

# POSSIBILITIES AND LIMITS OF CO-SIMULATING DISCRETE AND CONTINUOUS MODELS VIA THE BUILDING CONTROLS VIRTUAL TEST BED

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## ABSTRACT

This paper discusses the method of cooperative simulation of discrete and continuous models with the Building Controls Virtual Test Bed, a software environment that allows coupling different simulation programs. In the course of a project aiming the energy optimization in cutting factories, models of machines of differing complexity and a building containing them have to be implemented to further simulate the thermal processes. Since all partial models require individual modelling approaches, solver time steps, solvers or even simulators, the method of co-simulation is considered. The partial models will be implemented with Modelica, Matlab, Simulink and Simscape and accessed with the co-simulation tool BCVTB. The simulation results show that this method of co-simulation can be sufficient for the needs of describing thermal systems with large time constants but has to be found insufficient for simulations requiring high accuracy and variable step solvers in the overall simulation.

Keywords: co-simulation, energy optimization, thermodynamics, MATLAB, Dymola

## 1. INTRODUCTION

### 1.1. Motivation

To optimize the energy consumption in production halls, it's necessary to model the individual machines as well as the building itself in varying detail. To further install a feedback control keeping the room temperature at comfortable values for human beings which might enter the hall, the heat emitted by the machines and its distribution in the hall have to be simulated. The simulation of the temperature progression in these machine halls is part of the INFO (Interdisziplinäre Forschung zur Energieoptimierung

in Fertigungsbetrieben) project which is supported by the Austrian Research Promotion Agency (FFG).

In this paper a simulation of models implemented with Modelica, MATLAB, Simulink and Simscape will be described. An overview of the intended communication between the simulators is given in Figure 1.

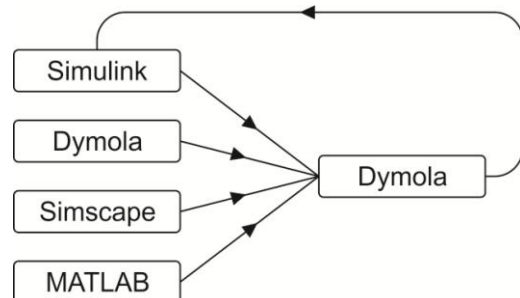


Figure 1: Desired Communication between the Individual Simulators

### 1.2. Co-Simulation

The basic idea of co-simulation is the parallel simulation of models using different simulators via one overall simulator. This simulator executes a model accessing the individual simulators and lets them synchronize at given time-steps. This way it's possible to match the individual modelling and simulation requirements of all partial models considering the fact that in our case the machine models result in differential algebraic equations describing electrical and mechanical circuits and the room model only deals with systems describing thermal processes, which react much slower and therefore don't require comparably small time steps and can use less complex solver algorithms for the simulation. This also explains why an external simulator is used to combine Simulink and Modelica

## 2. SOFTWARE

## 2.1. BCVTB

Although this might at the first impression sound like an easy way to co-simulate models with a variable step size adapting to the demands of the given problem, it will be shown later in this paper that regarding especially these simulation directors, limits are met very soon. Other actors especially developed for co-simulation with BCVTB are *simulator* actors. These actors access the individual simulators using BSD-sockets, an application programming interface enabling inter-process communication which, like BCVTB itself, also has been developed at the University of California in Berkeley. In the simulator actors the name of the simulator to be accessed as well as the file to be executed has to be defined. All values needed by the respective simulator have to be transferred to the simulator actor as inputs and all values BCVTB gets from the simulator can be accessed at the output port of the actor. BCVTB basically allows co-simulation of Ptolemy, EnergyPlus, Dymola, MATLAB, Simulink, Radiance and BACnet. For further information, see [Wetter, 2012].

## 2.2. Dymola/Modelica

### 2.3. MATLAB, Simulink, Simscape

MATLAB is a programming environment offering its own language and various toolboxes meeting the requirements of different modelling approaches. One of these toolboxes is Simulink. Simulink models basically represent signal flow charts and can be built graphically as block diagrams of directed graphs. In block diagrams for Simscape models, acausal connections are used allowing physical modelling similar to Modelica.

