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MODI: A Structured Development Process of Mode-Based Control Algorithms in the Early Design Stage of Building Energy Systems

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Abstract: The growing share of renewable energy sources in building energy systems leads to more complex energy conversion and distribution systems. The current process of developing appropriate control functions for energy systems is insufficient and consequently error-prone. Regarding this problem, a new method is expected to systematically develop appropriate control functions for buildings and reduce design errors in this process. This paper introduces the MODI method, aiming at a structured development process of mode-based control algorithms to reduce errors in the early design stages of buildings. A complete framework and a standardized application process of the MODI method will be established to systematically design mode-based control algorithms described through signal-interpreted Petri nets. Furthermore, we performed a simulation-assisted evaluation approach to test and improve the performance of the control algorithms generated by MODI. In a case study, we applied MODI to develop a mode-based control strategy for an energy system containing heating and cooling supply networks. The desired control strategy was tested and tuned in a simulation phase. Compared to a reference control, the mode-based control algorithm shows an improvement in system efficiency by 4% in winter and 8% during the transitional season phase.

Keywords: operating modes; Petri net; control engineering; control evaluation

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1. Introduction

Recently, energy consumption in the building sector has shown rapid growth, accounting for approximately 40% of the energy consumption in developed countries [1–4]. The increasing energy consumption has generated significant interest in the integration of renewable forms of energy supply into building energy systems (BES) and the improvement of energy efficiency to achieve energy and emission reduction [5–10]. However, the integration of renewable forms of energy supply leads to more complex building energy systems. Within such complex energy systems, the capture of all control relations and the design of suitable control functions are arduous tasks for planners and commissioners in the classical planning process, especially if they lack an overall knowledge of building infrastructures. Furthermore, different functional requirements are expected for different building types and building parts, which intensifies the challenges for planners and commissioners. Motivated by the aforementioned challenges, a proper method is needed to enable the systematical development of control functions and hence reduce the complexity of control tasks in the Building Automation and Control System (BACS) design process [11].

According to the EU Commission, the unused efficiency potential of the European building stock is large and could bring improvement in energy savings and emission reductions [12]. One of the reasons might be the faulty control design and implementation, which often lead to suboptimal system behaviors in building energy systems [13–15]. In the classical planning process, the development and implementation of control functions are often performed manually and are consequently prone to errors. Although Computer Aided Engineering (CAE) systems could be used during specific planning stages, the data exchange among different work phases is textual or in a low-level electronic format [16]. Hence, the information loss and the semantic ambiguities between the work phases of the planning and commission processes are also a source of failures. For example, planners design control functions in a textual format, which are often inaccurate and unstandardized. In the implementation process, the textual descriptions need to be further interpreted and may cause misunderstandings in programming the control functions. Furthermore, without tests, these errors are rarely detected in the planning and implementation process but are recognized in the initial operation of buildings [17]. Some errors are even corrected after a long-term operation. As a result, only a fraction of all construction projects can achieve the predicted energy efficiency [13,14,18,19]. To reduce the energy efficiency gap, a method supporting simulation-based test of control functions and a formalized description method could be beneficial to reduce design errors, information loss, and semantic ambiguities among the work phases [20,21].

In previous work, we introduced the concepts of the operating modes and discussed the possibility of implementing a control function based on the operating modes in practice [22]. The operating modes are basic elements to specify the system behaviors based on the system operating states. In this work, Petri nets were used as a formalized description method for mode-based building control development to avoid the above-mentioned misunderstandings between the planning and implementation processes. Petri nets were first introduced by C.A. Petri in 1962 and have gained popularity as a mathematical tool for modeling dynamical systems and system behaviors in recent years [23–25]. In the field of BES, Petri nets are also frequently used as a modeling formalism for control strategies of BES [26–28]. Based on Petri nets, G. Frey introduced signal-interpreted Petri nets (SIPNs) to analyze control algorithms for hybrid processes [29]. Using SIPN, Cai et al. presented an SIPN-based modeling approach for mode-based control algorithms and integrated this modeling approach into the so-called "MODI method" (MODI: Operating modes in German) [30]. Thus, the two main basic concepts of the MODI method, operating mode and SIPN as a formalized descriptor, were introduced in the previous work, which presented the potential to develop control algorithms in the early phases of the building planning process and to test the control algorithms in a simulation before being implemented in a real building. In this paper, we augment the MODI-method with a standardized and concrete application procedure to achieve a systematic development of mode-based control algorithms. We also present an evaluation method for mode-based control algorithms to test the control algorithms in the early design stages of building energy systems. In the application procedure, a hierarchical structure will be specified as a template for the stepwise decomposition of an energy system, hence reducing the complexity of a control task. According to this structure, mode-based control algorithms can also be developed structurally and then described in a corresponding hierarchical SIPN. Furthermore, a simulation-assisted evaluation and improvement approach will be performed to test the functionalities of the developed mode-based control algorithms. We use key performance indicators (KPI) to evaluate these mode-based control algorithms and tune the mode-switching conditions of operating modes to improve the performance of the control algorithms. Based on this work, we will discuss the potential contribution of MODI to supporting the digitization of the control strategy design in BACS.

