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Modeling of Petri-Net-based control algorithms for the simulation-based improvement of the planning process of building energy systems

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Abstract. The increasing integration of renewable forms of energy into building energy systems raises the need for the use of more complex energy conversion and distribution systems. These are often equipped with complex automation systems, which require methods for structured development of control algorithms. In practice, textual descriptions of control algorithms represent a considerable source of failures. The digitization of the planning process is a core element in facilitating control development and supporting the engineering in the process automation. With regard to the digitization of the planning process, we have introduced the MODI-method in previous work. This method allows structured control development in early stages of the planning process and can be extended by performing simulations, i.e. an algorithm implemented as a Petri-Net. In this paper, we investigate the integration of this method into the simulation-based planning and an approach to model an algorithm based on Petri-Net. The case study shows the functionality of this method and the modeling approach. In future work, the MODI-method will be compared with other control strategies and applied in complex systems for further development.

1. Introduction
In order to achieve the goal of a maximum global warming of 2°C, CO₂ emissions in the building sector would have to be reduced by 77% by the year 2050 [1]. While renewable forms of energy supply are gaining importance, building energy systems are becoming increasingly complex. This development brings considerable challenges to classic processes in planning and operation in the construction industry. Studies have shown that only 43% of all building projects in Germany achieve the predicted energy efficiency. The unused efficiency potential is quantified at 10 to 30% in relation to the calculated demand [2]. There are many reasons for this, in particular faulty control modes and faulty operating states lead to suboptimal system behavior. The complexity of the overall system is difficult to handle because information is constantly lost between the work phases in the course of construction projects. While digitization is gaining ground in all areas of life, in the construction process, textual descriptions are still common and state graphs, which could help to visualize the desired systems behavior, are rarely used. One promising approach to reduce the loss of information is Building Information Modeling (BIM). BIM stands for the digitization of the planning process and represents a common information
platform for architects, engineers, service providers and users. While semantic interoperability, technical building equipment and building design are addressed well, a formalized description of the control algorithm is still missing [3]. To address this, we previously used the signal-interpreted Petri-Net (SIPN) as a formalized descriptor for control code [4]. This procedure is embedded in the so-called ”MODI method” (MODI). It enables a structured control development in early phases of the planning process and can be extended by performing simulations. In research and development, there are many promising approaches for modeling and simulating building energy systems [5]. However, few of these methods are also used in practice [6]. Using MODI, a control concept can be tailored to the individual system and tested in the simulation model of the energy system. In this paper, we investigate how to use a SIPN controller, created using the MODI method, to facilitate the planning process and model the control algorithm based on SIPN in Dymola.

2. Method

Within this section, we present MODI as we have introduced in previous work [7] and introduce a SIPN based method to describe the control algorithm.

2.1. MODI-method

MODI describes a structured process for control strategy development at the beginning of the planning process. The method is based on systematic reduction of the system’s complexity and the use of operating modes. An operating mode represents an aggregated description of a control regime that specifies the functionality of the plant depending on the operating conditions.

The starting point is the topological model of the building energy system consisting of nodes and edges which stand for components and connecting relationships of these components. In this topological model, the longest track is identified and the system can be decomposed into cascaded subsystems along the longest track. In general, an energy system can be primarily divided into two subsystems, namely energy supply system (ESS) and energy consumption system (ECS). Each subsystem may contain series or parallel connections of actuators, which can be further decomposed. Operating modes are considered for actuators, which constitute subsystems. This method reduces the complexity of the control task. Subsequently, aggregations of operating modes is performed. All the possible combinations of modes in a subsystem are gathered and checked for admissibility using a rule-based approach. Based on this process, the permissible operating modes that can be considered in the control algorithm are identified step by step from subsystems. Stepwise aggregation of the subsystems control modes yields the total control system.

2.2. Petri-Net-based control algorithm

To describe the control algorithm, we make use of SIPN as a formalized description method. The application of SIPN for control algorithms was introduced in 2002 in the doctoral dissertation of G. Frey [8] and creates intensive flexibility and the possibility of mathematical processing. A Petri-Net (PN) is composed of three elements: place, transition and arcs. A place may contain marks called token that can be transported to the downstream place by firing the transition between these two places. When used for describing a control algorithm, this principle of PN enables the change of the operating mode.

In a hierarchical control algorithm, SIPNs are constructed from the highest level (energy system) to actuator level (actuators) with several signal-inputs and outputs. Outputs of the higher level can be used as inputs of the lower level to fire transitions. In this way, we define all the modes of a system that MODI generates as places of the SIPN, while the transitions between the places change the operating mode. The transition conditions are based on the operational concept and sensor data to enable mode transitions. These modes are connected to individual
partial SIPNs, in which the functionalities of subsystems are described. With activating a place in a partial SIPN, relevant actuators receive signals from this place. Applying this process, a control algorithm can be successively translated into a SIPN.

We use the Modelica Petri-Net-library [9] to create standardized MODI blocks in the simulation environment Dymola, which allows a fast and simple construction of the control model. In the following, we analyse the interaction of the energy system model with the SIPN-based control model and the dynamic behaviour in a simulation. We further evaluate the results using key performance indicators.

3. Case study
In this section we employ MODI for the control design of a simple energy system. The corresponding control algorithm based on SIPN is simulated and evaluated in Dymola.

