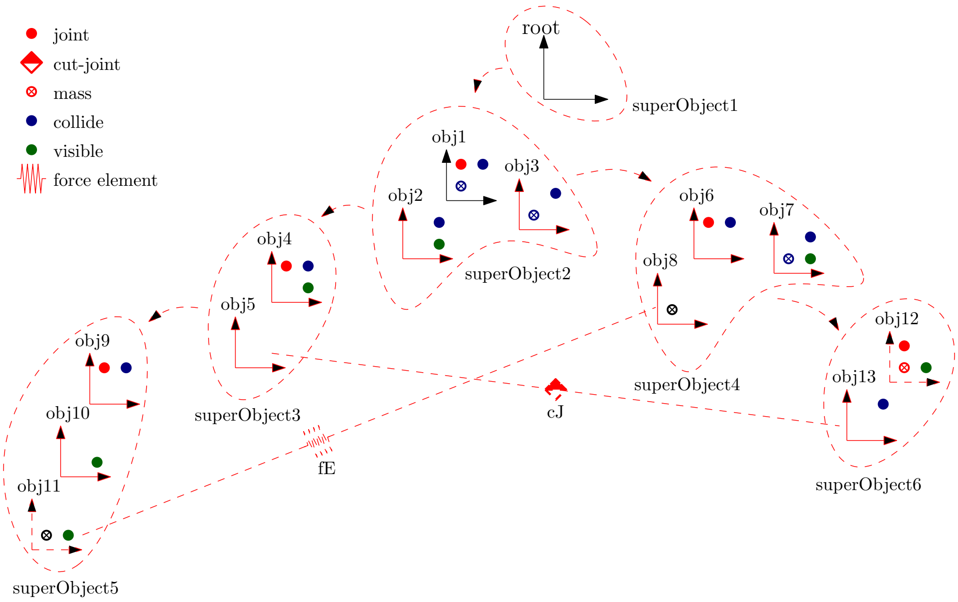

Figure 1. 14 Object3Ds with different properties like they are allowed to collide, can have a mass, are visible and/or can have a force element, are grouped into six rigidly attached general super-objects connected via joints and cut-joints.

Modia3D is still a prototype it is implemented for functionality and not tuned for efficiency. In the near future, Modia and Modia3D shall be closely integrated, e.g. using a Modia3D model in Modia or using Modia models in Modia3D. The overall goal is to apply the results of the Modia/Modia3D prototyping into the design of the next Modelica language generation.

A. Neumayr and M. Otter. Component-Based 3D Modeling of Dynamic Systems. In M. Tiller, H. Tummescheit, and L. Vanfretti, editors, *Proceedings of the American Modelica Conference*, Oct. 2018. URL https://elib.dlr.de/124126/1/2018_Modelica_Modia3D.pdf.

[1]https://github.com/ModiaSim/Modia3D.jl
[2]https://julialang.org
[3]https://github.com/ModiaSim/Modia.jl

Model visualization for e-learning

Kidney simulator for medical students

Jan Šilar, Filip Ježek, Arnošt Mládek, David Polák, Jiří Kofránek

The present paper introduces a recently developed tool for building web-based simulators called Bodylight.js. Simulators are applications composed of a mathematical model and a graphical user interface that allows the user to easily interact with the model and visualize the results. A modelica model is first exported to FMI with sources, transcompiled into JavaScript and WebAssembly and connected to a GUI, comprised of graphical animations created in Adobe Animate and elements that allow to control the input model such as sliders, buttons, etc.

A physiological e-learning application explaining the function of a nephron – the basic functional unit of kidneys – is presented later as a use-case. The model was developed primarily as a teaching aid for use in courses of physiology for medical students at our university.

Purpose of this work is to describe the new Bodylight.js tool and to prove its usability by building the medium-complex e-learning kidney simulator. The simulator helps medical students to better understand renal function at the very basic level.

Keywords: Modelica, JavaScript, WebAssembly, web technologies, physiology, kidney, e-learning

Platform for Microgrid Design and Operation

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This paper describes the development and requirement specification of a platform for design and operation of microgrids.

The goal is to have a platform based on open standards that can be used to efficiently solve current and future engineering problems for distributed energy sources and storage systems. By basing it on a unified architecture, collaboration and efficient work flows are enabled.

In this work we investigate the requirements on the model and on the tool side. We also demonstrate how an energy storage system can be designed to reduce the maximum peak power and how it can be operated in the most economic efficient way, taking into consideration constraints and limitations of the system.

This work is based on Modelon's web-based modeling and simulation platform and its Modelica library Microgrid.

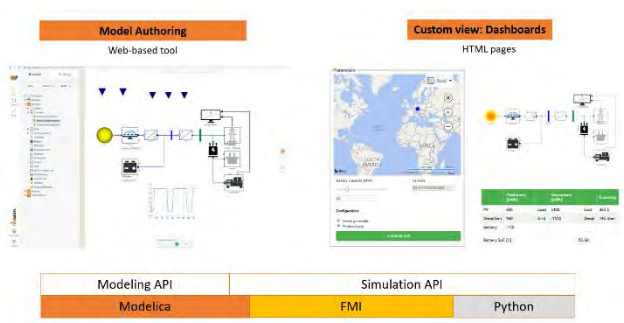

Figure 1 Microgrid models in an architecture overview of Modelon's web-based modeling and simulation platform.

Keywords: simulation, optimization, peak shaving, battery storage, energy management, economic dispatch

Influence of Excess Power Utilization in Power-to-Heat Units on an Integrated Energy System with 100 % Renewables

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Introduction and Previous Work

Reducing CO_2 emissions to limit the effects of climate change is one of the biggest challenges of today's society which will lead to a significant change of the architecture of our energy system.

To examine the configuration of the future integrated energy system of Germany, many studies have optimized the system using quasi-stationary models which neglect dynamic effects. To avoid this simplification, Bode and Schmitz (2018) have developed similar models in MATLAB® and Modelica®. The MATLAB models are used for the simplified simulation of the system consisting of the power, heat and gas sectors. Those results are then validated and modified using dynamic models from the TransiEnt Library (Hamburg University of Technology, 2018) written in Modelica including the dynamic effects. That way it is ensured that the system is within the physical boundaries which might be violated by quasi-stationary models.

The system consists of renewable power generation, biogas production, electric energy storage technologies, Power-to-Gas units, gas storage volumes, Gas-to-Power units, heat producers and hot water storage units. Different configurations, i.e. combinations of storage technologies and heat producers, can be compared by cost.

Method

In this work, the existing models are extended, adding curtailment of renewables to reduce the size of the Power-to-Gas plants in particular because they are not sized according to the maximal load anymore which can reduce the system cost. The former models are also improved by adding more detail especially in the heating system while also simplifying some models and the control structure for a faster and more robust simulation.

The system costs are optimized using the quasi-stationary models in MATLAB employing the algorithm `patternsearch` leading to the reference case System 1 (S1). It is then designed in detail including the dynamic effects in Modelica.

In the next step, the effect of excess power utilization in the heating system compared to curtailment is investigated. In S2, the electric heat pumps use excess power and in S3, additionally the electric heating rods in the hot water storage tanks consume electricity. This way, the heat generation is shifted to times with high renewable electricity generation. These effects are highly dynamic and are easily captured by using Modelica.

Results

The combination of both MATLAB and Modelica in this context shows the advantages and disadvantages of each language. The quasi-stationary models in MATLAB are fast but not as versatile as the Modelica models which ensure good reusability and capture dynamic effects. Also, the models are easily understood and adapted.

The results show that a combination of lithium-ion batteries, Power-to-Gas plants, combined cycle gas turbines and electric heat pumps is the most cost efficient under the given assumptions. If you compare S1 to S2 and S3, cost reductions of 0.36 % (S2) or 0.64 % (S3) can be realized. The shift of the heat generation leads to less curtailed electricity and thus to an increase of the overall system efficiency. This means that most of the components are required in smaller sizes, which lowers the overall system cost, and only control has to be added to the system.

Acknowledgements

The authors greatly acknowledge the funding from the German Federal Ministry of Economic Affairs and Energy for the project "ResilientEE - Resilience of integrated energy networks with a high share of renewable energies" (project number: 03ET4048).

Keywords: Integrated Energy System, 100% Renewables, Power-to-Heat, Energy System Analysis

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Model-Based Controls Development and Implementation for a Hydroelectric Power System

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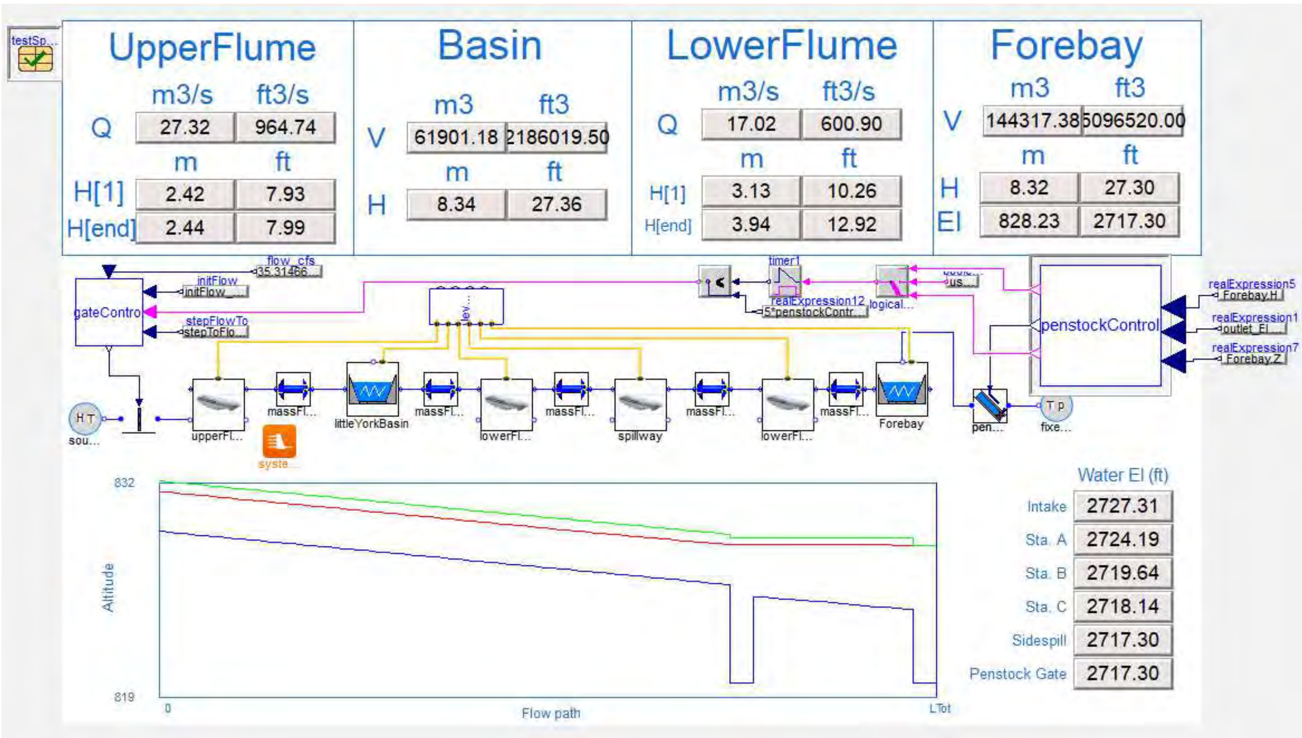
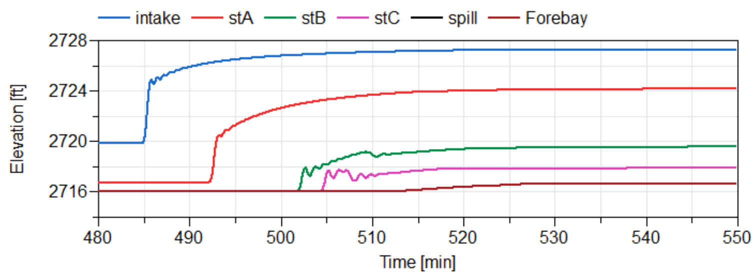
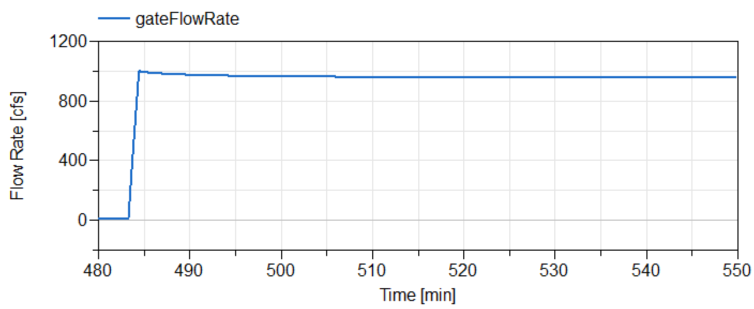
This paper describes the model-based control system development for a hydroelectric power plant to ensure water level control and mitigate spillage risk. The modeling of both the flume system and prototype controls is described. The integrated model is run over a suite of tests to verify the calibration of the control strategy. Results from the plant commissioning are compared with the virtual tests. The model proved capable of accurate predictions of the waterway dynamics, and the model-based calibration was successfully verified on the actual plant.







Fault Insertion for Controller Calibration in a Range of Engine Models

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Abstract

Predictive modelling is becoming increasingly popular to dimension or calibrate systems prior to the design stage. If current models are capable of modelling physical systems very accurately, they often only model the system's expected behaviour. Some particular tasks like Engine Control Unit (ECU) calibration require the models to work abnormally too to make sure that the controller detects the faults (OBD diagnostics).

The aim of this paper is to introduce various faults in a multidomain (pneumatic, hydraulic, thermal, mechanical and electrical) engine model developed in Dymola to demonstrate that it is capable of detecting and identifying these faults and of taking measures to limit their effect and/or to prevent further damage to the system. One of the requirements if that the ECU should be able detect a fault solely from the measurements given by the physical sensors that are used throughout the model.

The engines used in this study come from the VeSyMA – Engines library developed by Claytex. They are all (with the exception of the last one) crank-angle resolved engine models with varying features and levels of details depending on the area of interest. The ECU used is a software version of a real ECU.

The faults modelled are a leak in the air path of a turbocharged four-cylinder engine, a clogged injector in a naturally aspirated three-cylinder engine, a stretched timing chain in a naturally aspirated four-cylinder engine, a short-circuit in the control board of a throttle body in a naturally aspirated four-cylinder engine and a coolant leak in a naturally aspirated four-cylinder engine.

The paper will introduce the types of faults, show their physical consequences on the engine model's behaviour, detail the process and flow of information that allows the ECU to spot the abnormal results and finally explain what the ECU does in reaction to these faults.

Enhanced Motion Control of a Self-Driving Vehicle Using Modelica, FMI and ROS

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[2]Robert Bosch GmbH, Germany, {oliver.lenord, ralph.lange}@de.bosch.com

Extended Abstract

Industrial logistics is an important application area of autonomous robotics. In the last years, a number of elaborate algorithms for task scheduling, coordination and path planning for fleets of self-driving vehicles in such applications have been proposed. Prerequisite to apply these strategies is a reliable vehicle motion control. Trajectories commanded by the planner need to be properly executed by the drive platform to ensure that the goals of the mission are met in time and space.

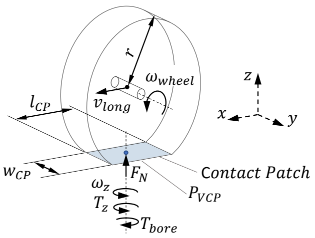

Figure 1. Tire road contact.

Model-based control design is a well established approach to design and apply motion control strategies. Model-in-the-loop (MiL) simulations allow to validate and test the control design early on. Optimized controllers can be designed that take the physical properties and system dynamics into account.