State of the Art

BACS provides services covering heating, cooling, ventilation, lighting, etc. within buildings and also supports control, monitoring, and optimization of the building energy system operation [31–33]. The impact of BACS on the energy performance of buildings has been evaluated by several studies [34–43], which proved that the BACS can contribute to energy savings and CO_2 emission reductions in buildings. In the classical building planning and design process, the planning of the BACS is considered at the end of this process, yet it is still expected to integrate all the building's infrastructure into a cohesive system of components that operate cooperatively and hence efficiently [16]. Therefore, the planning process of the BACS features the application and organization of multiple control functions and might result in errors that are only detected in the initial operation process of the buildings [17].

Based on this, a number of studies have been devoted to improving BACS design as well as specifications for appropriate control functions. The two main fields can be identified; namely the complexity reduction of the BACS design, in both infrastructure and control functions, as well as the selection of the BACS control functions for energy efficiency improvements [11]. The European Standard EN 15232 describes the effects of control functions and the corresponding guidelines on the energy performance of buildings. The standard classifies four different BACS efficiency classes and specifies BACS efficiency factors for these classes, which were tested in an experimental study by Bonomolo et al. [44]. However, this standard refers only to the BACS functions and does not take into account the building as a whole [11,16,45,46]. The categorization and the guidelines of the renewable energy sources are also lacking in this standard [11,47]. The work by Grela et al. [16] describes a software tool to guide the selection of BACS functions for possible energy efficiency improvements. The functional profiles of this software are function-block-oriented, depending on EN 15232, without implementing other standards. In [47], a hybrid approach to the design of BACS with a Smart Readiness Indicator was developed, in which some new control functions and a new set of these functions for renewable energy sources, such as photovoltaic panels, were introduced. However, to the best of our knowledge, there is still a lack of a generalized methodology, which enables systematically decomposing the control tasks and developing control functions of the BACS regarding the building energy systems as a whole at the early stage of the planning process.

Moreover, the detailed design of the data flow within the BACS is also a challenging issue in the planning process. The VDI 3813 was published for systematic documentation of control functions in building automation systems [48,49]. An abstract design represented as a dataflow graph was introduced in the standards to show control and monitoring functions in graphs. Nevertheless, the standards are insufficiently utilized in many building projects [22,49]. Based on the VDI 3813, an AutomationML-based description of the BACS functions was developed [17]. This work [17] also presented a Petri net model to simulate the desired BACS for early faulty detection. Yet, the cooperation of different energy components within a building was still ignored. The Petri-net-based simulation can only test the performance of the control functions. Integration of the Petri-net-based model into a physical model of an energy system can further promote the evaluation of the control functions.

In the next section, we introduce the MODI method for the structured development of mode-based control algorithms and a simulation-assisted evaluation method to analyze the quality of mode-based control algorithms at the early stage of the planning process. These methods will be tested and discussed based on a use case in Section 3. Section 4 is a conclusion.

2. Method

This section introduces a standard application process of MODI to structurally develop mode-based control algorithms, including the design, the modeling, the evaluation, and the improvement of the control algorithms. As basic elements in the design of mode-based control algorithms, the method for operating modes is identified in Section 2.1. Section 2.2 introduces the modeling method of mode-based control algorithms based on a hierarchical SIPN. To evaluate the designed control algorithms, a simulation-supported evaluation method is presented in Section 2.3.

2.1. Systematical Identification of Operating Modes

MODI enables a structured process for developing mode-based control algorithms for building energy systems. This method is based on a top-down decomposition of an energy system and a bottom-up aggregation of operating modes to obtain the operating modes of the total system [30]. An operating mode is a basic element in mode-based control algorithms and presents a control algorithm that specifies the functionalities of a component depending on operating conditions. It allows being aggregated to obtain the overall operating mode of a group of components. In this section, we introduce a hierarchical structure to standardize the previously mentioned decomposition process of MODI.

At the beginning of the decomposition, we need to transform the desired energy system into a corresponding topological model consisting of nodes and edges, which represent actuators and the connection of actuators. Such a topological model provides a schematic overview of the total system and hence simplifies the following decomposition of the systems. As Figure 1 illustrates, a whole building energy system is represented at the highest level, where actuators are basic elements at the lowest level. We primarily identify networks at the network level. A network features a complete energy supply system consisting of energy supply, distribution, and consumption systems. According to the functionalities, an energy network can be classified as a heat supply network (HSN) or a cold supply network (CSN). In general, a building energy system might contain these two types of networks. In each network, we can further decompose the network into the three basic subsystems at the subsystem level, namely energy supply, distribution, and consumption systems. As a distributed energy supply network, the subsystems (energy supply and consumption systems) may contain several energy supply stations and distributed buildings, respectively, which can be further decomposed into smaller subsystems. For example, two distributed cooling supply stations provide cooling for a cooling network. The two cooling supply stations can be regarded as two subsystems. Within a subsystem, several components, such as chillers, heat pumps, and boilers, can be identified at the component level. Each component can be further divided into actuators, such as pumps and valves, which help the operation of the components. Based on the decomposition, the desired energy system can be divided into a hierarchical structure containing four levels.