### 3. COMMUNICATION BETWEEN THE INDIVIDUAL SIMULATORS

For the communication with Simulink BCVTB provides a preimplemented block which basically represents the functions for the communication with MATLAB. To ensure the communication at the time steps given by the overall model despite using an individual solver with variable step size, the block has to be put in an If-Action-Subsystem which is only activated at the given synchronization references. The Simulink block for the communication with BCVTB is shown in Fig. 2:

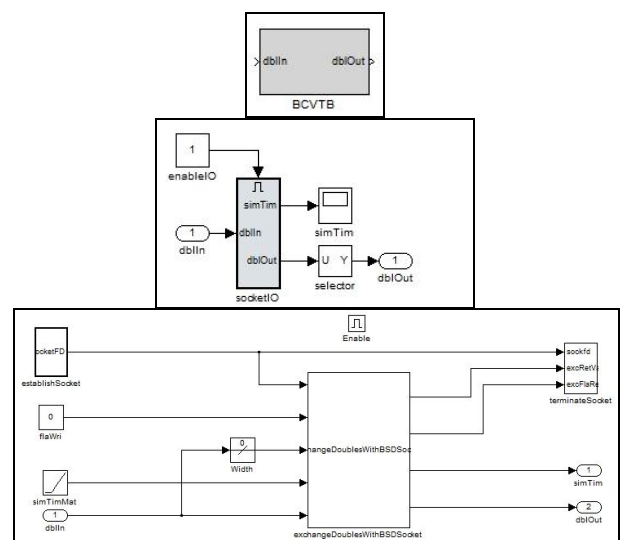


Figure 2: Simulink Block for the Communication with BCVTB

Apart from setting the number of values to be read from BCVTB and the number of values to be returned

to BCVTB, the initial return value and the time step for synchronization can be chosen in the block parameters.

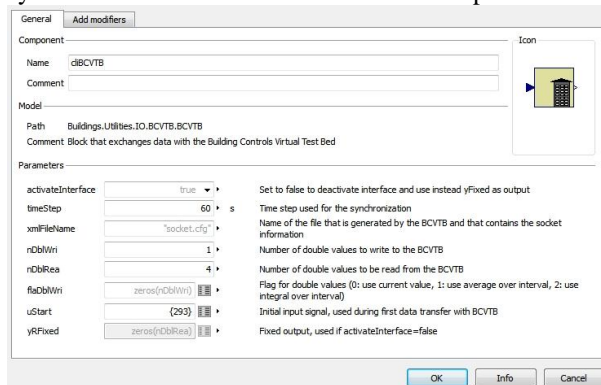


Figure 3: Block for the Communication with BCVTB in Dymola

This shows one of the first weak points of BCVTB: Dymola cannot communicate with BCVTB at variable points in time with the given resources since the synchronization time step in the BCVTB block for Dymola can only be chosen fixed.

#### 4. MODEL DESCRIPTION

To focus again on the problem of simulating the thermal processes in a production hall, the individual models will be described. The machines in the production hall are modelled in Modelica, Simscape and as simple data model in MATLAB. The room itself is implemented as compartment model in Modelica. To keep the room temperature in a tolerable interval around a desired temperature, a discrete-state three-point controller with hysteresis is also included to the model. All these partial models are finally co-simulated by executing an overall BCVTB model.

##### 4.1. Overall Model implemented in BCVTB

The BCVTB model for this problem uses a Synchronous Data Flow Director, which corresponds to a discrete fixed time solver forcing the individual simulators to exchange heat flow and temperature resp. every 60 seconds.

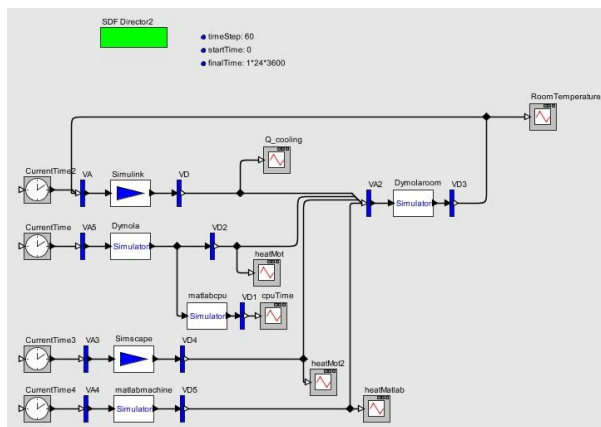


Figure 4: Overall Model for Co-Simulation via BCVTB

As you can see in Fig. 4, the dissipated heat from the machines simulated with Dymola, MATLAB and Simscape is transferred to the room model simulated with Dymola. The temperature in one compartment, where a thermometer can be pictured, is transferred to the control in Simulink. Depending on this temperature, a negative, positive or zero heat flow is returned from Simulink and transferred to the Dymola room model.