In this work, a common problem of motion platforms with differential drive and caster wheels is elaborated. By applying a model-based control design approach the reliability of the motion controller is significantly improved by the so called *Path Filter*. It is based on a new planar wheel model with bore friction (cf. Figure 1) and a control

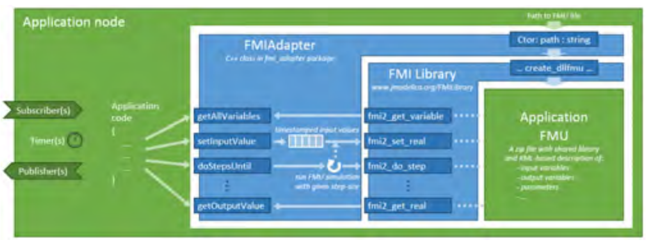

Figure 2. Architecture diagram from fmi_adapter package.

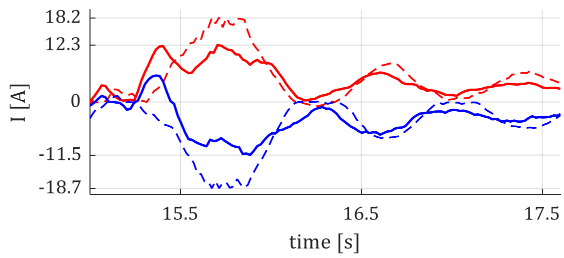

Figure 3. Measured motor currents for initiating a CW turn on the spot. The ActiveShuttle was driving forward prior to that. Dashed lines represent the results w/o path filter, solid lines the results with $\omega_{max} = 100$ rad/s and $T_\varphi = T_\omega = 0.01$ s. Red and blue lines represent the left and right drive, respectively.

strategy to avoid locking conditions caused by the caster wheels. The path filter has been designed as self-contained function that can be retrofitted into an existing control architecture between motion planer and motion controller.

The path filter has been applied to the *ActiveShuttle DevKit*, a self-driving vehicle (SDV) for industrial logistics. The software of the ActiveShuttle is based on the *Robot Operating System* (ROS). In order to enable a generic and efficient control design process, the integration of the Path Filter control function into ROS is facilitated through the Functional Mock-up Interface (FMI). For this purpose, we present the new FMI-Adapter software package (github.com/boschresearch/fmi_adapter/), which allows to integrate Functional Mock-Up Units into ROS nodes as illustrated in Figure 2. An introduction to ROS is given and the mapping between ROS and FMI concepts explained.

The functionality and performance of the Path Filter is tested on the ActiveShuttle DevKit prototype. Our experiments confirm, (cf. Figure 3), that the effort to perform movements that require the caster wheels to be turned on the spot is drastically reduced. Moreover, oscillations in the motor currents caused by the abrupt release of the counteracting bore torque decay much faster. Jerks are reduced, which increases the durability of hardware components and improves the stability of shaky loads. Most important, the risk of getting stuck in a lock condition is drastically reduced.

Systematic Simulation of Fault Behavior by Analysis of Vehicle Dynamics

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A new library for *System Reliability Analysis (SRA)* in *SimulationX* (www.simulationX.com) for systematic modelling of fault effects in multi-physical systems is introduced. The motivation is outlined, as well as a description of the library structure and two helper libraries (*FeatureExtraction*, *RequirementsFulfillment*). Additionally, an accompanying utility is presented that enables semi-automatic fault augmentation and analysis of fault-augmented models. The *SRA* library is exemplified in the automotive domain with the fault effect simulation by analysis of vehicle dynamics using a new modular library *Driving Maneuvers* in *SimulationX*, which contains various chassis model elements, wheel and axle suspensions, wheel elements with tire model, driver models, track and environment components and complete vehicle models. A vehicle model is systematically augmented with connector and component faults for the analysis of different fault effects on vehicle dynamics.

Throughout the paper, the term fault refers to any deviation from the nominal system's behavior. The Modelica® components developed for the *SRA* library in *SimulationX* simulate only the effect of a process on the system's behavior and focus on its dynamical evolution or interaction with other processes. For example, mechanical faults in joints, gears, shafts, springs or clutches because of breakage or slipping lead to the reduction of transmitted forces or torques. The current reduction because of bad or open connections in an electrical system, the mass flow decreases in a hydraulic system because of leakage or obstruction as well as changes of heat flows in a thermic system have comparable behavior and can be similarly structured, modeled and analyzed (Kolesnikov *et al*, 2018). As an example, the three oscillators from different physical domains shown in Figure 1 are similarly structured and augmented with faults in *SimulationX*. This follows from the analogies between the basic electrical, mechanical and hydraulic network elements.

In the presentation, we introduce the *SRA* and *Driving Maneuvers* libraries. Based on the developed fault-augmented vehicle model, a systematic method for the fault augmentation of multi-physical systems is outlined. In addition, we demonstrate two helper libraries and the *SRA* Add-In for semi-automatic fault augmentation, simulation analysis and post-processing of fault-augmented models.

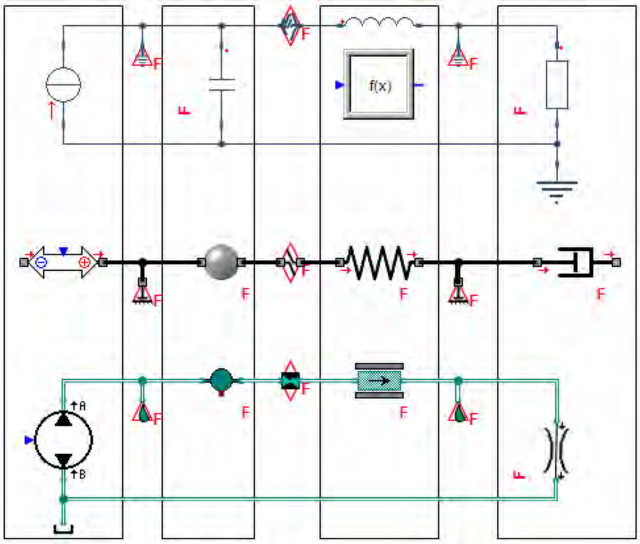

Figure 1. A model of oscillators in SimulationX with electrical, mechanical and hydraulic network elements after the augmentation with connector faults (red connectors) and parametric faults (components with the symbol F).

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Modeling and Simulation of Dual Redundant Electro-Hydrostatic Actuation System with Special Focus on Model Architecting and Multidisciplinary Effects

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Abstract

Electro-hydrostatic actuator (EHA) is a new trend in the more electric aircraft related research works and engineering applications. As a high-performance mechatronics product, however, the physical effects of actuator behavior are multidisciplinary, coupled and strongly nonlinear. Although many commercialized multi-domain and system-level simulation packages exist, they are rarely considered and analyzed as a whole, lacking of a unified model architecture, efficient modeling forms, and comprehensive simulation verification. In this paper, Modelica is used to build a multi-domain virtual prototype of the dual redundant electro-hydrostatic actuation system (DREHAS) that consists of two EHAs in parallel, which supports multi-view modeling and interdisciplinary application of the system. Finally, a simulation application case of the elevator actuation system is presented to demonstrate the effective role of Modelica models in system modeling and evaluation.

Keywords: more electric aircraft, dual redundant electro-hydrostatic actuator, working mode, system model, Modelica

A Modelica-based environment for the simulation of hybrid-electric propulsion systems

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Abstract

In order to meet the challenging CO2 emission goals defined for aviation in Flightpath 2050 (compare European Commission, 2011), new disruptive aircraft developments are required to accelerate the progression of aviation technology. Similar to the automotive field, hybrid electric propulsions systems constitute a promising avenue for reducing the emissions by extending the aircraft design space. This extension includes the usage of electrical energy storages, and airframe integration concepts of the propulsion systems like boundary layer ingestion and distributed propulsion. Lately, numerous studies have been published and announced by NASA (SCEPTOR, STARC-ABL, SUGAR Volt) and companies in Europe (compare Siemens Extra 330, Airbus E-Fan X).

In this context, novel power train architecture topics emerge enquiring for a propulsion system modeling tool providing means for the analysis of various power train architectures and operation strategies as well as trade studies amongst them.

In this paper, such an analysis framework is presented in form of a novel Modelica library. The framework is meant to accompany the design process thought the different design stages ranging from basic concept studies to detailed architecture analysis. The main challenges that had to be tackled during the library development include:

- High modularity for changing the model fidelity level according to the current design detail
- High flexibility to accommodate the different powertrain architectures (compare figure)
- High flexibility in operation strategies
- Confining the model complexity in sub-models to generate well-conditioned equation systems
- Initializing the power train in an arbitrary state
- Structuring the problem in handy subsystems

The presentation depicts the hierarchical structure of the modeling approach, key modeling concepts and closes with exemplary brief demonstration of the analysis capabilities. Furthermore, the library provides means of coupling the power train models with aircraft models and a framework for a holistic hybrid electric aircraft analysis. The holistic analysis is necessary since the subsystems of an aircraft are strongly coupled. E.g. the additional drag caused by the cooling of the power train losses and the additional weight of the power train might cancel the drive train benefits partially or even surpass them.

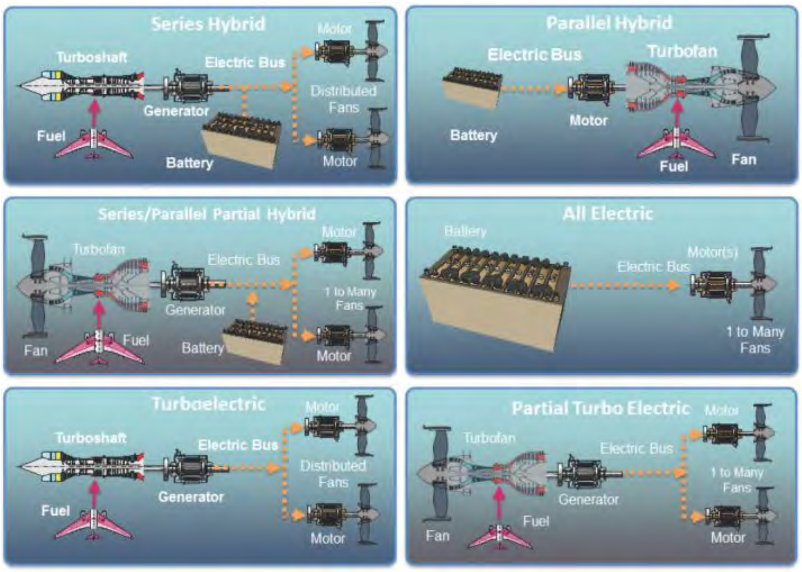

Figure 1. Categorization of the potential power train architectures for hybrid electric propulsion systems in aeronautics (National Academies of Sciences, Engineering, and Medicine, 2016).

Advances in Flight Dynamics Modeling and Flight Control Design by Using the DLR Flight Visualization and Flight Instruments Libraries

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Abstract

Modelica has become an important language in the field of flight dynamics modeling and flight control design. Moreover, the possibility of rapid prototyping within these fields has become a key technology within the development of modern aircraft.

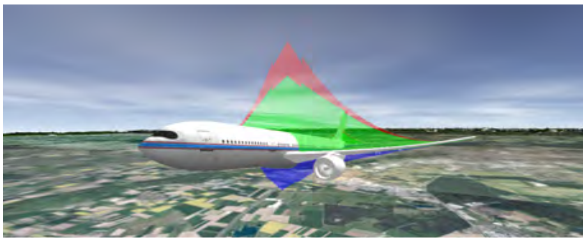

Figure 1. Example of a visualization created with the DLR Flight Visualization Library.

This paper presents the Flight Instruments and Flight Visualization Libraries developed within the DLR Institute of System Dynamics and Control. For the design of dynamic models and control systems, a visual evaluation of the dynamic simulation (Figure 1) is indispensable for a successful design and test process. Especially when it comes to aircraft models, an overview of the overall dynamics is needed. Therefore, the presented libraries provide fast assembly of fully configurable and generic flight visualization tools in which the view positions as well as the setup of Primary Flight Displays can be chosen freely. This provides the visual components of a rapid prototyping environment which can be used in the development of flight dynamic models and flight control laws.

In addition to the enhancement of this rapid prototyping process, a visualization framework has been developed and proven helpful in supporting the design process in terms of configuration analysis, simulation and experiments. The camera views and displays can easily be reconfigured for each purpose and research focus area. Furthermore, the libraries can be used for desktop simulation, motion simulator experiments as well as flight testing on a real aircraft (Figure 2).

Thus, the developed libraries close the gap for integrating flight dynamics visualization into the Modelica environment using the DLR maintained Modelica Visualization Library. The two libraries open up the possibility of a completely accessible, in-house developed aircraft visualization and simulation environment.

Figure 2. Cockpit instruments in use for flight testing on a Cessna Citation aircraft.

The libraries are not only restricted to use in aircraft simulation, but can also be used for any dynamic vehicle simulation, e.g. underwater vehicles. The first part covered is the simulation of a moving vehicle in an environment, which provides the user with easy accessible visual information of the vehicle's attitude and moving direction. Secondly, instruments and displays can efficiently be used to embed important information into the visualization model or to generate a separate display. Thus, the overall process chain from model development, control design, simulation and testing is further enhanced and simplified. Additionally, all steps of the process chain are kept completely accessible for the engineer and no "black box" visualization tools are required. Both libraries are currently not distributed since development and extension are still ongoing.

DAE Solvers for Large-Scale Hybrid Models

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Abstract

We present a strategy for DAE mode simulations of large-scale Modelica models with *state events*. DAE solvers can be orders of magnitudes faster than traditional ODE solvers when simulating models with large algebraic loops. Such loops are common in, for example, power grid models.

Central for our DAE mode approach is the accurate and efficient treatment of state events. Adapting, extending, and optimizing results known in the literature to the Modelica context resulted in a DAE mode implementation first released in Dymola 2019 and 3DEXPERIENCE 2019x.

The implementation is verified by efficiency experiments featuring the OpenIPSL power grid model *Nordic 44*. The run times are competitive with domain-specific, state-of-the-art simulation tools.

Table 1. CPU-times for the three Nordic 44 fault scenarios.

Fault scenario	*Rkfix2*	*Dassl*	
	ODE mode	*ODE mode*	*DAE mode*
Line	587 s	2 015 s	4.21 s
Bus 3100	270 s	7 810 s	33.7 s
Bus 5603	344 s	49 800 s	121 s

Adaptive Step Size Control for Hybrid CT Simulation without Rollback

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Hybrid systems demonstrate both discrete and continuous behaviour which makes their simulation challenging. A possible approach is *Hybrid CT* that uses *continuous time* simulation and provides wrappers for discrete event components (as opposed to *Hybrid DE* simulation where continuous time components are adjusted so discrete event simulation can be used). The modular architecture of FMI-based simulation makes it appropriate for hybrid co-simulation.Additionally, components can be co-simulated without revealing the Intellectual Property that went into their design, which makes FMI-based co-simulation industrially applicable.

Challenges Despite the fact that there are proper approaches to create FMUs from discrete event components, the co-simulation of continuous-time and discrete-event blocks is still in its early phases. From a simulation point of view, one of the main differences between the two types of components is the simulation step size: continuous systems are simulated by periodically calculating the value of the variables with relatively large step sizes but discrete event-based systems operate irregularly and their simulation requires smaller steps (often measured in nanoseconds) since discrete events can trigger other discrete events (almost) instantly. It is possible to simulate continuous time models with smaller step sizes (in fact, it yields more accurate results), but it is inefficient (often preventing industrial application) and mostly unnecessary. The sporadic occurrence of discrete events raises the need for *adaptive step size control*.

Contribution In this paper we propose an adaptive step size control approach to overcome the difficulties of hybrid CT simulation. The core idea is to adjust the step size when an event is expected in order to decrease the detection latency. Event prediction relies on identifying the causes that might trigger an event, based on high-level information about the model provided as configuration parameters. The proposed component calculates the step size based on global minimal and maximal values and the events predicted by the following types of triggers:

- Events may trigger other events (reactions/responses). In order to detect discrete event responses with low latency, a set of *event indicators* – i.e. variables where the change of the value represent an event – have to be declared.
- Discrete events may be triggered by the elapse of time. For accurate simulation, special variables, called *time indicators* can be declared that each indicate when an event will be fired.
- Discrete events may be triggered by continuous variables crossing a given threshold. In order to facilitate the detection of such scenarios auxiliary intervals should be described, representing when the value is considered *close* to the threshold.