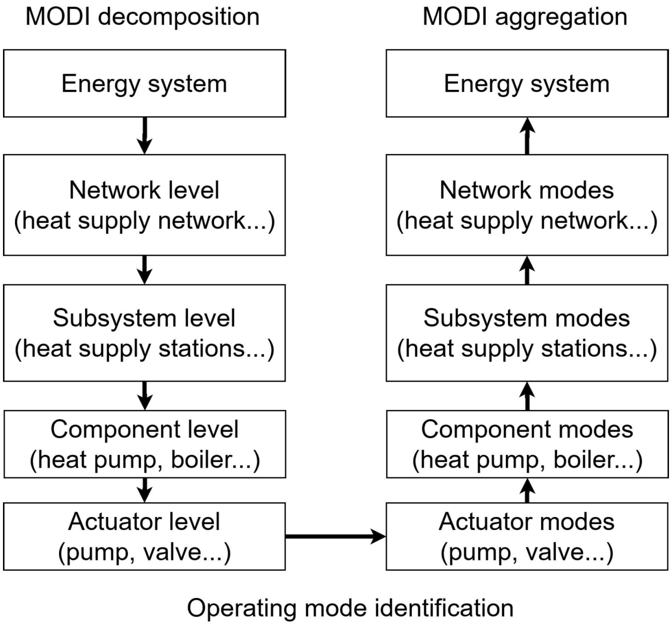


Figure 1. Strategy of the MODI method.

Based on the hierarchical structure, the identification of operating modes starts with the actuators at the actuator level. An aggregation of operating modes is performed using Equation (1) to gather all possible combinations of modes in a component:

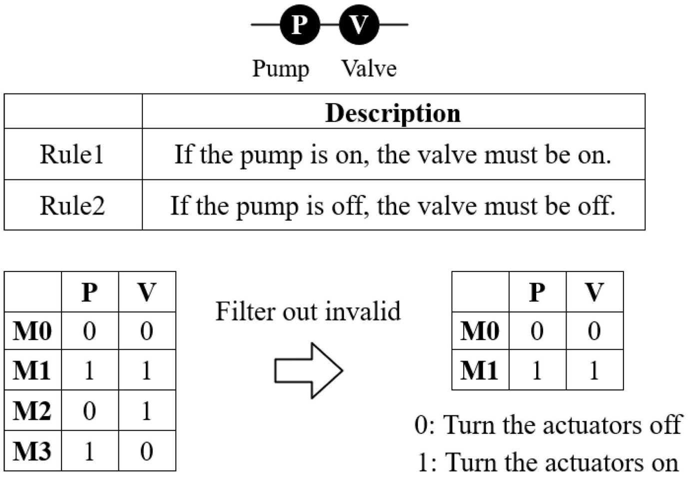
$$N_{operating\ mode} = \prod_{a=1}^{m} M_a, \tag{1}$$

where m is the number of actuators and components within a group and M_a is the number of modes of an actuator or a component. The operating modes of typical actuators and components are shown in Table 1. In general, only two operating modes are considered, namely off and on. We use the influence on the temperature and the pressure of an actuator or a component to assign it as a thermodynamic driver and a hydraulic driver, respectively. The difference in pressure and temperature for a component is presented in the tuple $(\Delta p, \Delta T)$, where "+", "−" and "0" mean positive, negative, and no differences, respectively. ∞ in Δp is used for an interrupted connection, such as a closed valve.

Table 1. Operating modes of typical actuators and components in an energy system. $(\Delta p, \Delta T)$: the difference in temperature and pressure caused by an operating mode; ∞ in Δp: an interrupted connection; +: positive difference; −: negative difference; 0: no difference.

Modes (Δp,ΔT)	Pump	Heat Pump	Valve	Description
0	(0, 0)	(0, 0)	(∞, 0)	Turn off
1	(+, 0)	(0, +)	(−, 0)	Turn on

In the next step, all possible operating modes in a component, resulting from combining the actuators, are determined. These operating modes are checked for permissibility applying a rule-based approach. For example, four possible operating modes are available for a branch containing a pump (off, on) and a valve (off, on), illustrated in Figure 2. These four operating modes are tested by the two rules and only two modes are identified as permissible operating modes. For the aggregation, only permissible modes are considered to identify the permissible modes step by step from the component level to the total control system level.



	Description
Rule1	If the pump is on, the valve must be on.
Rule2	If the pump is off, the valve must be off.

	P	V
M0	0	0
M1	1	1
M2	0	1
M3	1	0

	P	V
M0	0	0
M1	1	1

0: Turn the actuators off
1: Turn the actuators on

Figure 2. Strategy of the MODI method.

2.2. SIPN-Based Modelling Approach

To support the fault reduction in the planning process, we have verified the method using SIPN as a formalized descriptor for modeling and describing mode-based control algorithms [30]. Building upon this concept, in this section we introduce a hierarchical SIPN framework to model mode-based control algorithms corresponding to the standard decomposition process.