##### 4.2. Room Model in Dymola/Modelica

The room model implemented in Modelica is divided into twelve thermal compartments. These compartments have been modelled as cubes basically consisting of a certain heat capacity and thermal elements for heat exchange at the six surfaces. Each surface is represented by a heat port, a thermal conductor block and a thermal convection block. In this simplified model, the convectional heat transfer coefficient of air is kept constant as  $2 \text{ W}/(\text{m}^2 \cdot \text{K})$ , which corresponds to the average value for air at 20 degrees. Additionally, the temperature in the compartment is logged. The model graph as well as the parameters for a thermal compartment can be seen in Fig. 5:

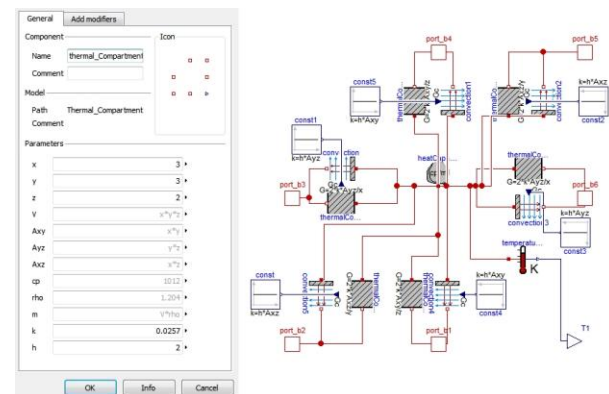


Figure 5: Parameters and Graph of a Thermal Compartment Model in Dymola

Each thermal compartment of the room is chosen to be  $3 \times 3 \times 2 \text{ m}^3$ . The whole room, which can be seen in Fig. 6, therefore accounts for  $9 \times 12 \times 4 \text{ m}^3$ .

The heat emitted by the individual machines and the output of the control are given as outputs of the BCVTB block. These signals are transferred as heat flow to the compartments where the machines and the cooling system are meant to be found. The first return value from BCVTB corresponds to the heat flow given by the control in Simulink and is sent to two of the upper compartments in the model. The other three outputs from the BCVTB block correspond to the dissipative heat from the machines models in Dymola, Simscape and MATLAB, which are found in three of the lower compartments. Additionally, an open window is represented by a constant temperature of zero degrees at the surface of one of the upper compartments.

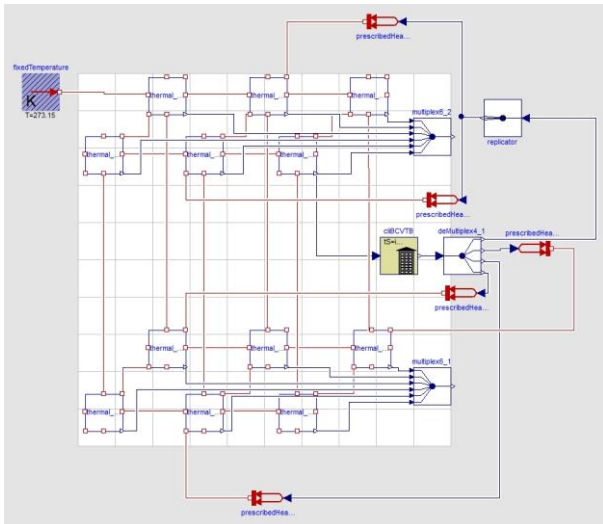


Figure 6: Room Model Implemented in Modelica/Dymola

#### 4.3. Machine Model in Dymola/Modelica

The machine model implemented in Modelica is held rather simple. Basically it consists of a DC motor emitting heat at the resistor and friction element.