Experimental findings We have integrated the proposed adaptive step size controller component in the OMSimulator - an FMI-based simulator for cyber-physical systems, developed by the Open Source Modelica Consortium - and run measurements on case studies with constant steps of different step sizes as well as using adaptive step size control. In order to find out how the step size controller affects performance we measured the runtime and then analysed the differences between the efficiency and the results of corresponding simulations.

The results show, that in case of constant step sizes an order of magnitude difference in the step sizes yields an order of magnitude difference in event detection latency. However, in case of adaptive step size control, the latency is almost as small as in case of fixed step size simulation with the minimal possible step size, while the runtime is almost as small as in case of fixed step size simulation with the maximal step size.

Advantages The proposed approach facilitates co-simulation of discrete and continuous components without relying on step rejection that discrete components often fail to support. The step size controller requires only high-level information (types of variables, expected events, critical thresholds) for simulation, thereby respecting Intellectual Property. Measurements show that using adaptive step sizes can be a beneficial compromise between performance and accuracy. We believe that the step size controller can bridge the gap between continuous time simulation and discrete event components.

Steady State Initialization of Vapor Compression Cycles Using the Homotopy Operator

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Modelica is nowadays widely used in industry and research for object oriented modelling and transient simulation of cyber physical systems. Several Modelica compilers are available and the compatibility between them is continuously improving.

Although Modelica is used for transient simulation of dynamic models, the user is often only interested in the steady state results. And even if the transient simulation is wanted, the initial state of the model is preferred to be in steady state.

Vapor compression cycles are computationally very expensive. The fluid properties used in these models are highly nonlinear and based on complex equations (multiparameter equations of state). The fluid properties also have a very limited numerical range of validity, e.g. evaluating these properties for a negative pressure, temperature or density is impossible. As the equations have been estimated to describe measurement data, they also have an even more restrictive physical range of validity. So it is essential that the system state always is within the range of validity.

Homotopy is a concept to increase the robustness and simplify the solving procedure for algebraic nonlinear systems. The idea is to use a simplified model (to replace complex dependencies by simplified ones), to calculate a first guess for the result of the actual equation system, and to make use of the similarity of the systems during the transition from the simple to the complex equation system.

We are focusing on finite volume models with balance equations for mass, energy, and momentum. Some components such as the valve and compressor have steady state balance equations. The dynamic heat exchangers are dicretized one-dimensionally. If the dynamic component models shall be initialized in steady state, then an additional initial equation has to be added to set the time derivative of the continuous time state to zero.

The basic concept for the simple equation system is to describe the state of a whole vapor compression cycle using a number of simple conditions:

- Fixed heat flow rates in each heat exchanger
- Fixed mass flow rate and power in the compressor
- Fixed pressure and filling level in the separator
- Linear characteristic in the valve

For this simplified nominal working state, all mass flow rates, enthalpy and pressure states can be calculated.

To evaluate the homotopy concept, a common R-134a automotive vapor compression cycle is examined. The whole system including the controllers is initialized in steady state. All results have been calculated using Dymola 2019.

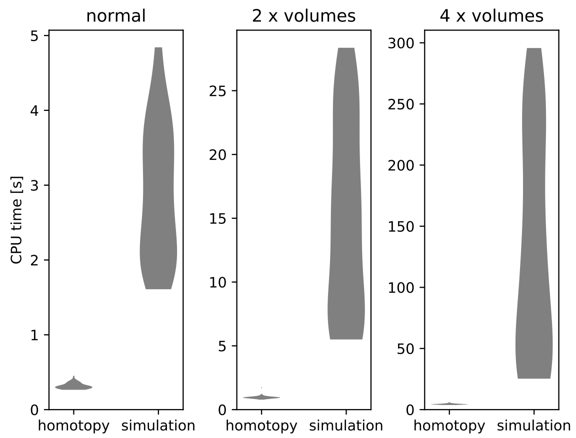

Figure 1. CPU time of a parameter variation compared between simulation with Dassl (tolerance = 1e-4) and homotopy initialization. "2 x volumes" indicates that the number of control volumes has been doubled compared to the normal example. The thickness of this violin plot indicates the density of occurrence.

In figure 1 the CPU times for the different cases are shown. For the three variations (three levels of dicretization) of the system homotopy method is computationally less expensive than a simulation by a factor of 5-10.

The simplified equation system to describe a vapor compression cycle that was presented in this paper is easy to parametrize, and defines a reasonable system state. The simple model is very abstract but it particularly enables separation of different flow paths and different cycles, so it is potentially able to handle large scale problems, even though this still has to be proven.

The experiments show that initialization using the presented approach is very robust and leads to a reduction of the computational effort.

Co-Simulation Through Exchange of Time-Series Data Applied to an Energy System Model and Detailed Ground Heat Exchanger Model

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Abstract

In recent years, building energy systems have become an important area of application for Modelica. However, few components, such as ground heat exchangers, remain difficult to implement in Modelica, and thus require co-simulation with an external model. We present a method for coupling a building energy system modeled in Modelica with an external ground heat exchanger model. The so-called waveform relaxation method (WRM) realizes co-simulation by exchanging arbitrary time-series data, instead of constant/polynomial values, as currently possible with the FMI standard. This may allow for performance improvement compared to FMI under certain conditions. A major advantage of this method is the applicability to simulation tools that do not yet support FMI. First, we briefly explain the energy system model (implemented in Modelica) as well as the ground heat exchanger model (implemented in external software DELPHIN). Next, we present different implementations of the WRM coupling method and their results. Finally, we discuss the performance of WRM under certain conditions and compare it to the FMIco-simulation approach.

Greenhouses: A Modelica Library for the Simulation of Greenhouse Climate and Energy Systems

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Abstract

This paper presents Greenhouses, an open Modelica library for the simulation of greenhouse climate and energy systems. In the literature, a small number of models are available for grenhouse climate simulation and crop growth. However, an open-source simulation platform is still lacking. The Greenhouses Modelica library aims at providing a robust open-source framework to simulate greenhouse climate and its integration with energy systems (e.g. generation and storage units). The goal is to provide an integrated and fully open-source solution ranging from the computation of energy flows in a greenhouse, to the simulation of complex systems with their control strategy. To that end, the library proposes models covering the following aspects:

- Greenhouse climate, to compute the energy consumption of a greenhouse given its specific design, outdoor conditions and a specific control.
- Thermal systems, with models ranging from heat distribution systems in greenhouses to generation and thermal storage units.
- Crop yield, to account for crop requirements as well as crop behavior (e.g. transpiration and photosynthesis), which influence the indoor climate and thus, the greenhouse energy consumption.

Climate control systems (heating, ventilation, CO_2 enrichment and supplementary lighting) are also included in the library. Furthermore, several numerical methods are developed and implemented in order to enhance the robustness and the simulation speed of the models during initialization and integration.

The proposed modeling framework can be used for multiple purposes, such as the optimal control of the greenhouse actuators, the optimal sizing of the heating appliances, or the optimal integration of the units in the power system. The Greenhouses library also comprises multiple example models, making it readily usable for both research and industrial applications.

The full compatibility (connector-wise) of the library allows the connection with other libraries more specialized in modeling thermal systems (e.g. Buildings, ThermoPower, ThermoCycle), thus increasing the simulation possibilities of the Greenhouses library.

The presented library is released as open-source (using the permissive Modelica License 2) and can be downloaded from `https://github.com/queraltab/GreenhouseLibrary`. The library is simple to implement and intuitive to use. The required information for a new user to get started is provided in this paper. Moreover, an additional documentation including a user guide with the required steps to run the models and extended documentation of the library content is available online (`https://greenhouses-library.readthedocs.io`). Ongoing and future works will mainly focus on the integration of new components and on the validation of the proposed models.

Keywords: Greenhouse climate, CHP, Crop yield, Thermal systems, Climate Control, Dynamic modeling

Modeling of Low Temperature Thermal Networks Using Historical Building Data from District Energy Systems

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Abstract

A Modelica library for modelling and comparing District Energy Systems (DES) and Low Temperature Thermal Networks (LTTN) has been developed. The library consists of six unique models and a series of replaceable sub-models that allow for different scenarios for thermal energy generation.

District Energy Systems have historically been implemented in areas with high heating demand and/or cooling to increase energy efficiency due to the utilization of larger industrial generation stations. These systems use a centralized Energy Management Center (EMC) that heats and/or cools a thermal transport fluid to a set temperature before distributing the conditioned fluid to different buildings within the community using a piping network. Traditionally these piping networks consist of four pipes, a supply and return for heating and a similar two for cooling. Although these systems have proven effective, increased awareness of the effects of greenhouse gases has spurred research interest in developing more efficient thermal microgrids.

One promising manifestation of a District Energy System is a Low Temperature Thermal Network. Low Temperature Thermal Networks replace the two fluid, four-pipe system present in traditional District Energy Systems with a singular low temperature working fluid. Like District Energy Systems, this low temperature fluid is supplied to buildings within a community using a thermal network which interfaces with each building through an Energy Transfer Station (ETS). Traditionally these ETSs consists of a heat exchanger that interfaces between the building's HVAC system and the thermal loop.

LTTNs differ from traditional systems because they also require the use of heat pumps at ETSs to transfer energy to and from the building and meet the internal building temperature set point. The benefit of this is that the low temperature of the thermal loop allows for a higher level of thermal energy capture from waste energy sources within the community and thus allows for greater system level energy utilization. For example, heat could be captured from cooling operations, off-setting the need for additional thermal energy generation. A consequence of this LTTN is that each of these heat pumps will create an additional electrical load.

In order to determine the net benefit of this energy recovery when weighed against the additional electrical loads, a Modelica library was created to model both DESs and LTTNs. This library was then validated against a nine-building district energy system located in a high-density community within Southern Ontario, Canada. To accomplish this real-world data was gathered on a DES, including the pipe layout, pipe geometry and equipment efficiencies. Additionally, historical building data from the community was gathered at five-minute intervals and was used to tune the model's predicted generation of the system, against that of the actual facility.

An analysis was then performed to compare the performance of an existing, operational four-pipe DES against an alternative design that consists of two one-pipe LTTNs. This comparison was done during a two-week period in the transitional season of October, during which the community experienced 52.96 MWh of thermal demand with approximately half of the demand being heating loads and the other being cooling. By simulating the system with the Modelica library, the results showed that the LTTN can drastically reduce the system's natural gas usage and reduce carbon emissions by over 90% while utilizing 34% less energy than the traditional district system. These reductions were the direct result of the LTTN's ability to capture waste energy within the community during this period of mixed loads. Although the LLTN led to a 55% increase in peak electrical demand, the unique capabilities for thermal energy sharing within a LTTN shows promise for greater levels of energy utilization and improved system level efficiencies.

Keywords: thermal microgrid, district energy, thermal transport systems, carbon emissions

Robust Calibration of Complex ThermosysPro Models using Data Assimilation Techniques: Application on the Secondary Loop of a Pressurized Water Reactor

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Abstract

ThermoSysPro (TSP) is a library for the modeling and simulation of power plants and energy systems. It has been developed by EDF and it is released under open source license. When developing models with TSP it is necessary to ensure that they match reality. In practice, this operation is performed by adjusting the value of the parameters appearing in the model. This major step corresponds to model calibration.

Calibration can be performed through various methods. A classical way to do so with Modelica models is by model inversion. The major inconvenience of this method, in addition of potential convergence problems for complex models, is that it is necessary to have exactly the same number of measurements as parameters to be calibrated, which is not often the case in practice.

This paper shows how data assimilation techniques can robustly be used for calibration of complex TSP models avoiding the inconveniences associated to calibration by model inversion while ensuring an optimal use of the available measurements. A complex TSP model of the secondary loop of a Pressurized Water Reactor (PWR) is considered for this purpose.

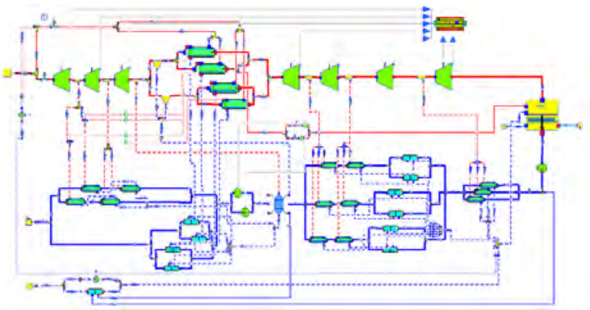

Figure 1. 1300 MW PWR model with ThermoSysPro

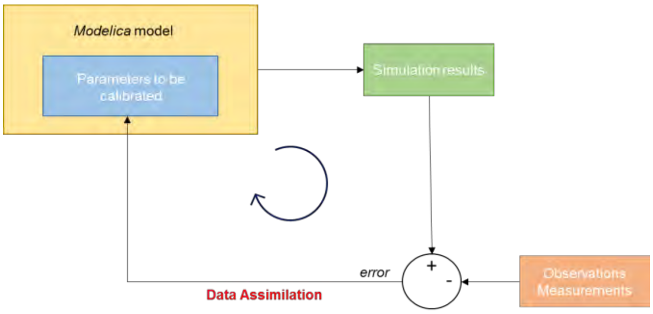

Figure 2. Illustration of the calibration procedure using data assimilation techniques

Keywords: Modelica, ThermoSysPro, data assimilation, model calibration, thermal-hydraulics, pressurized water reactor.

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Modelica, open-source modelling language, information available at: https://www.modelica.org/

OpenModelica, open-source Modelica-based modeling and simulation environment, information available at: https://openmodelica.org/

SALOME The Open Source Integration Platform for Numerical Simulation, information available at: http://www.salome-platform.org/

Coupling Power System Dynamics and Building Dynamics to Enable Building-to-Grid Integration

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Abstract

The interactions between power system dynamics and building dynamics are usually ignored or over-simplified in existing power system and building modeling and simulation tools, which limits how system modeling can support Building-to-Grid integration. This paper discusses a new approach to consider those interactions by modeling motor-driven building devices or systems. The motor-driven model is based on simplified mechanical rotation equations and allows us to study the coupling relationship between frequency/voltage in the power system and motor-driven device operation. This model is validated by performing one proof-of-concept case study with Modelica. The simulation results suggest that the proposed model can yield better representations of these interactions than the existing simplified models, especially the ones with the fast transient dynamics.

Modelling of the Central Heating Station within a District Heating System with Variable Temperatures

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Within this paper, the concept of developing a detailed model for an existing district heating system (DHS) with variable temperatures is described. This DHS uses central heat generators as well as distributed heat pumps (HPs) at the consumers' substations. This work focusses on the central heating station with multiple different supply units. In the present case, the model is implemented with a close-to- reality-control and will be used for testing new control strategies for the DHS. Therefore, a model with both realistic behavior as well as control interfaces similar to the real control is necessary. Within the NATAR research project (Local heating grids with lowered temperature as provider of balancing power), different targets for the improvement of the control will be investigated. One major target is an intelligent linking between the heat and electrical sector to demonstrate the opportunities of heating grids, as the investigated one, to balance the power grid.

This work uses the free and open-source programming language *Modelica* and the commercial software tool *Dymola* with the *Modelica Standard Library* (MSL) and libraries based on the common core library IBPSA *(International Building Performance Simulation Association*). A new, more specialized library is created for the simulation of the DHS with variable temperatures. Main purpose of this library is the use for this application, but the library will be created object-orientated and flexible to ensure that the library can be easily used and adjusted for further simulations of low-temperature district heating systems (LTDHS). In this way, the library may constitute the basis for a district heating library at the Institute of New Energy Systems (InES).

The requirement for entire model and the different component models is on one hand the capability of simulating periods up to one year, within a reasonable time, to evaluate the systems performance for new operation approaches. One the other hand temperature changes as well as shut-on and shut-off behavior in minute resolution needs to be provided to balance the electrical grid on this scale.

The component models of the heating station are validated with measurement data from the actual operation mode. Temperatures, heat flow rates as well as electrical power and energy sums are used for the validation. The heat generators within the heating central are a combined heat and power plant (CHP), a HP, a peak boiler and a solar thermal system. Two heat storages with different temperature levels complete the central heating station.

The simulation results and the measurement data for the different components match well for the most components and periods, but also show some weaknesses that need to be improved. The simulation of the boiler model shows that supply temperature, heat flow rate as well as the generated heat match the measurement data very well. The electricity demand of the HP is also close to the measured one, but this model needs adjustment with respect to the heat generation. The simulated temperatures of heat storage meet the measured data with different accuracy depending on the height within the heat storage.