In 2002, G. Frey introduced the application of signal-interpreted Petri net (SIPN) for control algorithms in his doctoral dissertation [50]. A signal-interpreted Petri net consists of three elements: place, transition, and arcs, as Figure 3 shows. Tokens contained in a place, for example, P_1 in Figure 3, can be transported to the downstream places (P_2) along the arcs by firing the transition between the two places. If a place receives a token, this place will be active and output a corresponding signal, such as $f_1(x)$ and $f_2(x)$. Based on this principle, SIPN can be used to organize transitions of operating modes and construct a hierarchical control model. Furthermore, SIPN allows the visualization of control behaviors by presenting the flow of tokens and document control algorithms in a graphic format. The possibility to implement SIPN-based control algorithms in PLC code was also proved in Frey's dissertation [29,50,51].

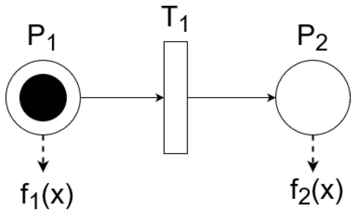


Figure 3. Basic elements of a signal-interpreted Petri net. P: place; T: transition; f(x): output functions.

According to the standard decomposition structure in Figure 1, a corresponding hierarchical SIPN framework was developed. As Figure 4 illustrates, for each element identified in the decomposition process, a corresponding SIPN will be set to organize the element operation, which determines a currently appropriate operating mode from these modes and performs mode changing by firing transitions and activating places. In our case, operating modes are places of SIPNs and switching conditions are the transitions. Inputs of an SIPN to a level are the outputs from the higher level and the state variables, which are relevant for the switching conditions. These inputs determine the mode changing of an SIPN. If a place in an SIPN is active, a corresponding signal will be transferred as output to the next level as input. Communication among levels is organized through such signal inputs and outputs.

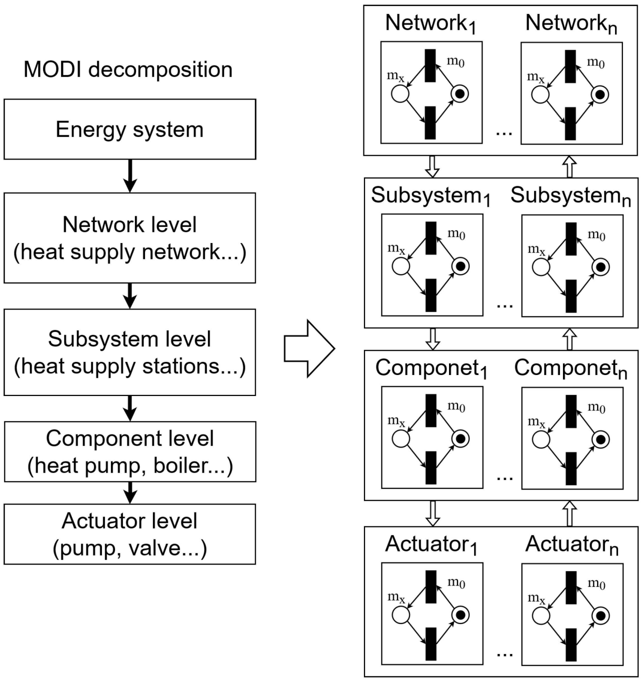


Figure 4. A hierarchical framework of signal-interpreted Petri nets for modeling a mode-based control strategy corresponding to the standard decomposition structure of the MODI-method.

At the network level, the operating mode of a network is primarily chosen by determining the demands. For example, if there is a heat demand, a heat supply network will be running; at least one of the subsystems within the network must cover the demand. This decision is passed to the subsystem level. At the subsystem level, the mode of the subsystem is determined and all the permissible combinations of the subsystem modes are available as places with corresponding transition conditions. The places of the subsystem level activate the SIPNs at the component level, which describe the performances of the corresponding components within the subsystems. By activating a place at the component level, relevant devices and actuators receive signals of operation.

2.3. Simulation-Based Evaluation and Improvement of the Control Algorithm

We use simulations to evaluate and improve mode-based control algorithms. The desired energy systems and the corresponding control algorithms can be modeled using the modeling language Modelica. Based on the simulation results, failures in the control design and the description of the control algorithms could be detected in the simulation phase and hence avoid being transferred into the following implementation process. Furthermore, transition conditions of operating modes have a significant impact on the performance of mode-based control algorithms. How to determine these transitions is always a challenging issue in developing mode-based control algorithms. We desire to find appropriate transition conditions and tune them to improve the performance of the control algorithms in the simulation phase.

To evaluate the control algorithms, the following parameters as key performance indicators (KPI) are used:

- Satisfaction rate (SR): Percentage of time that demands are satisfied;
- Seasonal Coefficient of Performance (SCOP): Ratio of demands and the sum of used electrical energy and chemical energy of fuel in the simulation;
- Signal-changing frequency (SCF): Frequency of mode changing during the simulation;
- Percentages of renewable/non-renewable energy consumption (PR/PNR): Distribution of energy consumption on different types of energy resources, i.e., renewable or non-renewable.

A normalization function is applied to normalize and compare these KPIs from different simulation results:

$$NKPI_i = \frac{KPI_i - KPI_{i,min}}{KPI_{i,max} - KPI_{i,min}}, \tag{2}$$

where $i \in \{SR, SCOP, SCF, PR, PNR\}$, $NKPI$ means the normalized key performance indicators, and $KPI_{i,max}$ and $KPI_{i,min}$ represent the maximum and minimum of KPI values from these results. We use a fitness value to evaluate simulation results considering $NKPIs$:

$$Fitness\ Value = \frac{\sum w_i \cdot NKPI_i}{\sum w_i}, \tag{3}$$

where w_i are the individual weights of $NKPI_i$, which can be defined individually for the considered system.