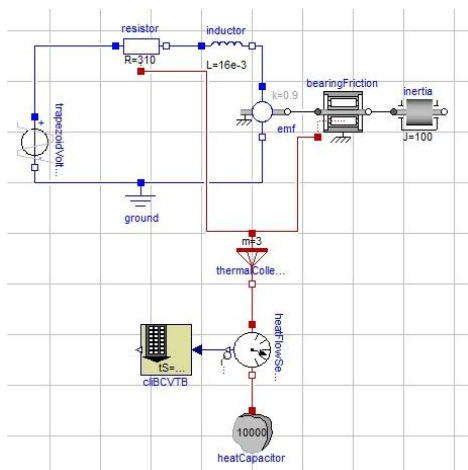


Figure 7: Model of a DC Motor in Modelica/Dymola

Since version 3.2, Modelica provides optional heat ports for further use of the heat emitted by dissipative electrical or mechanical components in thermal circuits. This way the waste heat can easily be diverted and transferred to BCVTB.

#### 4.4. Data Model in MATLAB

The data model in MATLAB accesses an Excel-file containing measured values of the heat emission of a typical machine tool. The file only provides data at every hour, so it is continued uniformly in between.

#### 4.5. Machine Model in Simscape

The machine modelled in Simscape again represents DC motor. In contrast to the Dymola motor, this model

doesn't take into account any friction. Since Simscape doesn't provide any heat ports for dissipative elements, the emitted heat is calculated manually from the voltage drop across the resistor, transferred to a thermal circuit and further to BCVTB (see Fig. 8).

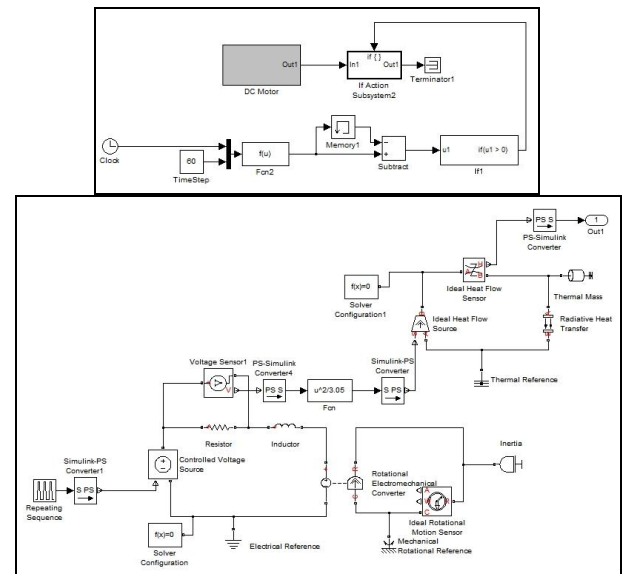


Figure 8: Graph of the DC Motor Model Implemented in Simscape

#### 4.6. Control in Simulink

To keep the temperature in the machine hall bearable for human beings, a three-point control with hysteresis has been implemented in Simulink. Simulink receives the room temperature measured in one compartment (see Fig. 6) and compares it to the desired temperature of 20 degrees.

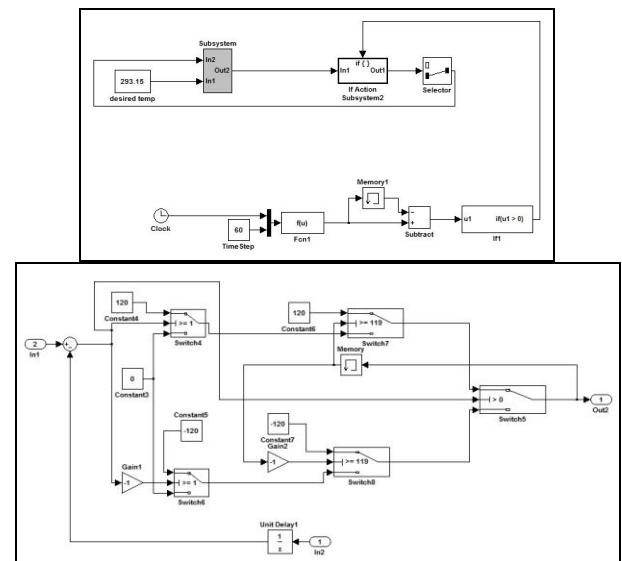


Figure 9: Graph of the Control Model Implemented in Simulink

If the room is warmer than 21 degrees, the system starts to cool by sending a negative heat flow to two



compartments of the room. As soon as the measured room temperature descends again under 20 degrees, the system stops cooling. If the room is cooler than 19 degrees, heating starts until the room is again warmer than 20 degrees. The model graph of this control can be seen in Fig. 9.