To model the entire system, a model of the heating grid including the consumers needs to be added. This model extension is necessary to improve the entire control system including the control of the circulator pumps and the use of the distributed HPs.

Acknowledgements

The authors are grateful to *Bundesministerium für Wirtschaft und Energie* (BMWi), which finances the project NATAR (Local heating grids with lowered temperature as provider of balancing power; grant number: 03ET1425A), the founding agency *Project Management Jülich (*PtJ*)* as well as all project partners.

Towards Hard Real-Time Simulation of Complex Fluid Networks

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Real-time simulation is a very useful tool, especially since it is a key enabler for virtual testing: control units can be tested against a virtual plant model or single components can be tested with software-in-the-loop in order to emulate a yet unavailable environment.

Unfortunately, complex fluid systems created with Modelica have often been difficult to simulate under hard real-time constraints since they typically involve non-linear equation systems that are difficult to solve especially within a predictable finite time.

This paper explores the usage of a new approach that avoids non-linear equation systems and its suitability for real-time simulation. This progress was triggered by the needs to achieve a high level of robustness. Robustness in this context means that the simulation shall not return any errors due to solvability of non-linear equation systems and that the modeler shall not have to care overly about initialization of the system.

To this end, a computational scheme was developed that ensures that once the components robustly compute, also the complete system will robustly compute. We can use the same scheme to avoid non-linear equation systems altogether. If every single component has a form that enables an explicit computation of the thermodynamic state in downstream direction, then the thermodynamic states of the whole system can be computed explicitly in downstream direction.

In order to enable the application of explicit ODE-solvers with fixed stepsize, the stiffness of the system needs to be reduced. To this end, we present methods to manipulate the mass flow dynamics without distorting the steady-state solution and the time-constants of the main thermal dynamics.

A model of an aircraft environmental control system is taken as a use case for this study. Figure 1 shows a Modelica example system that (simplistically) describes the flow of fresh and recirculation air on board of a conventional aircraft.

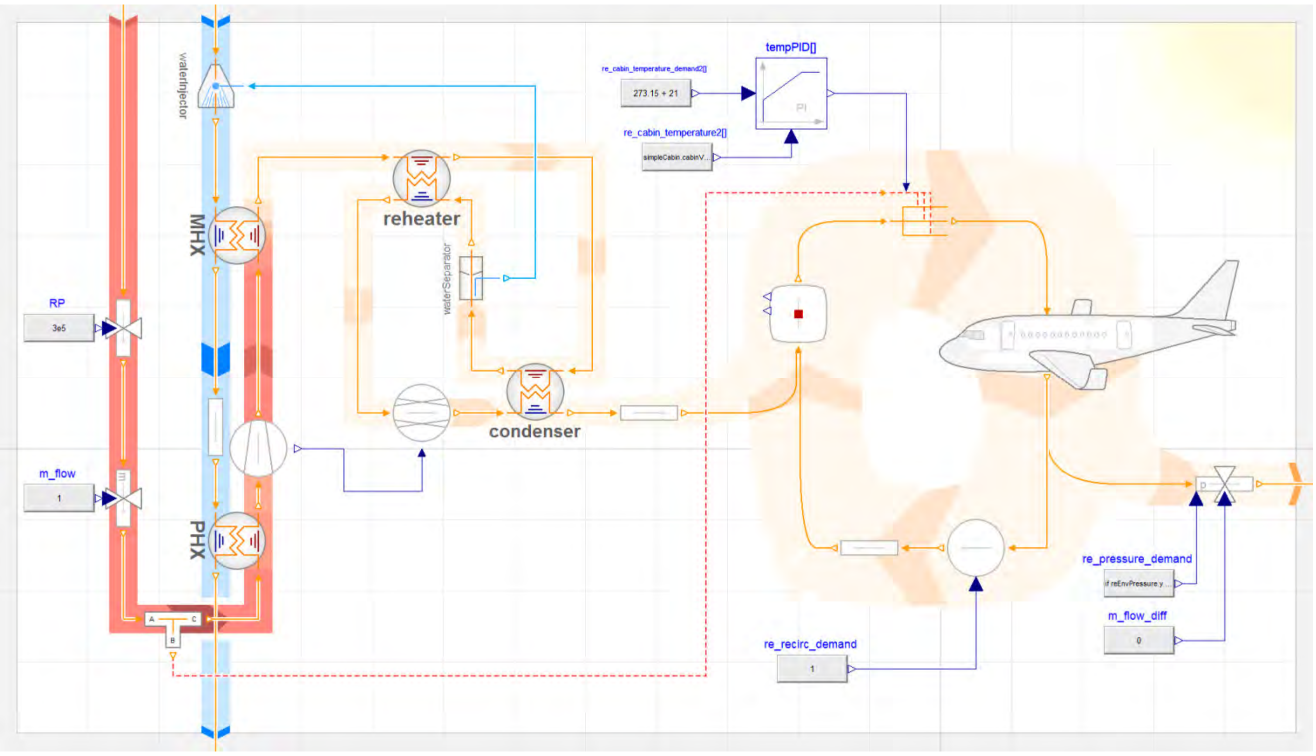

Figure 1: Modelica model of a simplistic aircraft ECS: bleed-air is being cooled against the ram-air channel and flows in a unit where it mixes with recirculated air. This mixture is then being warmed for 3 zones by further bleed-air and let into the cabin. From the 3 upper floor zones, the air flows to the underflow zone where a valve controls the cabin pressure. This model is derived from the work of Alexander Pollok (Pollok, 2017)

Thermodynamic Property and Fluid Modeling with Modern Programming Language Constructs

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Abstract

Modelica is used extensively to model thermo-fluid pipe networks. Experience shows that Modelica models in this domain have limitations due to missing functional expressiveness of the Modelica language. In this paper, a *prototype* is described that demonstrates how thermodynamic property and thermo-fluid pipe component modeling could be considerably enhanced via modern language constructs. This prototype is based on the Modia modelling and simulation prototype and relies on features of the Julia programming language. It utilizes some key ideas of Modelica.Media, and part of Modelica.Media was semi-automatically translated to Julia.

Thermodynamic property models (abbreviated as Media models below) require a great deal of flexibility with regards to the choice of thermodynamic and dynamic states to achieve robust and fast simulations. These medium models need functions to describe thermodynamic relationships with different inputs and differential equations to describe dynamic behavior. When such medium models using the Modelica language were first introduced, the only mechanism available that satisfied these requirements was that of a replaceable Modelica package. Special constructs for functions were also added to enable media modeling. This use of packages was not part of the initial language design, however, as they were primarily intended for the organization of model components. As a result, compilers typically handle packages completely at compile time. This fact has several significant implications, such as the restriction from changing the medium during simulation or the level of detail of the medium model during simulation.

This paper investigates alternative media and fluid modelling architectures available in the modern programming language Julia. Mechanisms of interest instead of replaceable packages include member functions, function references and multiple dispatch of functions[1]. The resulting architecture provides more dynamic flexibility and uses common language constructs so that it is easier to understand and maintain.

The design of the fluid library prototype for Modia is based on a new approach by (Zimmer et al. 2018)[2]. This approach is currently used in aircraft industry and enables the robust modeling of fluid streams and avoids the creation of large non-linear equation systems that are still a major source of problems for conventional fluid libraries in Modelica. For example the following part of a model:

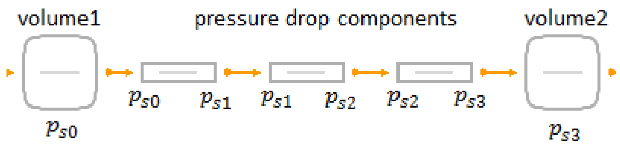

Figure 1. Three pressure drop components connected between two volumes ($\boldsymbol{p_{si}}$ is the static pressure at the indicated location).

would result in nonlinear-equation systems with Modelica.Fluid, since nonlinear pressure drop components are present without volumes in between. With this new approach used within the Modia fluid library, only one linear equation system with constant coefficients appears and can therefore more robustly solved.

In the Modia fluid library prototype, a Medium is an instance of a Julia data structure and the reference to the instance is treated as Modia variable that is propagated through connections.

In the Modelica.Fluid package there are many options that can be set on component level or globally. In the Modia fluid library prototype the complexity of the code and of the options is drastically reduced, by only providing the dynamic momentum balance, only describing pressure drop components as function of mass flow rate and having only one discretization scheme for a pipe. Still the simulation is potentially more robust as when defined with Modelica.Fluid, because no nonlinear algebraic equations occur if pressure drop components are connected together without a volume in between.

[1] Multiple dispatch in Julia means that method selection is based on the types of all non-optional function arguments (if possible at compile-time, otherwise at run-time).

[2] https://elib.dlr.de/120701/

Simulative Potential Analysis of Combined Waste Heat Refrigeration using Ammonia in an Intercity Bus on dynamic route

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Abstract

In this work, a simulative potential analysis of a possible topology for combining waste heat recovery and passenger compartment refrigeration using ammonia is carried out. The focus is on the energetic assessment using a detailed simulation model of a long haul intercity bus.

The topology combines a conventional refrigeration cycle with an Organic Rankine Cycle (ORC). Both systems share the working fluid and the condenser. The used refrigerant is Ammonia (R-717). Expansion machine and compressor are both connected to the drive belt of the vehicle. In order to evaluate the fuel consumption reduction potential of that topology the intercity bus simulation model, equipped with a CO2 (R-744)-refrigeration system, is used as a reference.

The results show that using an Organic Rankine Vapor Compression Cycle (ORVC) equipped with ammonia leads to an effective reduction of fuel consumption for a long-haul journey. The ORVC topology reduces fuel consumption by 7.9 %.

Keywords: ORC, ORVC, CO2, Ammonia, R-744, R-717

Modeling of PMU-Based Automatic Re-synchronization Controls for DER Generators in Power Distribution Networks using Modelica and the OpenIPSL

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Keywords: Automatic re-synchronization controller; phase angle difference controller; power distribution network; synchrophasors; Modelica; OpenIPSL

Abstract

Re-synchronization is traditionally coordinated between the electric power transmission network operators and power plants in an isolated portion of the grid in order to maintain the balance between the power supply and demand. This task can be challenging when one portion of the distribution grid contains small generators having low inertia which is the case of Distributed Energy Resources (DER), such as small hydro, wind and solar power plants. As the number of DER continues to increase with the rise of renewable energy sources located at the lower voltage networks, automatic re-synchronization method that can be applied to a great number of DER are desirable.

The paper describes the architecture and modeling of an automatic re-synchronization controller shown in Figure 1, which can be applied to synchronize an islanded portion of the grid by using remote measurements to drive a Distributed Energy Resource (DER) within the islanded network. The controller's re-synchronization function uses bus frequency measurements, which are derived using bus voltage phasors and a new bus frequency computation technique that can be used during the execution of dynamic simulations.

This paper also introduces a new bus-angle difference control function within the re-synchronization control system, which allows monitoring the phase angle difference between two buses so to avoid unwanted re-synchronization. The effect of the angle difference control function is evaluated using a controlled circuit breaker considering different power dispatch levels of the generator in the distribution network model. Both deterministic and stochastic load models are used to analyze the performance of the automatic re-synchronization control system.

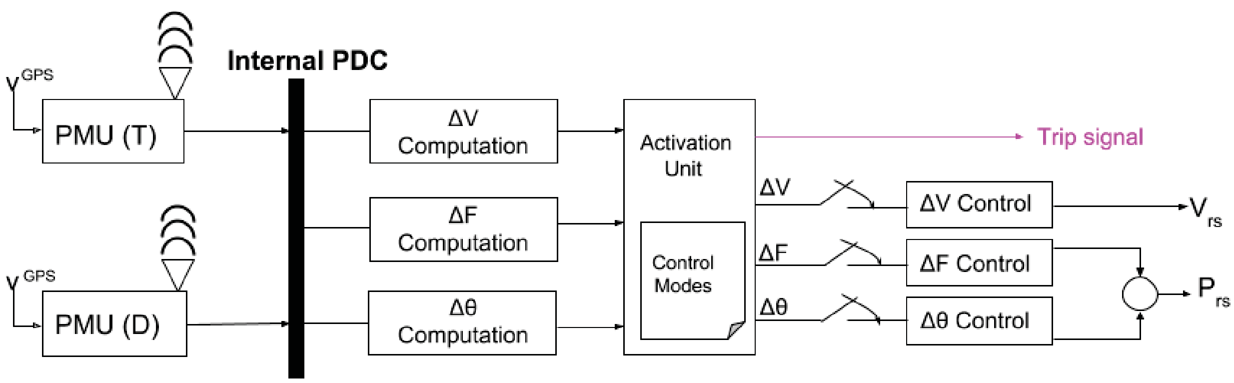

Figure 1. Architecture of the Automatic Resynchronization controller

A Fundamental Time-Domain and Linearized Eigenvalue Analysis of Coalesced Power Transmission and *Unbalanced* Distribution Grids using Modelica and the OpenIPSL

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Abstract. This paper present mathematical modeling and implementation in Modelica language of a coalesced electric power transmission and distribution system model. To this end, a newly developed feature in OpenIPSL that allows to amalgamate power transmission and distribution networks at the equation level is described and implemented in Modelica. Mathematical models for three-phase components such as lines and loads are also presented and implemented in Modelica. The models are used to assemble two different, small-scale, sample power systems, and three simulations are performed for each of them in a Modelica-compliant software. Dynamic simulations are carried out to perform comparisons between different modeling approaches for a distribution feeder and among different load characteristics. Each simulation is linearized using a script in ten different time instants and an eigenvalue comparison is performed. The results from all dynamic simulations presented expected results. Voltage behavior observed using positive sequence models and three-phase model with balanced load increase are similar. In addition, results coming from three-phase unbalanced load increase and positive sequence model diverge. The comparison between eigenvalues values corroborates the dynamic simulation results and show that a misused positive-sequence model may lead to wrong conclusions about system stability. The results are meaningful as distribution networks gain relevance due to increasing level of distributed generation being introduced in low-voltage grids. The analyses performed in this paper are easily conducted, showing that Modelica language and compliant software packages may have key role in the development of new computational tools to study complex emerging power systems.

Keywords: Modelica · Power Systems · Hybrid Models · Linearization · Eigenvalues · Transmission Networks · Distribution Networks

Towards Pan-European Power Grid Modelling in Modelica: Design Principles and a Prototype for a Reference Power System Library

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Abstract

This paper presents the PowerGrids library, which is aimed at the modelling of large-scale power transmission and distribution system.

Several open source Modelica libraries exist for the modelling of electrical power systems, each with a different design philosophy. The scope of the library presented in this paper covers electro-mechanical, phasor-based models of power generation and transmission systems, possibly up to the scale of full pan-European grid models.

The target audience of the library are transmission and distribution system operators, as well as scholars and students in this field. The library is not only meant to be used, more or less as a collection of black-box models, to build system models, but rather to be easily accessible at the source code level by domain experts, which normally do not have an extensive Modelica training, so that they can understand what's inside the models and may contribute new ones avoiding too steep a learning curve.

For this purpose, advanced Modelica features should then be used judiciously as long as they can actually make reading and writing the code easier, by using basic types and classes which are already defined in the library.

For example, existing base classes in the library define basic concepts such as 3-phase balanced AC connectors, 3-phase balanced AC ports, components with one or two AC ports, and one-port components with Park transformation to dq-axis per-unit variables, so that one is spared the tedious task of defining such basic quantities and to do so in a way that Modelica tools can exploit to generate efficient code, e.g. by setting the appropriate `start` and `nominal` attributes. One can then write the equations of a synchronous machine model as shown in Fig. 1, which are immediately recognizable by a domain expert. On the other hand, excessive use of abstraction, multiple inheritance, and replaceable classes should rather be avoided, because they can make the code unreadable to people without a deep experience in advanced Modelica code writing.