3.1. Control algorithm of an energy system based on the MODI-method
Figure 1 shows a heat supply system with its topological model, which contains a heat pump as renewable ESS, a boiler as a non-renewable ESS and an ECS. The figure also shows the decomposition process of the model, which supports the development of control strategies according to MODI. Table 1 shows all possible operating modes of all components of this system. Each component can be assigned actions that can influence the pressure as a hydraulic driver and the temperature as a thermodynamic driver. \((\Delta p, \Delta T)\) respectively represent the difference in pressure and temperature which a component causes along the supply path to the energy system. \(\infty\) in \(\Delta p\) stands for interrupted connection. By checking the permissibility and successively aggregating the permissible operating modes, the four operating modes that can be used in the control algorithm are identified. 0 and 1 in 2-4 columns of table 2 represent the mode numbers of the components in the corresponding subsystems.

![Scheme and topological model of a heat supply system with a decomposition process](image)

**Table 1.** Operating modes of all components in the case study

| Modes \((\Delta p, \Delta T)\) | P   | B   | H   | V   | S   | C   | Description                      |
|------------------------------|-----|-----|-----|-----|-----|-----|----------------------------------|
| 0   (0,0)                    | (0,0) | (0,0) | (0,0) | (0,0) | (0,0) | Turn components off               |
| 1   (+,0)                    | (0,+) | (0,+) | (\(\infty\),0) | (0,+) | (0,+) | Turn components on, discharge storage |
| 2   (0,−)                    | (0,−) | (0,−) | (0,−) | (0,−) | (0,−) | Charge storage                    |
3.2. Modeling of the control algorithm based on SIPN

According to section 2.2, the hierarchy of the energy system is illustrated in figure 2, where W represents the entire system and the above-mentioned components are grouped below it (see figure 1).

SIPN-based MODI blocks are constructed for all levels of this system to describe the control algorithm. Starting from the highest level, there are signal inputs from sensor data at which the boolean signal Qc indicates whether there is an energy demand. Based on this, the SIPN at the top level passes its mode as a signal to the lower levels (see (a) of figure 3), namely ES and EC. The control algorithm in ES is presented in (b) of figure 3 with inputs from interface $> ES <$ and sensors and outputs to blocks HS1 and HS2. With $> ES < = 1$, this block is active and three modes are accessible, which depend on signals B1, B2, $Q_{in}$ and $Q_{out}$ (see table 3). Only if failures are detected in HS1 or if HS1 is overload, HS2 is allowed to supply heat for the demands. (c) of figure 3 describes the strategy of operating HS2 with two main-modes and four sub-modes, which determine the sequence of running actuators. By activating these blocks, the pump in this subsystem starts, followed by opening of the valve and the boiler with delay time 15s and 30s, respectively. In reverse order, these three actuators are switched off by deactivating this block.

| Signals | Type  | Description                                |
|---------|-------|--------------------------------------------|
| B1      | Boolean | True: HS1 can operate; False: HS1 is in maintenance mode. |
| B2      | Boolean | True: HS2 can operate; False: HS2 is in maintenance mode. |
| $Q_{in}$ | Boolean | True: Power ratio of HS1 exceeds the upper limit; False: In the limit. |
| $Q_{out}$ | Boolean | True: Power ratio of HS1 below the lower limit; False: In the limit. |

![Figure 2. The hierarchy of the aggregated actuator groups of the energy system.](image-url)
3.3. Simulation-based evaluation of the system

The simulation model is based on the following libraries: Modelica-library; PNlib [9] to construct the control blocks; Aixlib [10] and Buildings [11] for the modelling of the physical model. The simulation time is 14 days with environment temperature approximated by a modified sinusoidal signals (see figure 4). In order to evaluate the strategy, following parameters are considered:

- Availability: Percentage of time that head demands are satisfied
- Seasonal Coefficient of Performance (SCOP): Ratio of heat demands to the sum of used electrical energy and chemical energy of the fuel
- Signal-changing frequency (SCF): Frequency of mode changing during the simulation

Figure 5 illustrates the thermal power of HS1 and HS2 during the simulation, which present mode-changing of HS1 and HS2 according with the environment temperature. These thermal powers are calculated through the enthalpy difference across the storage and the boiler. Due to the sequence of closing actuators, the boiler stops supplying heat before the valve is closed, which results in a negative power of the boiler after turning HS2 off. The above mentioned key performance indicators are shown in table 4. The availability of the system is satisfied with 99.16%. The high frequency of changes in the pump and compressor would have a negative effect on the life time of the components. The system behaviour could be further improved by optimising the transition conditions.

4. Conclusion

The digitalization of the planning process of complex building energy systems requires formalized descriptions of the control strategies. In this paper, the MODI method and a SIPN-based modelling approach were chosen and the integration of the method into a simulation-based
planning process was presented. The results show that MODI indeed enables control design through structured development of control algorithms and allows testing of the algorithm and associated system behavior in early phases of the planning process.

We derive future research activities from these findings: On the one hand, we want to further develop MODI by applying this method in complex energy systems and compare the resulting control strategies with other strategies. On the other hand, we want to investigate the possible integration of higher control algorithms into the method. In order to further simplify the use of MODI, the launch of an open-source library, to provide Petri-Net-based control algorithms as standard function blocks, is considered.

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