3. Case Study

According to MODI, we will develop a mode-based control strategy for an energy system with two networks in the early design phase. The available information at this stage is limited to only the topology of the desired system. The decomposition of the system and the aggregation of resulting operating modes are primarily demonstrated in Section 3.1. Based on the operating modes, a mode-based control strategy will be developed and modeled using SIPNs (Section 3.2). We use simulations to evaluate the proposed control strategy and further show how to tune the control strategy using KPIs (Section 3.3). A comparison between the tuned algorithm and a standard control approach will also be performed by using KPIs.

3.1. Identification of the Permissible Operating Modes of the Desired Energy System

Figure 5 depicts the system scheme of an energy supply system with the translation to its corresponding topological model. The system consists of a heat pump (HP), a borehole-heat-exchanger field (BHE), a boiler, and two energy consumer systems with heat and cold demands, respectively. The heat pump is connected to a cold storage and to a heat storage, preventing intensive temperature fluctuation in the energy system. According to the topological model in Figure 5, two different networks are identified, namely the heat supply network and the cold supply network. The heat pump is not directly connected to the heat demand but supplies heat by charging the heat storage. Therefore, the heat supply network is divided into two distributed subsystems. The decomposition of the whole system is shown in Figure 6.

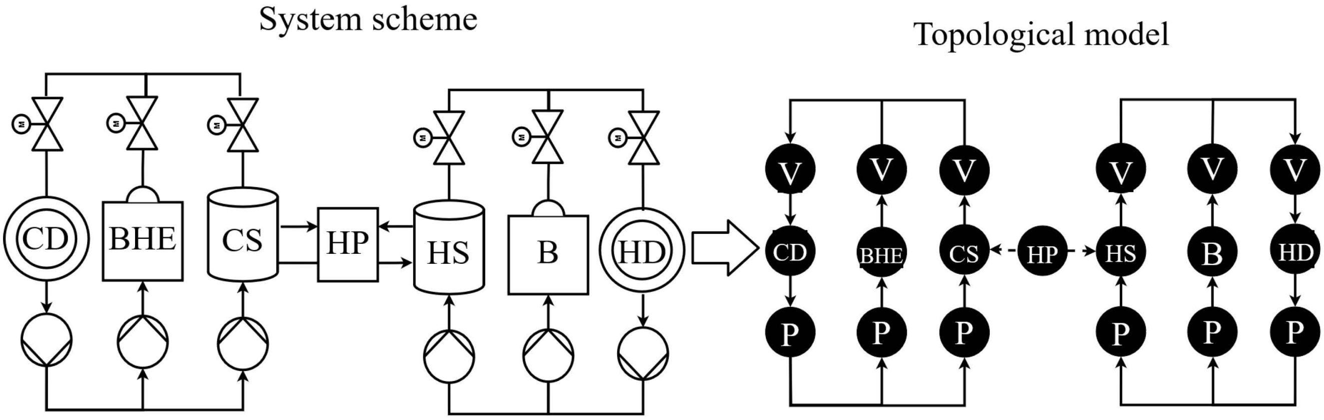


Figure 5. Scheme and topological model of an energy supply system. CD: cold demand; BHE: borehole-heat-exchanger field; CS: cold storage; HP: heat pump; HS: heat storage; B: boiler; HD: heat demand; V: valve; P: pump.