The design of the library is fully declarative, exploiting features such as nominal attribute for sound numerical scaling of physical variables, Complex numbers, and a-causal modelling.

```
equation
// Flux linkages
lambdadPu = (MdPu+LdPu)*idPu + MdPu*ifPu + MdPu*iDPu;
lambdafPu = MdPu*idPu+(MdPu+LfPu+mrcPu)*ifPu+(MdPu+mrcPu)*iDPu;
lambdaDPu = MdPu*idPu+(MdPu+mrcPu)*ifPu+(MdPu+LDPu+mrcPu)*iDPu;
lambdaqPu = (MqPu+LqPu)*iqPu+MqPu*iQ1Pu+MqPu*iQ2Pu;
lambdaQ1Pu = MqPu*iqPu+(MqPu+LQ1Pu)*iQ1Pu +MqPu*iQ2Pu;
lambdaQ2Pu = MqPu*iqPu+MqPu*iQ1Pu+(MqPu+LQ2Pu)*iQ2Pu;
// Equivalent circuit equations in Park's coordinates
if neglectTransformerTerms then
  udPu = raPu*idPu - omegaPu*lambdaqPu;
  uqPu = raPu*iqPu + omegaPu*lambdadPu;
else
  udPu = raPu*idPu-omegaPu*lambdaqPu+der(lambdadPu)/omegaBase;
  uqPu = raPu*iqPu+omegaPu*lambdadPu+der(lambdaqPu)/omegaBase;
end if;
ufPu =  rfPu *ifPu  + der(lambdafPu)/omegaBase;
0    =  rDPu *iDPu  + der(lambdaDPu)/omegaBase;
0    =  rQ1Pu*iQ1Pu + der(lambdaQ1Pu)/omegaBase;
0    =  rQ2Pu*iQ2Pu + der(lambdaQ2Pu)/omegaBase;
// Mechanical equations
der(theta) = (omegaPu - omegaRefPu) * omegaBase;
2*H*der(omegaPu) =
  (CmPu*PNom/SNom-CePu) - DPu*(omegaPu-omegaRefPu);
CePu = lambdaqPu*idPu - lambdadPu*iqPu;
PePu = CePu*omegaPu;
PmPu = CmPu*omegaPu;
omega = omegaPu*omegaBase;
```

Figure 1. Equation section of the synchronous machine model

The paper discusses the design of the library thoroughly, as well as the implementation of a few basic components, such as transmission lines, transformers, loads, and synchronous generators.

The components in the library have been successfully verified against analytical solutions in simple test cases, and validated against the corresponding models of the iPSL Modelica library in a number of test cases.

The library has also been successfully demonstrated to work in scalable test cases up to 4000 nodes and about one million equations using the OpenModelica tool, although the results show that above about 500 nodes a breakthrough in Modelica compiler technology is required, to avoid the performance penalty brought by the very large size of the simulation executable code, which turns out to be above 100 MBytes.

The library is planned to be released as open source during the year 2019.

The WaterHub Modules: Material and Energy Flow Analysis of Domestic Hot Water Systems

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Domestic Hot Water (DHW) systems are large energy consumers. Mitigation measures involve more efficient hot water appliances and distribution systems, waste heat recovery systems, or changes in consumer habits. However, the implementation of these measures must be investigated carefully, as combinations may lead to unforeseen systemic interactions limiting their potential. Inter-level interactions, for instance, have been identified: a significant performance drop occurs when decentralized heat recovery appliances are implemented simultaneously to sewer-level energy recovery facilities. Similar intra-level interactions are hypothesized to occur in households. In addition to technological competition or synergies, water consumption patterns strongly influence systemic energy- and cost-efficiencies of DHW technologies.

The WaterHub Modules

We present modeling tools to identify and optimize household level interactions, in order to avoid competitive and promote synergetic combinations. The WaterHub modules were developed for Material and Energy Flow Analyses (MEFA) of DHW systems. Two modules are available: (i) the WaterHub Modelica library includes models for MEFA system definition, and (ii) The HydroGen Python module provides methods for the stochastic generation of appliance-specific hydrographs, used as input data for the simulation of the system energy and water flows.

The modules facilitate the workflow of DHW systems MEFAs and allow fast scripting of single simulations or Monte-Carlo processes. As an example, Figure 1 presents the water and energy flows in a DHW system containing a shower-level heat recovery device.

WaterHub Modelica Library

The WaterHub Modelica Library, inspired by the Modelica Standard Library (MSL) *Fluid* library, contains models for the construction of DHW systems:

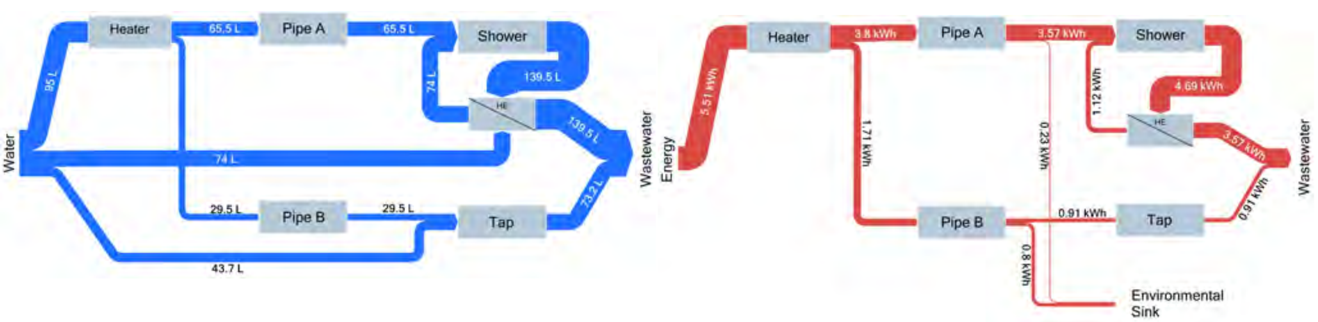
- *Appliances*: Technologies at the interface between the water consumer and the DHW system.
- *ImportExport*: Models for imported/exported water and energy flows.
- *Pipes and Carriers*: Water and energy carrier models.
- *DHW Systems*: Building blocks for DHW systems, e.g., boilers, reservoirs, water treatment units, etc.

HydroGen Python Module

The HydroGen Python module samples from distributions to generate appliance flows stochastically. *Events* are characterized by (i) a starting time, (ii) a flow rate, (iii) a temperature and (iv) a total event volume.

Conclusion

The WaterHub modules provide tools for the analysis of water and energy flows in households, facilitating (i) the identification of technological/behavioral interactions within DHW systems, (ii) consequent Life Cycle Assessment (LCA) or Multi Criteria Decision Analysis (MCDA).



(a) Water flows. (b) Energy flows.

Figure 1. Average daily water and energy flows in a didactical DHW system containing a shower-level heat recovery device (HE).

Comparison of a usual heat-transfer-station with a hydraulic modified version under the aspect of exergy saving

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Abstract

In this investigation, a usual heat-transfer-station (HTS) with a domestic warm water (DWW) storage is compared with a modified, more advanced HTS, where the DWW storage is used for further cooling of the primary return of the district heating network (DHN). The question posed in this article is, whether a slight change in the hydraulic system and control strategy can profitably reduce the return temperatures in periods with space heating.

Especially in rural areas with a low specific heat demand, the economical operation of DHN is challenging. To cope with this challenge, this paper focusses on non-retrofitted single-family homes as heat consumers, which accounts for a high proportion of houses in rural areas. The return temperatures are a decisive factor for reducing heat losses and improving the overall efficiency. The hydraulic setup of a HTS has a great impact on the level of return temperatures. The question will be answered on an exergetic basis and a comparison of the return temperatures.

In the research article, the hydraulic system of the advanced HTS is described. The simulation models are built for an initial simulation-based estimation of the advantage of the advanced heat-transfer-station and are modelled with *Modelica*. The heating and DWW demand is taken from the VDI 4655 profiles.

For a fair comparison of the both HTS, the same state of charge should be ensured. It can be shown that the HTS, which uses the return temperature of the heating system for preheating the DWW, can almost satisfy the DWW demand by charging from this return flow.

In the outlook, the further steps for this comprehensive investigation are described. Therefore the research article refers to current research of DHN simulation with *Modelica* and Hardware-in-the-Loop simulations.

Evaluating the Resilience of Energy Supply Systems at the Example of a Single Family Dwelling Heating System

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Introduction and Previous Work

Since the 1980s, the term "resilience" occurs more and more frequently in energy system analysis. However, the consideration and definition of the term primarily occurs in a qualitative way. In the last century, the term was mainly defined by Holling (1973) as a "measure of the persistence of systems and of their ability to absorb change and disturbance". Francis and Bekera (2014) and Nan and Sansavini (2017) introduce quantitative assessment methods that are adapted in this paper to be used for Modelica® simulation results.

Definition of the Resilience Index

When evaluating a system's answer to disturbances, a physical value needs to be defined as indicator for the system's functionality, e.g. the room temperature for the heating system. The room temperature profile after a disturbance is characterized by the recovery time RT, the maximum deviation MD outside of the value's tolerances and the performance loss PL. These elements can be used to determine the resilience index:

$$RI = \frac{1}{1 + RT \cdot MD \cdot PL}$$

To obtain a dimensionless figure, normalization values are introduced for each element.

Case Study

The presented assessment method is applied to a heating system of a single family dwelling in which heat is supplied by a gas boiler.

For this system, the failure of the supply pump and the failure of the boiler are modeled. Furthermore, the reference system is improved by implementing windows with a lower heat transfer coefficient or/and a hot water buffer storage. The results of the simulations are used to compute the resilience indices for each disturbance and improvement.

Conclusion

Overall, it becomes obvious that large temperature drops and recovery times lead to small resilience indices which shows that the resilience index reliably reflects the resistance and recovery ability of the system.

Another general aspect that becomes evident, is that the resilience indices vary for the same system in accordance to the disturbance it is exposed to. Hence, one can derive that there is no "absolute" resilience index, especially when keeping in mind that the concept of resilience also contains the system's capability to keep its functionality up when facing unknown disturbances. Therefore, the significance of a resilience analysis rises with its number of considered incidents.

Furthermore the resilience analysis enables the location of a system's weak points which helps to choose and initiate system improvements that are the most efficient in regard to increasing the resilience.

Further research should focus on using the resilience index on more complex systems including integrated energy systems and the evolutions that are necessary for these kinds of systems. Hence, it is proposed to allocate one resilience index for each integrated sector and combine them into one overall index which will make it possible to evaluate complex system changes, e.g. a rising share of renewables, with regards to resilience aspects.

Acknowledgements

The authors greatly acknowledge the funding from the German Federal Ministry of Economic Affairs and Energy for the project "ResilientEE - Resilience of integrated energy networks with a high share of renewable energies", project number: 03ET4048.

Keywords: Resilience, Energy Supply Systems Assessment, Heating

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Application of a Real Gas Model by Van-der-Waals for a Hydrogen Tank Filling Process

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Hydrogen fuel tanks operate at high system pressure levels. In these regions effects occur, which cannot be handled by an ideal gas model. One of these is the Joule-Thomson effect. It describes an adiabatic throttling without change in enthalpy, but a change in temperature. The tank filling process can be simplified to a throttling valve, so the effect is of interest. In this investigation the van der Waals equations are implemented in a real gas model for the *Hydrogen Library* and the *Pneumatic Systems Library (PSL)* by Dassault Systèmes and the model is applied to a hydrogen tank filling process. Performance and accuracy are compared to the CoolProp fluid properties library, which is imported with the ExternalMedia library.

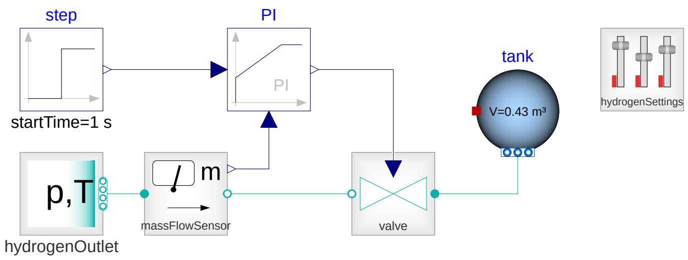

Figure 1. Dymola model to simulate a tank filling process for hydrogen.

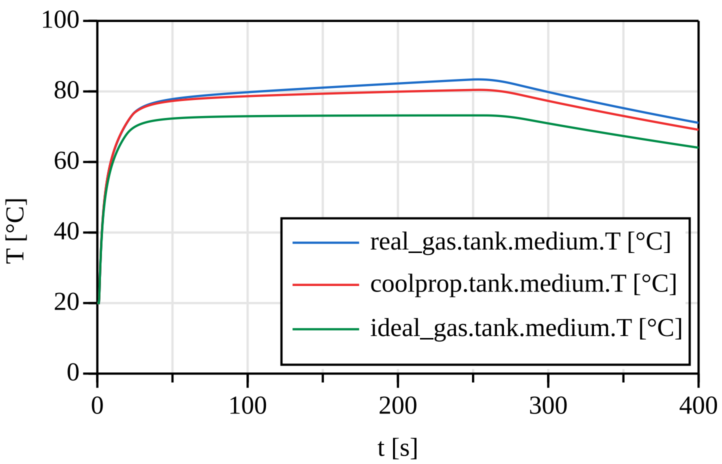

Figure 2. Results of the tank filling process simulation.

Modeling of the Flow Comparator Prototype as New Primary Standard for High Pressure Natural Gas Flow Metering

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Introduction

For the trade with natural gas the uncertainty of high pressure natural gas flow meters is of major importance. The calibration of the flow meters is done with transfer standards which are calibrated by the German national primary standard for high pressure natural gas flow. The current primary standard is a High Pressure Piston Prover (HPPP) (Schmitz and Aschenbrenner; PTB, 1991, 2009). It is owned and operated by the National Metrology Institute of Germany Physikalisch-Technische Bundesanstalt (PTB) and installed on the calibration facility for gas meters pigsar™ in Dorsten, Germany. The HPPP can be operated with inlet pressures up to 90 bar and flow rates up to 480 m^3/h (PTB, 1991).

The PTB is developing a new concept for volumetric primary standard to calibrate high pressure gas flow meters. The TUHH is supporting these R&D activities with its competence to elaborate computational models for detailed analysis of complex mechanical systems including fluid flow aspects. The new primary standard is based on a actively driven piston prover to measure the gas flow rate using the time the piston needs to displace a defined enclosed volume of gas in a cylinder.

Experimental Setup

The key element of the Flow Comparator is a piston in a cylinder. Together they act as an asynchronous linear motor. For this, the cylinder has two layers, one with magnetic properties and the other one acts as an electrical conductor. The stator core with its windings is integrated into the piston. For the electrical power of the stator core a supply cable is connected to the piston. The velocity of the piston is controlled by using a frequency inverter to set the control voltage and frequency for the stator core. The differential pressure over the piston is measured with a sensor in the piston. A specified leakage in the piston with a flow sensor measures the fluid flowing through it. With the two sensors, it is possible to compare the piston movement relative to the fluid flow. The piston has an integrated check valve to limit the pressure drop across of the piston. The position of the piston is measured using a distance measuring equipment (DME). The ambient temperature and pressure as well as the temperature and pressure downstream of the cylinder are measured.

Computational Model

A computational model written in Modelica® is developed to investigate the Flow Comparator's dynamic behavior. The measuring cylinder is divided into one volume upstream and one volume downstream of the piston. As a first approach to model the force of the linear motor, a function depending on control voltage input and velocity of the piston is derived. Verification of the model shows correct physical implementation and accurate solution of the equation system. Validation of the model shows good compliance of the piston velocity and differential pressure at the piston in the model with measured data.

Conclusion and Outlook

With the model the frequency inverter control voltage trajectory is optimized to maximize the available measuring time. With this simple optimization, the measuring time could be increased by 80 % in the model. This result of optimization will allow to extend the upper limits of flow rate usable for calibrations. Furthermore, the possibility to gather detailed information about pressure and temperature development at arbitrary chosen locations in the system with high time resolution enables much better and more reliable statements about the accuracy of flow rate measurement with this system.

In the future, the linear motor should be modeled using physically based equations. Additionally, it will be essential to extend the model by heat transfer from the motor components to the gas.