## 5. SIMULATION RESULTS

### 5.1. Temperature and Heat Flow

Fig. 10 shows the heat emitted by the individual machines over one day. All of the machines are switched on in the morning and turned off at night.

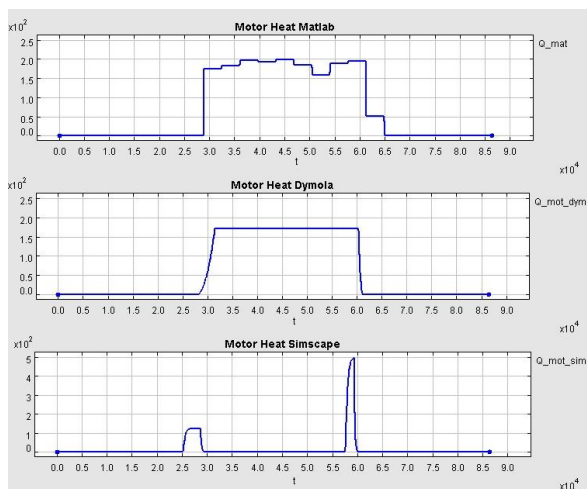


Figure 10: Heat Emission of the Machines Over One Day

The output of the MATLAB machine represents the heat emission of a machine measured every hour. For the Simscape motor, only changes in motor speed (represented by rising or falling supply voltage) cause electrical losses and emission of heat due to the fact that no friction is considered. On the contrary, the emission of the Dymola machine doesn't cease as long as the machine runs.

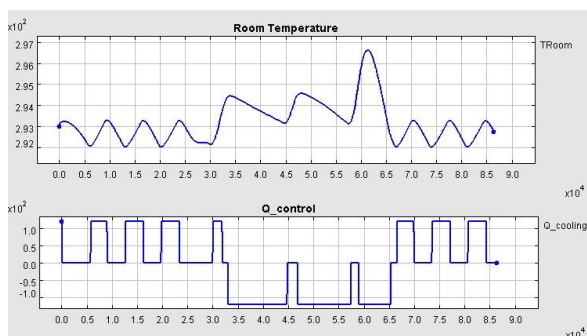


Figure 11: Room Temperature at the Thermometer for the Control and Output of the Control Over One Day

In the first plot of Fig. 11 the progression of the temperature in the compartment with the fictional thermometer for the control can be observed. The legend shows Kelvin, in degrees the temperature range

would be 18 to 24 degrees. As long as the machines are turned off, the room cools down due to the open window so the control has to heat from time to time. As soon as the machines start to work and therefore to emit heat, cooling is necessary. To give an impression on the reaction of this temperature on the output of the control, the latter is shown in the second plot in Fig. 11.

Fig. 12 shows the temperature in the six lower compartments of which three contain a machine and therefore warm up fastest (blue, black and green). The legend again shows Kelvin.

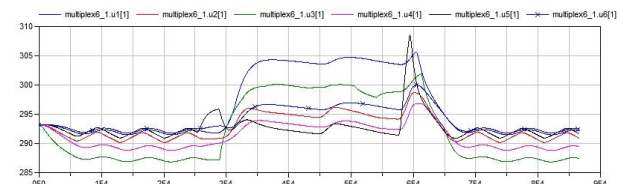


Figure 12: Temperature in the Lower Six Compartments Over One Day

The temperature of the upper six compartments can be observed in Fig. 13. Caused by the output of the Simulink control, two of them react slightly faster (red and black).

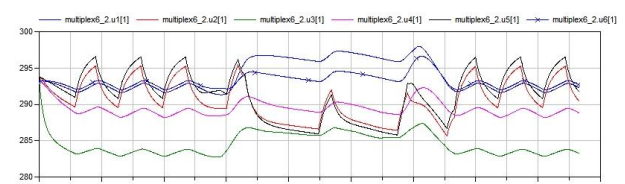


Figure 13: Temperature in the Upper Six Compartments Over One Day

As can be seen in Fig. 14, simulating the same model over one week results in an approximately periodic progression of the room temperature due to the fact that all machines are turned off at night giving the room the possibility to cool down.