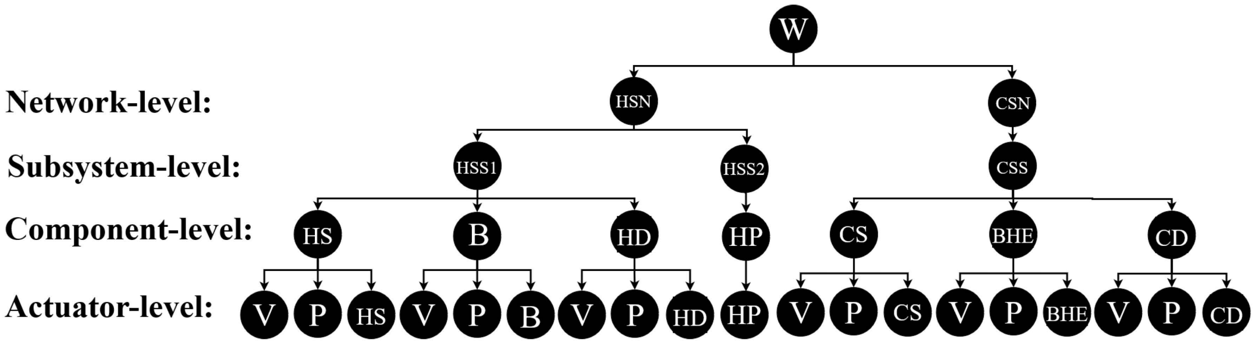
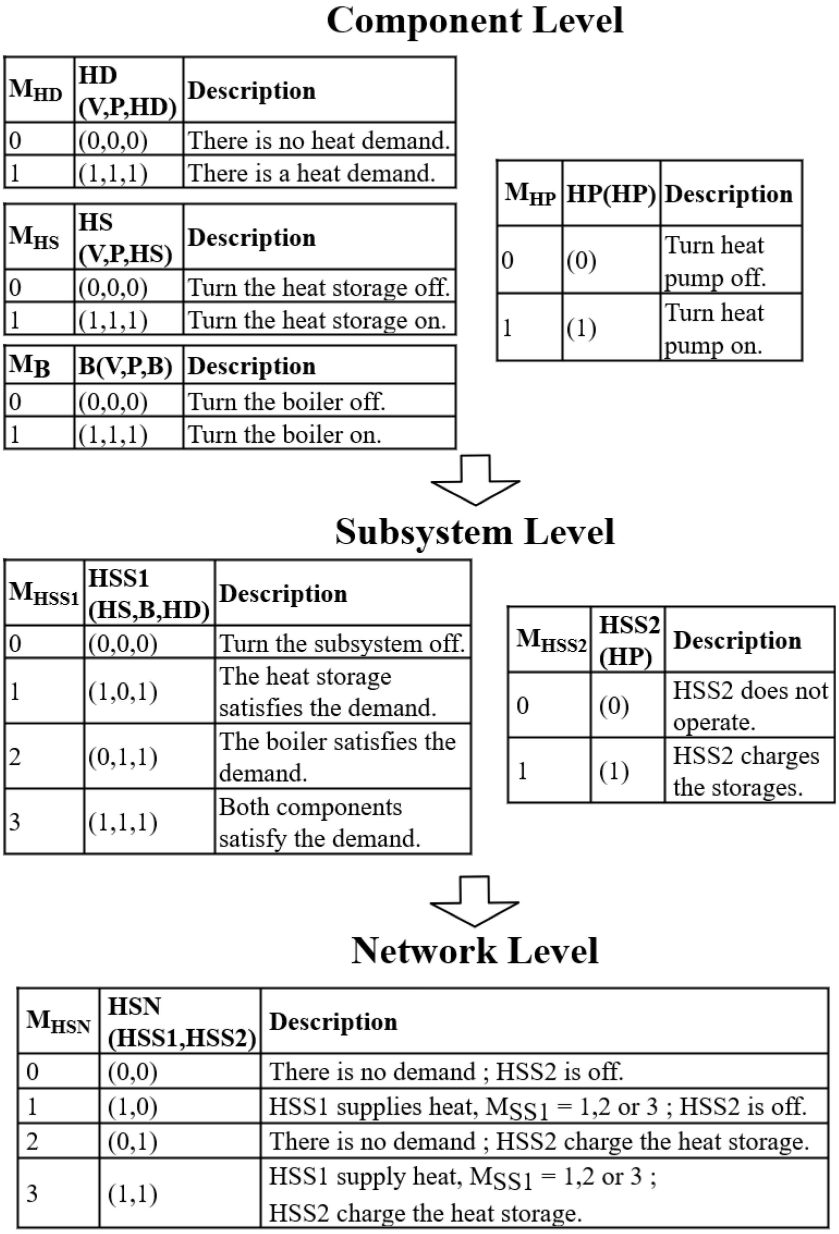


Figure 6. Hierarchical structure of the energy system after decomposition. W: whole system; HSN: heat supply network; CSN: cold supply network; HSS: Heat supply subsystem; CSS: cold supply subsystem; HP: heat pump; HS: Heat storage; B: Boiler; HD: heat demand; CD: cold demand; V: valve; P: pump; BHE: borehole-heat-exchanger field; CS: cold storage.

Stepwise aggregation of permissible operating modes is performed from the actuator level to the network level. To simplify the planning process, two operating modes are mainly considered, namely “0” (turn components/systems off) and “1” (turn components/systems on). According to the aggregation, permissible operating modes from the component level to the network level are obtained. Figure 7 illustrates the aggregation for the heat supply network. At the component level, we determine the operating modes of the heat storage, the boiler, and the heat demand in subsystem 1 and the modes of the heat pump in subsystem 2, respectively. These modes are aggregated at the subsystem level, in which four permissible operating modes for subsystem 1 and two modes for subsystem 2 are identified. Finally, we obtain the operating modes of the network by aggregating these six modes of both subsystems. The aggregation of the cooling supply network is similar.



Component Level

M_{HD}	HD (V,P,HD)	Description
0	(0,0,0)	There is no heat demand.
1	(1,1,1)	There is a heat demand.

M_{HS}	HS (V,P,HS)	Description
0	(0,0,0)	Turn the heat storage off.
1	(1,1,1)	Turn the heat storage on.

M_B	B(V,P,B)	Description
0	(0,0,0)	Turn the boiler off.
1	(1,1,1)	Turn the boiler on.

M_{HP}	HP(HP)	Description
0	(0)	Turn heat pump off.
1	(1)	Turn heat pump on.

Subsystem Level

M_{HSS1}	HSS1 (HS,B,HD)	Description
0	(0,0,0)	Turn the subsystem off.
1	(1,0,1)	The heat storage satisfies the demand.
2	(0,1,1)	The boiler satisfies the demand.
3	(1,1,1)	Both components satisfy the demand.