Keywords: modeling of multi-domain physical systems, flow comparator, high pressure natural gas flow metering, linear motor, optimization

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Transient modelling and simulation of a double-stage Organic Rankine Cycle

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Keywords: transient simulation, Organic Rankine Cycle, geothermal heat and power production

1 Introduction

Geothermal energy is a renewable resource for power and heat production. For low enthalpy reservoirs, the geothermal energy is usually converted to electricity by an Organic Rankine Cycle (ORC). The efficiency and profitability of these power plants can be increased by an additional heat supply. In this study, a dynamic model of a double-stage ORC power plant is developed to investigate and evaluate geothermal combined heat and power (CHP) plant concepts.

2 Methodology

For modelling and simulation of the double-stage ORC the software Dymola (Dassault Systèmes, 1992-2004) in combination with the library ThermoCycle (Quoilin et al., 2014) is used. The fluid properties are calculated with the software CoolProp (Bell et al., 2014).

3 Results

For the validation of the double-stage ORC a period of 24 hours in steps of one minute is simulated and the results are compared to operational data of a real geothermal power plant in the German Molasse Basin. The relative root mean squared error (RRMSE) between simulation and operational data is 3.6 % on average. An important parameter for the evaluation of different CHP-concepts is the generated electrical power. The validation results for the electrical power output of the generator are shown in Figure 1. The RRMSE is 3.9 %. The dynamic behavior is evaluated by the coefficient of correlation. For the electrical power output this coefficient is 0.99, which means that the both curves are almost identical in shape and the simulation model can predict the dynamic behavior of the real power plant.

4 Conclusion

In this study, a transient simulation model of a double-stage ORC is developed and validated by operational data of a real power plant. The electrical output of the generator can be predicted by 3.9 %.

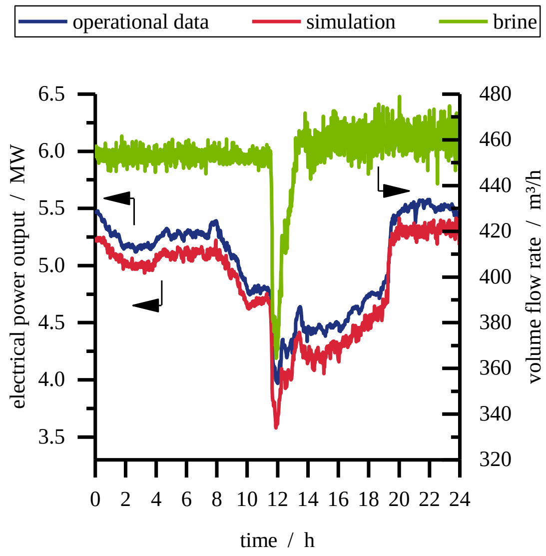

Figure 1. Validation results for the electrical power output of the double-stage Organic Rankine Cycle.

In future work, based on the dynamic simulation model different geothermal combined heat and power plant concepts are investigated and evaluated by annual return simulations.

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A New OpenModelica Compiler High Performance Frontend

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Abstract

The equation-based object-oriented Modelica language allows easy composition of models from components. It is very easy to create very large parametrized models using component arrays of models. Current open-source and commercial Modelica tools can with ease handle models with a hundred thousand equations and a thousand states. However, when the system size goes above half a million (or more) equations the tools begin to have problems with scalability. This paper presents the new frontend of the OpenModelica compiler, designed with scalability in mind. The new OpenModelica frontend can handle much larger systems than the current one with better time and memory performance. The new frontend was validated against large models from the ScalableTestSuite library and Modelica Standard Library, with good results.

The results for selected ScalableTestSuite (STS) models and the Vectorized.SolarSystem are presented in Table 1. One can see that the new OpenModelica frontend performs very well in comparison to Dymola, in some cases faster, in some cases slower. The comparision between the current frontend (CF) and the new frontend (NF) is also included where possible. From these benchmarks one can also see that investigation is needed to find out why parameter arrays are scaling poorly in the new frontend (models 6, 7, 8). For models 10 and 11 the figure in the parentheses is for the new frontend not expanding arrays at all during the flattening. The performance improvement in this case is extreme.

In Table 2 we compare the current frontend (CF) with the new frontend (NF) when instantiating and flattening models from `Modelica.Mechanics.MultiBody` and evaluating their graphical annotation. The OpenModelica compiler API function that is called to evaluate the graphical annoations is `getComponentAnnotations()`. The new frontend performs 20 to 200 times better than the current OpenModelica frontend, allowing to obtain a nearly immediate response time of the OMEdit GUI, which relies on this API.

Keywords: OpenModelica, compiler, flattening, frontend, modelling, simulation, equation-based, scalability

No	Model	Equations	Dym (s)	OMC NF/CF (s)
1	Electrical.DSystemAC.SE.DistributionSystemLinear_N_40_M_40	99776	15.53	06.32 / 91.33
2	Electrical.DSystemAC.SE.DistributionSystemLinear_N_80_M_80	397936	40.50	17.76 / 435.32
3	Electrical.DSystemAC.SE.DistributionSystemLinear_N_112_M_112	779312	74.21	32.31 / 1076.54
4	Electrical.DSystemDC.SE.DistributionSystemModelicaActiveLoads_N_80_M_80	129929	18.04	08.33 / 159.28
5	Electrical.TransmissionLine.SE.TransmissionLineModelica_N_1280	26915	09.84	04.45 / 47.77
6	Elementary.ParameterArrays.SE.Table_N_100_M_100	0	06.59	05.09 / 06.21
7	Elementary.ParameterArrays.SE.Table_N_400_M_400	0	10.25	12.19 / 18.03
8	Elementary.ParameterArrays.SE.Table_N_1600_M_100	0	09.77	19.04 / 28.17
9	Power.ConceptualPowerSystem.SE.PowerSystemStepLoad_N_64_M_16	11907	17.29	03.99 / 28.57
10	Vectorized.SolarSystem(n=10000)	60001	146.30	34.12 / 314.8 (**02.95**)
11	Vectorized.SolarSystem(n=100000)	600001	14458.68	2450.57 / 19760.42 (**02.95**)

Table 1. Flattening performance comparison Dymola vs. OpenModelica (NF vs CF included). Bold numbers in parentheses are with Scalarization disabled `-d=-nfScalarize`. Shortened names: SE=ScaledExperiments, DSystem=DistributionSystem.

Model	CF (s)	NF (s)	Factor
World	9.53	0.28	33.9
Joints.FreeMotionScalarInit	28.90	0.14	199.4
Joints.Planar	3.56	0.13	25.6
Joints.UniversalSpherical	6.99	0.22	30.5
Joints.SphericalSpherical	4.64	0.11	39.5
Joints.Universal	2.31	0.12	18.4

Table 2. Flattening performance comparison of the current (old) vs the new frontend in OpenModelica (OMEdit GUI impact).

OMJulia: An OpenModelica API for Julia-Modelica Interaction

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Abstract

Modelica is an object oriented, acausal equation-based language for describing complex, hybrid dynamic models. From a control systems point of view, the support of models with inputs and outputs is of particular importance. About ten Modelica implementations exist, of which most are commercial and two are open source; the implementations have varying levels of tool functionality. Many Modelica implementations have limited support for model analysis. It is therefore of interest to integrate Modelica tools with a powerful scripting and programming language, such as Julia.

Julia is a modern and free language for scientific computing. Julia has very good support for plotting, linear algebra, random numbers/statistics, automatic differentiation, optimization, machine learning, differential equations, signal processing, data frames, graph algorithms, file handling/databases, etc. Although support for control tools is lacking compared to MATLAB, control packages are more developed and simpler to install than, e.g., in Python. In summary, integration of Modelica with Julia facilitates many needed analysis possibilities and can speed up the development of effient simulation models.

A number of design choices for interaction between Julia and Modelica tools are discussed. The simplest approach is to interact via text strings of command code. A more convenient approach is to use an API in Julia (the script tool) which hides the interaction code details. For simulation, both of these approaches lead to interaction between Julia and compiled Modelica code, with some resulting run-time overhead in the call. A third approach could be to translate Modelica code into Julia code instead of C code. The produced Julia code can then be included in a Julia session, and can take advantage of Julia tools with no run-time overhead for the simulation. A fourth possibility is to utilize meta programming capabilities of Julia and extend Julia with the possibilities of Modelica (as in the Modia project). Some advantages and disadvantages of the approaches are discussed.

In this paper, the second approach is taken, and Julia package OMJulia is introduced with an API for interaction between OpenModelica and Julia. Some discussion of the reasoning behind the OMJulia design is given. The API is based on a new class *ModelicaSystem* within package OMJulia, with systematic methods which operate on instantiated models. OMJulia supports handling of FMU and Modelica models, setting and getting model values, as well as some model operations such as simulate and linearize. Results are available in Julia for further analysis.

OMJulia is a further development of a previous OMPython package; a key advantage of Julia over Python is that Julia has better support for control engineering packages. OMJulia represents a first effort to interface a relatively complete Modelica tool to Julia, giving access to an open source set-up for modeling and analysis, including control synthesis, easily installable from a unified package manager.

In addition to documenting OMJulia with some basic examples, slightly more advanced examples are included to illustrate the possibilities of implementing dynamic models in OpenModelica and carry out control systems analysis in Julia. Because Python has poor design for control systems analysis, Modelica-Julia interaction is more intersting for control applications. The examples illustrate use of Julia for linearization of Modelica models, control analysis, controller synthesis, and comparison of the control design.

Although not shown in the paper, the Modelica-Julia integration makes it straightforward to do state estimation (random number generators, linear algebra), test out optimal control and model predictive control (control systems package, optimization code), develop surrogate models (machine learning), carry out structural analysis (graph theory algorithms), etc. Some of the methods take advantage of OpenModelica's algorithm for translating DAE models to state space models.

The Julia API/OMJulia makes it possible to utilize a mature Modelica implementation (OpenModelica) out of the box, and add tools that are not part of Modelica. The approaches for tighter integration of Modelica with Julia (Modelica-to-Julia translation, Modia) are, of course, also interesting — tighter integration promises better performance compared to the OMJulia approach. These tighter integration approaches are currently limited in scope, but are interesting developments for the near future. *Keywords*: Modelica, FMI, FMU, OpenModelica, Julia, Julia API, OMJulia

"hello, (Modelica) world": Automated documentation of complex simulation models exemplified by expansion valves

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Abstract

The constantly increasing computing power enables the implementation of complex simulation models. Therefore, it is possible to create more detailed models to predict system behavior more accurately. Modelica, for example, has proven great suitability in modelling complex systems, because of its high degree of reusability. However, understanding these models is quite difficult and many simulation models are poorly documented. Consequently, it is very time-consuming to retrace given model structures especially for novice. The Unified Modeling Language (UML) provides a user-friendly and graphical structure for documentation to simplify working with existing simulation models. Hence, an algorithm (ADoCSM) is developed to automatically present the structure of a Modelica simulation model in UML. This algorithm is exemplarily applied to a refrigerant circuit expansion valve model. Thereby, we contribute to an increase of simulation model quality as well as simplifying the entry in the world of Modelica. ADoCSM and the expansion valve model are freely available on GitHub:

https://github.com/RWTH-EBC/ADoCSM
https://github.com/RWTH-EBC/AixLib/tree/issue590_ExpansionValve

Integration and Analysis of EPAS and Chassis System in FMI-based co-simulation

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Abstract

The vehicle steering characteristics and active functions can be virtually developed with a high-fidelity electric power assisted steering (EPAS) model and a multi-body chassis model. The simulation of the EPAS model requires small integration step due to high stiffness and interfacing with the controller. The multi-body chassis model is computationally heavy for each integration step due to calculation of large matrices. A mono-simulation based on a single solver is not efficient for this case. Instead a co-simulation (solver coupling) approach has been used to overcome the drawbacks.

In this paper we model the EPAS system and chassis system in Dymola. The models are exported as separate functional mockup units (FMU)s and integrated with the control algorithms in Matlab. A co-simulation based on the explicit parallel calculation scheme (Jacobi scheme) has been used. A huge simulation speed-up has shown the potential and effectiveness of the approach. To understand its accuracy and tolerance, analysis on the numerical error and system dynamics are given.

Keywords: EPAS system, Chassis system, Co-simulation, FMU

Virtual Proving Ground Testing: Deploying Dymola and Modelica to recreate Full Vehicle Proving Ground Testing Procedures

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Physical testing of new automobiles is often a lengthy and expensive process. Capital costs associated with physical testing include production of prototype vehicles and travel to various locations around the world of personnel and equipment. Aside from the cost, the amount of resource time required to embark on a comprehensive testing programme is far from ideal, often constraining the product development process. The environmental impact of such testing programmes should also be considered.

This paper presents how the VeSyMA suite of Modelica libraries contains the necessary features to address the above concerns, by recreating 2 typical physical proving ground tests in the virtual world; a high speed accelerated durability test using a test track and rough-road structural testing. Key new features added to the VeSyMA suite to enable this are presented, namely: a new method of defining the proving ground road model using GPS and body accelerometer data, a new driver model capable of conducting a series of scheduled driving tasks (mimicking a human test driver) and new tyre contact models more suitable to typical proving ground rough roads. Each new development is explained in detail, along with additional options available to VeSyMA users to add further fidelity to their simulations. Qualitive results of these tests are presented using a generic vehicle model, demonstrating the capability of the VeSyMA suite to recreate these real-world proving ground tests in the virtual environment.

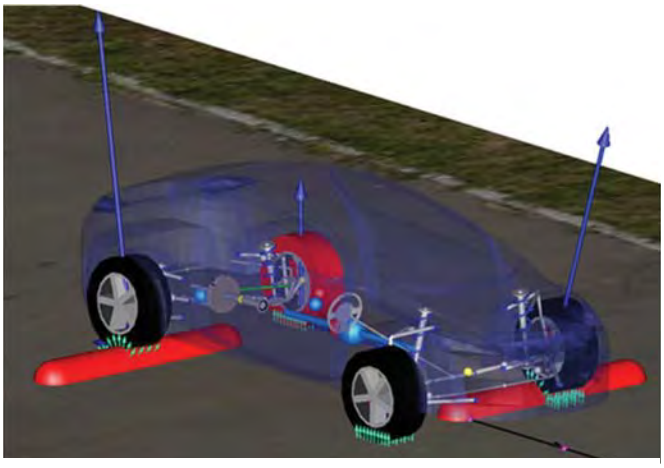

Figure 1. A vehicle model traverses a road specifically designed to structurally test the vehicle chassis

Virtual testing of vehicles offers an inherently more flexible, efficient solution to testing new vehicles, whilst also providing a more consistent and easier to manage testing environment. Harnessing total vehicle virtual simulation tools can endow multiple benefits, addressing the waste and inefficiencies of physical testing programmes described above. Proof-of-concept testing can be done at a much earlier stage of the design process, whilst durability evaluation can begin to be conducted at earlier stages of the design cycle. Immature designs can be evaluated in the same manner as mature designs at the full vehicle level, without the need to wait for a prototype vehicle to be produced and tested. This leads to the possibility of shortened development schedules, as design issues can be identified earlier and eliminated sooner, with less resources going into failed design elements.

Hierarchical Coupling Approach Utilizing Multi-Objective Optimization for Non-Iterative Co-Simulation

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Abstract

A hierarchical scheduling approach for non-iterative co-simulation is presented. With an increasing number of subsystems the number of possible combinations and permutations increases dramatically, resulting in a unsolvable problem to define a proper co-simulation scheduling for application engineers. This paper shows an approach to get an optimal trade-off between simulation duration and simulation accuracy by the usage of a multi-objective optimization approach to find an optimal scheduling for hierarchical co-simulation.

Coupling Mechanism

The most common used coupling approach for co-simulation is to calculate all sub-models at the same time. Each subsystem has not to wait for each other and so this coupling mechanism has the best simulation performance. Nevertheless, this parallel coupling approach causes the most coupling errors, due to the high number of extrapolated inputs. If subsystems are calculated sequentially, i.e. a subsystem starts the calculation when the previous subsystems already finished the calculation step, no inputs have to be extrapolated. With a sequential coupling approach a minimum number of extrapolation can be reached, but the simulation performance will suffer. A hierarchical approach on the other side allows a combination of sequential and parallel scheduling (see table 1). Several subsystems can be nested, where e.g. the subsystems within a group are calculated in sequential order and the several subsets (group) are calculated in parallel.