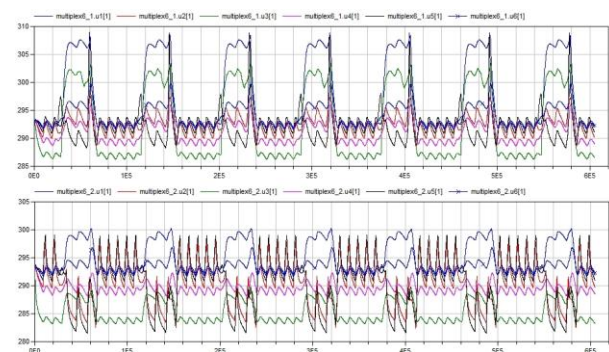


Figure 14: Progression of the Compartment Temperatures Over One Week

### 5.2. Solver Time Step Documentation

One of the most important and interesting results of a co-simulation is the documentation of the individual

solver step sizes. In this simulation, *DASSL* has been chosen as the solver for the room model in Dymola and the machine model in Dymola. For the Simscape motor *ode15s* was most suitable since it deals with stiff systems. The control in Simulink handles discrete states only, hence a variable step discrete algorithm is used. A significant advantage of co-simulation becomes obvious at one glance at Fig. 15 which shows the time steps taken by the individual solvers during one synchronization interval.

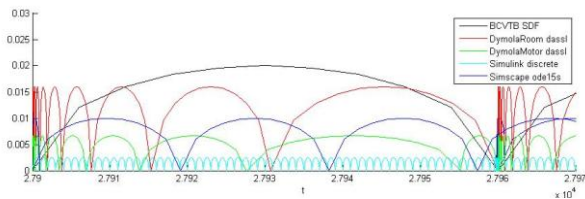


Figure 15: Different Solver Time Steps during One Synchronization Interval

Simulating the machine models requires much smaller solver time steps than simulating the room model. The steps of the *ode15s* solver for Simscape are plotted in blue, those for *Dassl* in the Dymola machine model in green, Simulink discrete in turquoise, *Dassl* for the Dymola Room in red and the overall simulation time step of constant 60 seconds in black.

If for example the machine model in Modelica and the room model were combined in one Modelica model, the simulation would demand many time steps necessary for the machine but superfluous for the needs of the room. Simulating even models which – considering Modelica and MATLAB – could to some extent be coupled without an external interface becomes way more efficient for the same reason.

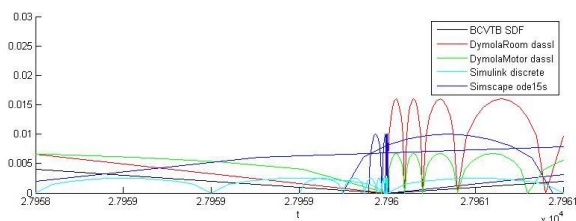


Figure 16: Time steps taken by the individual solvers at a synchronization reference

By looking the time steps in a small interval around one synchronization reference shown in Fig. 16, the redundant steps made by the Simscape solver to iterate the time for synchronization can be seen. In Dymola, the synchronization time is met without iteration since the time step for synchronization can be set in the BCVTB block. On the other hand, the direct setting of this time step prevents the possibility of synchronization at variable points in time as has already been mentioned in section 3.

## 6. CONCLUSION AND OUTLOOK

The aim of this paper has been to evaluate the possibilities and limits of co-simulating discrete as well as continuous systems with BCVTB.

One of the first important decisions to be made in this regard is the choice of an adequate time step for the overall simulation. Since thermal processes act rather slowly, the synchronization time step for this problem can be chosen comparably big in contrast to the solver time steps of the machine models. On the other hand due to the fact that all values received from BCVTB are kept constant between two synchronization references, the synchronization time step has to be considered small enough to keep the resulting error within adequate tolerances. This shows that for models focusing particularly on precise interaction, the method of co-simulation with BCVTB has to be found insufficient.

As mentioned above, this tool is going to be used for the simulation of the thermal processes in a production hall over one year. The simulation of these rather simple and few partial models for 7 days already takes about eight minutes on an average computer station. In the final model for the production hall, way more detailed and complex machine models are meant to be included. This will lead to very expensive computing times so one might have to consider that this tool is not suitable for co-simulations of such dimension.

All in all, BCVTB can be found as a quite helpful tool to quickly combine models implemented in modelling environments which are executed with different simulators using individual solvers but has to be considered deficient regarding accuracy and requirements of variable step sizes for the overall simulation of complex models.

## ACKNOWLEDGEMENTS

This work has partially been supported by the Austrian Research Promotion Agency (FFG).

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