M_{HSS2}	HSS2 (HP)	Description
0	(0)	HSS2 does not operate.
1	(1)	HSS2 charges the storages.

Network Level

M_{HSN}	HSN (HSS1,HSS2)	Description
0	(0,0)	There is no demand ; HSS2 is off.
1	(1,0)	HSS1 supplies heat, M_{SS1} = 1,2 or 3 ; HSS2 is off.
2	(0,1)	There is no demand ; HSS2 charge the heat storage.
3	(1,1)	HSS1 supply heat, M_{SS1} = 1,2 or 3 ; HSS2 charge the heat storage.

Figure 7. The aggregation of the permissible operating modes of the heat supply network. HSN: heat supply network; HSS: Heat supply subsystem; HP: heat pump; HS: Heat storage; B: Boiler; HD: heat demand; V: valve; P: pump.

3.2. Modeling of a Mode-Based Control Strategy Using the Hierarchical SIPN Framework

In this section, the modeling of a mode-based control strategy for the heat supply network will be presented to show the application of the hierarchical SIPN framework. The modeling of the control function for the cold supply network is similar to that of the heat supply network and hence will not be shown. Moreover, the definition of the transition conditions is also a vital part of this section.

Regarding the heat supply networks, four operating modes are available at this level (see Figure 8), which are determined by two factors, namely the heat demands and the state of charge (SOC) of the heat storage. We use sensor data of the flow temperature in the consumption system as an indicator for heat demands, while sensor data from the temperature of the heat storage present the state of the heat storage. Based on this, a place of the SIPNs at the network level will be active and pass corresponding signals to the subsystem level. For example, if there is a demand and the heat storage is fully loaded, $M_{HSN} = 1$ will be passed to the subsystem level. Figure 8 illustrates the algorithm using SIPNs with the corresponding transition conditions and signal outputs.

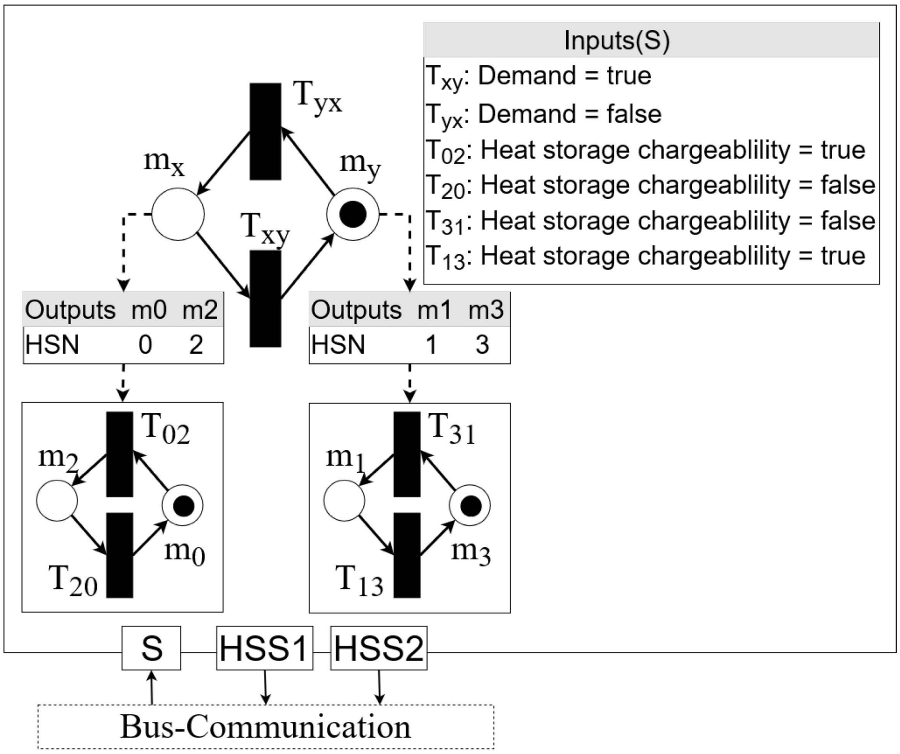


Figure 8. The control model of the heat supply system at the network level based on SIPNs. HSN: heat supply network; HSS1: heat supply subsystem 1; HSS2: heat supply subsystem 2; S: sensor data.

Based on M_{HSN} from the network level, the operating modes of the two subsystems will be further determined at the subsystem level. In heat supply system 1 (HSS1), we can use the heat pump and the boiler to satisfy heat demands, which leads to three operating modes (see Figure 9a). The heat pump is considered a renewable energy supply system. Hence the heat storage, which is charged by the heat pump, is preferred to be used unless it is in a maintenance mode or it is empty ($M_{HSS1} = 1$). If the heat storage runs until it is empty, the boiler will run to take a part of the demands ($M_{HSS1} = 3$). If the heat storage is in maintenance, only the boiler runs to satisfy all demands ($M_{HSS1} = 2$). Figure 9b illustrates the control function of heat supply system 2 (HSS2), which will be turned on or off according to the output of the heat supply network. The decision of the used operating mode at the subsystem level will be transferred to the component level through the corresponding signal interface.