Table 1. Real-time capability w.r.t. a HEV example.

Coupling Mechanism	*Real-Time Factor*
parallel	0.44
sequential	1.1
hierarchical	$0.5-0.75$

Optimal Hierarchical Approach

A multi-objective optimization problem with minimisation of number of extrapolated inputs and minimisation of the simulation duration can be formulated as follows:

$$\min\{(1-w)J_E + wJ_D\}, \tag{1}$$

where the factor w enables to set the focus of the optimization to the extrapolation error J_E or to the calculation duration J_D. A small factor w weights the optimization in the direction of the minimum extrapolation error and so sequential calculation is preferred. On the other hand the factor $w=1$ is the focus on the optimization of the simulation duration and so parallel approach is selected.

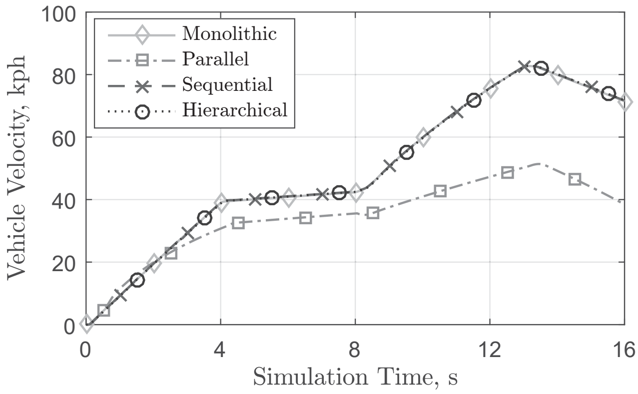

Figure 1. Simulation result (Vehicle Velocity) regarding different coupling mechanisms.

A comparison of sequential and parallel coupling approach (in contrast to the monolithic simulation) is shown in Figure 1. The sequential and hierarchical simulation delivers almost the same results than the monolithic simulation. The results of the parallel coupling approach clearly differ from the reference.

Acknowledgements

This work was accomplished at the VIRTUAL VEHICLE Research Center in Graz, Austria. The authors would like to acknowledge the financial support of the COMET K2 - Competence Centers for Excellent Technologies Programme of the Austrian Federal Ministry for Transport, Innovation and Technology (bmvit), the Austrian Federal Ministry of Science, Research and Economy (bmwfw), the Austrian Research Promotion Agency (FFG), the Province of Styria and the Styrian Business Promotion Agency (SFG).

Flow Network based Diagnostics for Incorrect Synchronous Models

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Abstract

Modelica 3.3 (released in 2012) added synchronous primitives that are intended to make it easier to model control systems that run on a sampled clock and connect to the continuous plant model. However, the synchronous primitives have seen limited use so far – and are not even used in the Modelica Standard Library.

We have found that one barrier preventing users from starting to use the synchronous primitives are unclear diagnostics in case of errors. This presentation reduces this barrier by demonstrating how the separation into clocked and continuous parts can be diagnosed, including a possible correction.

The underlying idea is to transform the model to a flow network, and the error then corresponds to a "leak-flow" between the partitions, which can be efficiently found using max-flow/min-cut techniques.

The new method is efficient, easy-to-adapt, and gives diagnostics focused on correcting the issue. In particular, it is possible to handle both normal clocked partitions and clocked partitions with solverMethod.

The ideas in this paper were introduced in Dymola 2019 (released in June 2018) and also in 3D Experience Platform 2019x.

Example

The new method is best illustrated by a small example.

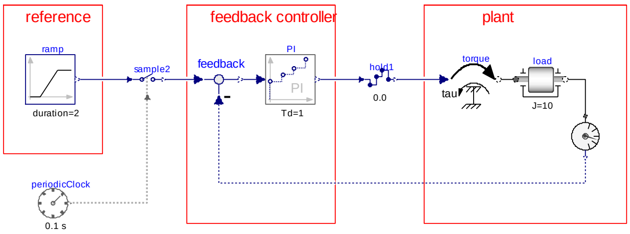

Figure 1 Incorrect textbook controller

Diagnostics for the incorrect synchronous model in Figure 1, showing that the new method correctly identifies the problem.

Continuous time parts and discrete parts don't decompose, when there is no solverMethod attached to the clock.
It is necessary to introduce sample or hold elements replacing:
connect(speed.w, feedback.u2);

Study on Efficient Development of 1D CAE Models of Mechano-Electrical Products

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Compact, high-precision, and high-performance mechano-electrical products such as multifunctional copiers, printers, and digital cameras are products of manufacturing industry in which Japan has demonstrated its excellence traditionally. To realize a high functionality and a low price of a mechano-electrical product, it is important to utilize the computer simulations effectively in the design processes so that the feasibility of the functions is evaluated and the appropriate design options are narrowed down at an early stage.

In the design of automobiles and aircrafts, a problem-solving method known as model-based development (MBD) is widely adopted. In MBD, the various conditions related to the requirements and functions of a product are defined by mathematical models. By evaluating the models, the product functions can be verified at the early design stages. Considering that simple analyses are often employed prior to determination of the 3D information, the MBD that is applied at the early functional design stage is specifically known as 1D CAE.

To promote the use of 1D CAE in the mechano-electrical industry, it is necessary to resolve various issues associated with the use of 1D CAE as much as possible, and to reduce the cost of creating the model. We consider that the following two methods are effective in increasing the efficiency of creating a 1D CAE model.

1. **Development of modeling guidelines:** Creation of a 1D CAE simulation model is a complex task, and therefore, a trial and error process is indispensable. Accordingly, the cost of creating the model increases. To reduce the cost arising out of the trial and error process, we are developing guidelines for creating the 1D CAE models especially for mechano-electrical products. In the guidelines, the desirable steps in the modeling process (see Figure 1) as well as the important points to be noted in each step are mentioned. Accordingly, the guidelines help reduce the trials and thereby minimize the modeling cost.
2. **Clarification of important points in the combined use of Modelica, MATLAB/Simulink and SystemC:** A mechano-electrical product is generally a complex system comprising mechanical, electrical/controlling, and software components. In the industry, Modelica and MATLAB/Simulink are emerging as popular tools for modeling the mechanical and electrical/controlling components, respectively. Programming languages derived from C are usually used for describing the software necessary in the mechano-electrical product. For example, SystemC is recognized as a standard tool for describing a hardware behavior in the design of electronic circuits to be incorporated in the product. We are investigating to consolidate the important points to consider in the combined use of Modelica, MATLAB/Simulink, and SystemC. Through the development of simplified models of the plain paper copying machine, we found that there are three critical issues in their combined use: 1) management of simulation step time, 2) signal transmission between the models, and 3) selection of proper design parameters.

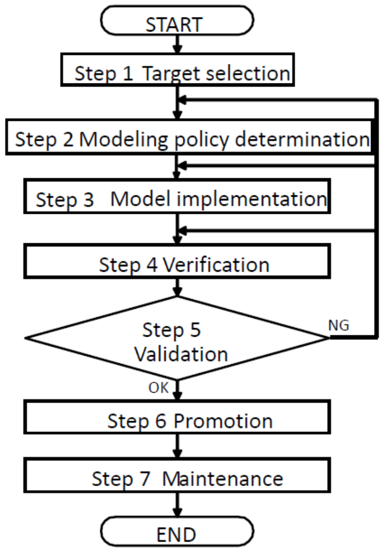

Figure 1 Flowchart for creating proper 1D CAE model.

It is a difficult task to quantify the effectiveness of the developed guidelines and the points learnt in the combined use of Modelica, MATLAB/Simulink, and SystemC, but we strongly believe that these results are helpful in creating the models without mistakes. We plan to distribute our research results to the member companies of the Standardization Committee of New Digital Verification Technology so as to evaluate its applicability thoroughly.

Advanced Modeling of Electric Components in Integrated Energy Systems with the TransiEnt Library

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Abstract

In the context of the German Energy Transition, it is planned to increase the share of renewable energies in the next decades in order to decrease the carbon dioxide emissions. Furthermore, the nuclear power phase-out was decided after the Fukushima incident in 2011. In the electrical sector, the renewable energies should have a share of at least 80 % in 2050. The fluctuating generation of the renewable energies must be balanced with the volatile consumption. This is only possible by using storage technology. Electric storages are considered, but their power output and storage capacities are limited and costs per kWh energy storage are high. Hence, the idea of Integrated Energy Systems (IES) to couple the sectors electricity, gas and heat is considered.

For the necessary energy system analysis of IES with respect to dynamics and stability, powerful tools are needed. Such tools should be provided in open toolboxes to make the research more transparent, comprehensive and communicative. It is aimed that scientists collaborate on models for multimodal energy system analysis.

The dynamic simulation is a method that allows to consider transient, non-linear effects and controller design. The TransiEnt Library, developed and established at Hamburg University of Technology (TUHH), offers such a toolbox. Previous versions of the library worked with limited electrical models. The TransiEnt Library is extended with new models. Compared to the limited models, the new electrical models allow much more detailed dynamic modeling and analysis of electric power grids. Load flow calculations can be performed. The stability of the electric grid can be analyzed by considering frequency, voltage and angle stability. This is enabled by new models based on a new connector that allows interconnected networks without overdetermined DAE. Numerically efficient transmission line, transformer and generator models are provided in the TransiEnt Library. Generator models allow different levels of detail in dynamic modeling of the electric grid, starting with simple models that only regard active-power-frequency behavior up to models with excitation systems, Two Axis Method based equations and distinct frequencies. The high modularity of Modelica allows the simple adaption of existing models as well as the extension of existing models.

The main goal is the simulation of a representative coupled system of northern Germany within one simulation model without Co-simulation. Co-simulations typically need interfaces between different partial simulations. These interfaces handicap physical constraints such as mass and energy conservation and reduce the numerical efficiency.

In this complex model, dynamics of the technologies from different energy sectors are coupled in order to cover their interaction. In general, the electric part of the coupled system has higher dynamics than the processes in the gas and heat sector. Consequently, the risk of a stiff problem occurs. To deal with this risk, models are created in different levels of detail for different time scales which can be replaced by each other. Additionally, it is deemed to be reasonable to consider only dynamics with time constants above 1 s in order to avoid stiffness. Furthermore, it is investigated which stability phenomena should be regarded in the electric grid for the chosen time and scenario horizon in order to investigate the overall system resilience.

Keywords: Integrated Energy System, Electric Energy System, Load Flow Calculation, Frequency Stability, Voltage Stability, Renewable Energy

Robust and accurate co-simulation master algorithms applied to FMI slaves with discontinuous signals using FMI 2.0 features

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Abstract

Error control in system simulation using co-simulation techniques is a task for the employed simulation master. With the availability of the FMI standard version 2.0 and rollback capabilities of simulation slaves, master algorithms can be implemented with support of error controlled integration. Particularly, for automated integration tools, the problem-specific dynamic adjustment of communication interval lengths becomes a necessity to obtain reliable co-simulation results while maintaining calculation efficiency.

The article discusses various master algorithms and time step adjustment strategies using a test case with discontinuous input/output signals. As expected, fixed-step Gauss-Jacobi and Gauss-Seidel algorithms are found to be generally unsuited for the task. Accuracy can only be improved by reducing communication step sizes, thus creating a large computation overhead in simulation time spans with smoothly changing or constant variables.

Iteration-based time step adjustment rules are an improvement, yet cannot recognize discontinuities resulting from time-event. Since the traditional Richardson/step-doubling error estimate also fails to recognize discontinuous signal changes, a slope-based modified Richardson-test is introduced and successfully applied. This new method reliably detects discontinuities and allows the master to adjust its communication step size accordingly.

Finally, it is concluded that a suitable master algorithm for such problems is the non-iterating Gauss-Seidel with modified Richardson communication interval adjustment.
Keywords: FMI, co-simulation, master algorithm, error control, adaptive

Development of a General-purpose Analytical Tool for Evaluating Dynamic Characteristics of Thermal Energy Systems

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Abstract

The Central Research Institute of Electric Power Industry (CRIEPI) in Japan has developed an original tool for analyzing the dynamics of a wide range of thermal energy systems using Modelica. This tool was originally developed to analyze thermal power generation systems to evaluate to evaluate the dynamic characteristics of a new and an existing thermal power generation systems and has been validated against several sets of operational data so far. As a next step, the tool was extended to calculate the thermophysical properties of not only water/steam and air/gas but also various refrigerants implementing the ExternalMedia library to model a customer-side equipment such as a heat pump system (Fig.1). Consequently, various and complex energy systems can now be analyzed with this tool.

As a case study to test the new adding part, a dynamic modeling of a hot-water supply system with CO2 as the refrigerant at CRIEPI was carried out. The target test facility comprises a compressor, gas coolers, an electro-motion expansion valve, and evaporators (Fig.2). A simplified dynamic model was constructed with this tool (Fig.3). The validity of the tool was assessed via comparison with experimental data measured from a hot-water supply system with CO2 refrigerant. The model accuracy of some elements of the system needs further improvement, though sufficiently accurate results for constructing a dynamic model were obtained.

Keywords: Modelica, energy system, heat pump

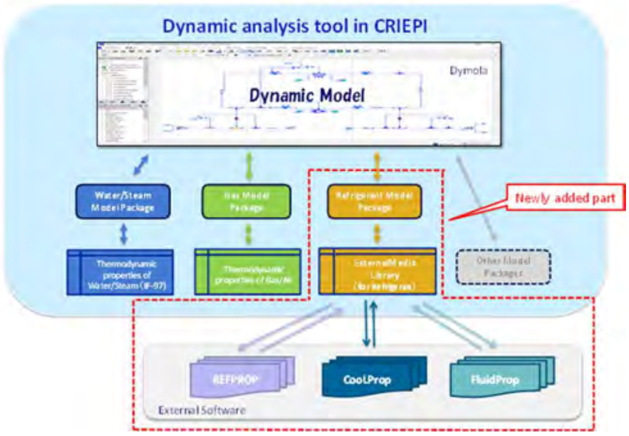

Figure 1. Schematic of the developed tool.

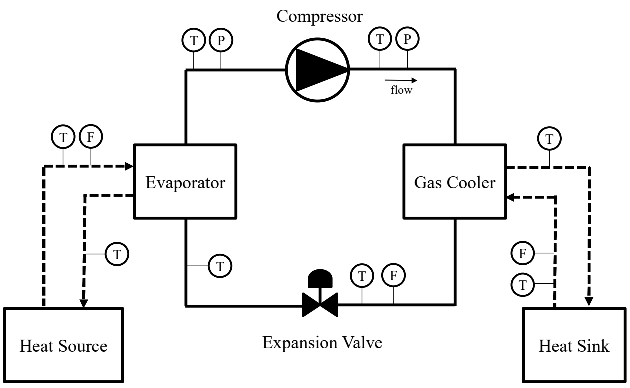

Figure 2. Schematic of the CO_2 heat-pump loop.

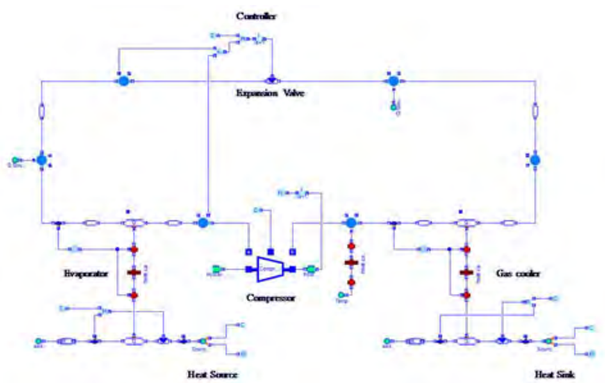

Figure 3. Dynamic model of CO_2 heat-pump-loop facility using CRIEPI's tool.

Daccosim NG: co-simulation made simpler and faster

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Abstract

This paper introduces the last evolution of Daccosim co-simulation environment, with Daccosim NG developed in 2018. Main features of Daccosim NG are described: enhanced Graphic User Interface and Command-Line Interface, algorithm and mechanism of co-simulation, co-execution shell, software architecture designed for both centralised and distributed architectures, aggregation of a co-simulation graph into a Matryoshka FMU, and declarative language to design large scale co-simulation graphs. A new industrial use case in simulation of energetic systems is also introduced, and first performances of Daccosim NG on multi-core architectures are analysed.

Keywords: co-simulation tool, multithreaded execution, master algorithm, FMI standard, energy system, runtime performance

1 Introduction

The study of Smart Grids, which are intelligent energy systems enhanced by additional communication means and modern IT features, requires a complex analysis of many components considering different aspects. These aspects are amongst others, the demand, production (including renewable), stability of the power grid and flexibility assessment. This is the case for Electricité de France (EDF) and the European Institute For Energy Research (EIFER), where Smart Grids and, more in general, Multi-Energy System analysis are performed through simulations representing the power grids considering multiple aspects. To this end, EDF and EIFER are working in the development of simulation models.

For instance, there are teams working in the modelling and simulation of customers by representing how devices consume energy at their homes: fridges, stoves, washing machines, etc. The analysis of the energy demand of these devices also requires to study thermal dynamics, since many of these devices produce heat or cold. Besides of thermal dynamics, the sociotechnical behaviour of the customers must also be represented as they are the ones who operate the devices. There are also teams developing models for representing thermal gains and loses for houses, buildings, districts, etc. Other teams are dedicated to optimise the grid operation with massive renewable energy and storage units.

Some examples of these kinds of business models are ThermoSysPro, BuildSysPro, PlantSysPro, TelSysPro and EPSL. ThermoSysPro (Hefni et al., 2011) is a library devoted to the modelling and simulation of power plants and energy systems. BuildSysPro (Plessis et al., 2014) is designed to be used in several contexts including building physics research, global performance evaluation, technology development and impact assessment. PlantSysPro is devoted to industrial processes like hot water system. TelSysPro is a new Modelica library able to model the impact of telecommunication networks on complex systems from failure/repair rate of components and stochastic latency.

These teams develop their models using the tool that is the most appropriate according to their work habit or affiliation. There are many tools or programming languages that can be used for developing these models: Anylogic (Borshchev, 2013), Dymola (Elmqvist et al., 1996), Matlab (Guide, 1998), Java (Gosling et al., 2014), Python (Rossum and al., 2007), etc. So, it happens very often that teams want to collaborate by making their models interoperable with others. This is challenging since models are developed in different tools. At this level, the interoperability challenge is double: syntactic and semantic (Hernandez et al., 2016).

The syntax challenge consists in being able to technically communicate models that are developed in different tools. For instance, this problem is equivalent to two people trying to speak when they do not have a common language. The semantic problem has several axis when talking about data exchange between two models: meaning of the words, units that are used, data types, etc. The most common semantic problem in models communication is to have different words to express the refer to the same concept.

The syntactic problem is addressed in FMI (Blochwitz et al., 2011). FMI, the Functional Mock-Up Interface, is a tool-independent standard that supports both model

Dynamic Parameter Sensitivities: Summary of Computation Methods for Continuous-time Modelica Models

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Abstract

Applications of Sensitivity Analysis (SA) encouraged several Modelica platforms to independently provide facilities for externally computing Dynamic Parameter Sensitivities (DPS). FMI specifies an optional function call for evaluating directional derivatives. On the other hand, mathematical foundation for uniform representation of DPS at the Modelica language level has been established. This has resulted in a platform-independent approach demonstrated through example libraries: The ADGenKinetics and the ADMSL libraries.

This paper summarizes couple of methods for computing DPS including:

1. finite difference methods
2. platform-dependent approaches via specialized solvers coupled with specific simulation environments
3. a general approach via equation-based algorithmic differentiation for computing DPS directly at the model / library level with Modelica syntax

The paper neutrally hints that already conducted efforts may converge to the integration of language facilities for DPS without neglecting mathematical difficulties. Surprisingly, many of what could be thought to be algorithmic obstacles have intuitive solutions throughout a minimalist implementation approach.

The PSTools Library

Having DPS at the model level simplifies many applications, e.g. Figure 1. The application

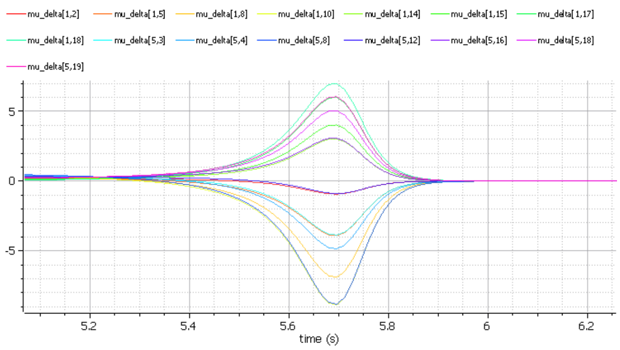

Figure 1. Parameter sweeping study based on one DPS-enabled simulation with two parameters. Instead of running multiple simulations, Taylor series expansion is exploited

is an example taken from the PSTools library. The PSTools library provides the following services for arbitrary Modelica models and libraries via generic models:

- Several demonstrative examples for computational methods of DPS that serve as examples for computing DPS analytically or numerically
- Generic models for computing DPS based on advanced finite difference methods
- Using analytically or numerically computed DPS, further mathematical tools for applications of DPS are accessible through generic models

Frequency Response Estimation Method for Modelica Model and Frequency Estimation Toolbox Implementation

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Abstract

The frequency-response method is widely used because of its convenience and applicability in the control system analysis and design, and the premise of the design based on this method is to obtain the frequency response of the system. Aiming at the problem that the strong nonlinearity is difficult to be linearized in practical engineering systems, this paper presents a method for estimating the frequency response based on the time domain simulation data of Modelica models. The spectrum of the appropriate IO data at the steady-state operating point of the system is analyzed by Fourier transform, and then converted into the frequency response of the system. The proposed method is applicable to the multi-domain Modelica model, FMU, and the black box model. A frequency response estimation toolbox is implemented and integrated into the MWorks platform based on this method, which provides important support for the control design for Modelica model. Simulation examples illustrated the validity of the proposed method and the toolbox.

Keywords: Strongly nonlinear system, Frequency response estimation, Toolbox

Modelica Models for the Control Evaluations of Chilled Water System with Waterside Economizer

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Abstract

Chilled water system with waterside economizer is a common cooling system used for large commercial buildings and data centers. To evaluate the design and control of the cooling system, modeling and simulation techniques are essential. This paper presents an equation-based modeling package for chilled water cooling system and a library of system- and equipment-level control. Then a case study is conducted to evaluate performance of the system-level control under different climate zones. Simulation results show that both temperature and humidity of the climate zone have influences on the economizing hours of the system, which thus influences the energy consumption.

Predicting the Vehicle Performance at an Early Stage of Development Process via Suspension Bushing Design Tool

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Abstract

This paper describes a method for verifying vehicle performance when applying a new suspension bushing at the concept phase of vehicle development. At the concept phase, it is difficult to obtain the nonlinear characteristics of the bushing, which plays an important role in the performance of the vehicle. Thus, a tool to design bushing has been developed.

The vehicle performance is verified at the concept stage by using the results of the developed bushing design tool and a Modelica system model. Designers can make various bushing characteristics in an intuitive and easy way using the bushing design tool. First, designers use original model's test data as an input of bushing design tool and determine the number of cells for the bushing model. The bushing design tool proceeds with the parameter identification through an optimization process based on the input test data and the number of cells of the model. The designers then determine the new bushing characteristics to get the desired static and dynamic characteristics in the original characteristics. The bushing design tool calculates the parameters of the bushing model according to the bushing characteristics changed to the result value. From simulation results, the vehicle performance is changed according to the characteristics of the suspension bushing. The designers can confirm the vehicle performance at the concept stage if the bushing, determined by the designers, is applied.

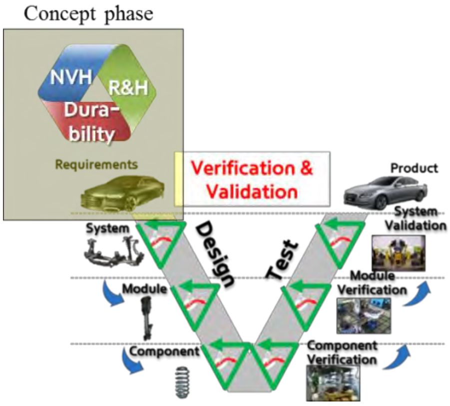

Figure 1. Vehicle development cycle and concept phase.

The developed bushing design tool allows designers to evaluate vehicle performance by reflecting bushing characteristics without actual products.

Keywords: suspension bushing, bushing design, vehicle dynamics, parameter identification.

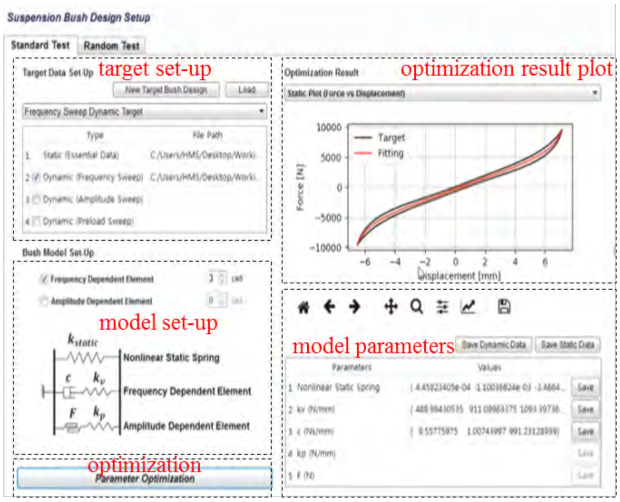

Figure 2. Interface of suspension bushing design tool.

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Modelica-Based Modeling and Application Framework on Hybrid Electric Vehicles

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Abstract

In order to meet low-emissions criteria outlined in Chinese regulations, which require a progressively increasing percentage of automobiles to be ultralow or zero emissions, in this paper a sort of light hybrid electric drivetrain is studied and modeled in detail using Modelica. An application framework is also designed to improve the usability and the efficiency of the models. Performance of the whole vehicle and some key components are analyzed.. Comparison between simulation results and experiment results is performed, which validates the effectiveness of the models. Based on the comparison, we conclude that, the methods presented in this paper can support a rapid design of hybrid electric vehicles and further optimization.

Keywords: hybrid electric vehicles, Modelica, MWorks, application framework, signal bus

Implementation of a Non-Discretized Multiphysics PEM Electrolyzer Model in Modelica®

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Abstract

This paper outlines the development of a multi-physics model of a proton exchange membrane (PEM) electrolyzer with selectable physics submodels in Modelica®. The Hamburg University of Technology is currently conducting research on coupled power, gas, and heat grids using software models written in Modelica in hopes of increasing the efficiency of these systems. The TransiEnt Library is an open source Modelica library of components for modeling coupled energy networks with high shares of renewable energies (Hamburg University of Technology, 2018). The electrolyzer model outlined in this paper will be included in the TransiEnt Library to increase the scope of studies on energy storage for intermittent renewable sources and the coupling of power, gas, and heat grids.

The model is derived almost explicitly from a previous research paper by (Espinosa-López et al., 2018) but uses different models for cooling system power and anode/cathode gas pressures. Some model components were also neglected that appear in other papers, such as concentration overvoltage and mass transport due to diffusion, since they do not significantly affect industrial electrolyzers under normal operation. The cooling model is implemented using a feedback controller connected to a RealOutput, which can be connected to an external model to utilize waste heat if desired. The hydrogen pressure is kept constant for simplicity in the validation of models in this paper, but can be connected to a dynamic model if desired. Categorized physics submodels of voltage, pressure, temperature, and mass flow models allow users to define their own models if desired. This also allows for the library to be updated with ease with evolving research models. There is also a Specification record that contains system specific parameters for any electrolyzer configuration, such as thermal capacitance and activation energy required for proton transport in the proton exchange membrane. Most of these parameters can be found using the procedures outlined in (Espinosa-López et al., 2018). Shared variables and parameters are declared using the Modelica modifiers `inner` and `outer` to allow for interconnectivity between the submodels.

The electrolyzer model is validated against the experimental results in (Espinosa-López et al., 2018) with minimal error in behavior. The most noticeable differences are between the working temperatures of the models during simulation, which can be explained by the alternative implementation of the temperature and pressure models. These models can vary quite widely from system to system regardless.

The model is suitable for a new study, which is performed using wind speed records from a wind farm in northern Germany to estimate the potential power generation and corresponding amount of hydrogen produced over the course of one year. The results show that one Vestas112-3.0MW wind turbine generated the potential power to produce 1.906 tonnes of hydrogen gas in 2015 at the Wwrohm-Osterrade wind farm with the electrolyzer system from (Espinosa-López et al., 2018). The average energy conversion efficiency is 75.3% using the net calorific value of hydrogen combustion. This is enough hydrogen to fill approximately 400000 tanks of the Toyota Mirai, a fuel cell powered sedan. The electrolyzer model has great potential for further studies in applications such as overload operation or waste heat recapture and reuse.

Acknowledgements

The authors would like to acknowledge the German Federal Ministry for Economic Affairs and Energy for its funding for the project "ResilientEE - Resilience of integrated energy networks with a high share of renewable energies" (03ET4048).

Keywords: Renewable Energy, PEM Electrolyzer, Power-to-Gas, TransiEnt Library, Energy Storage, Efficiency

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Translating Simulink Models to Modelica using the Nsp Platform

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Abstract

We present a new Simulink to Modelica translation chain embedded into Nsp. Translated models can be edited (original Simulink diagrams are preserved through translation) and simulated. This translation chain makes use of the Simport tool, originally designed to translate Simulink models to Scicos models, and also relies on Modelicac, i.e. Scicos' Modelica companion compiler.

Using some examples, we demonstrate the effectiveness of the translation process and detail some technical aspects of it. This new Nsp feature extends Nsp's simulation capabilities and makes it a reference platform for users looking for means to simulate Simulink models within a Modelica framework. Resulting Modelica code can even be exported to other Modelica compatible tools. *Keywords: Nsp; Simulink; Modelica*

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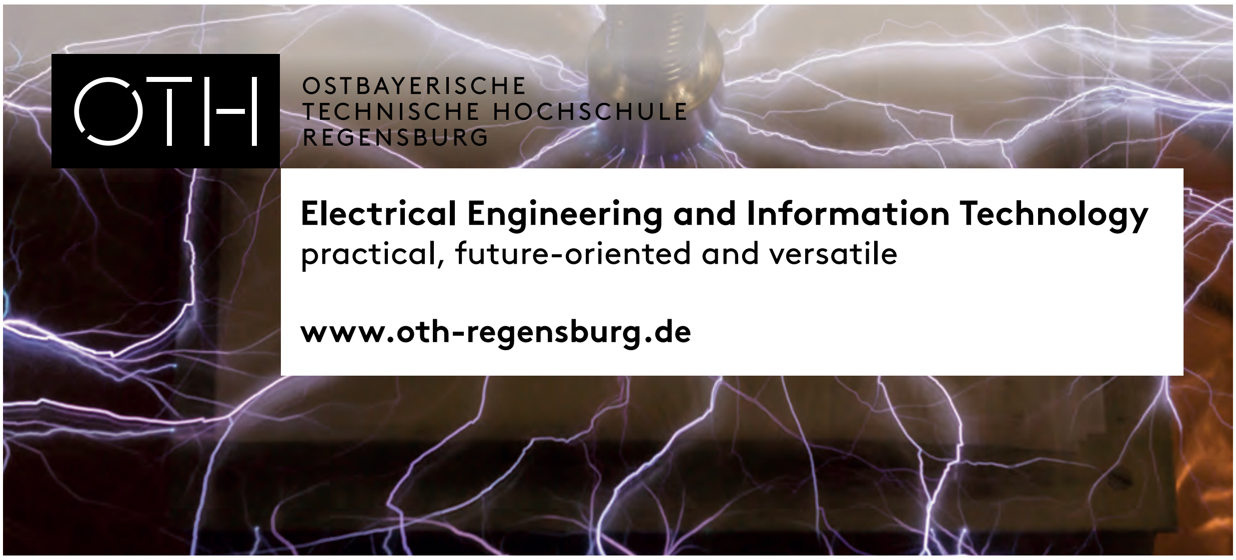

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