As shown in Figure 10, the control functions of the heat supply system at the component level consist of three SIPNs, which drive the components of the heat storage, the boiler, and the heat pump, respectively. The inputs from the subsystem levels will fire transitions. Then the SIPNs transport the token to the corresponding place along the arcs. In the process, a delay time of 1200s has been defined to avoid frequent state changes. For example, if HSS2 = 1, T_{011} and T_{012} will be fired and then the token will go to m_1. However, the token cannot arrive in m_1 directly but in m_{01} with a delay time. Within the delay time, the output of the SIPN is not changed. After the delay time, the transition conditions will be tested once again to decide, in which place the token should arrive. If HSS2 is still 1, the token will be passed further to m_1 and the mode change will be achieved. Otherwise, the token returns to m_0 without a mode change. This process can protect the components from frequent state changes.

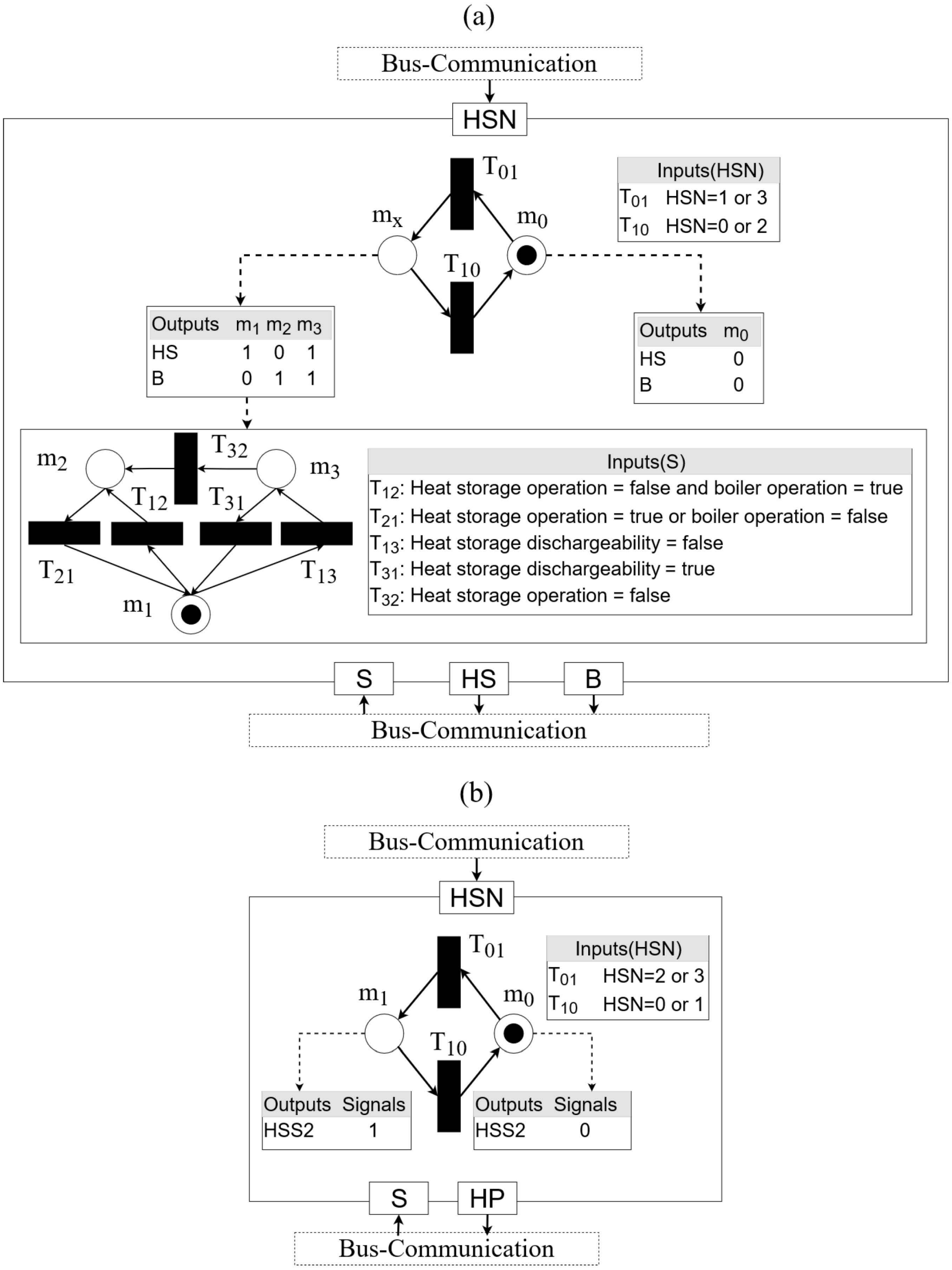


Figure 9. The control function of the heat supply system at the subsystem level based on SIPNs. (**a**): the control model of heat supply subsystem 1; (**b**): the control model of heat supply subsystem 2. HSN: heat supply network; HSS2: heat supply subsystem 2; S: sensor data, HS: heat storage; B: boiler; HP: heat pump.

The control function of the cold supply system is similar, except for different operating modes and transition conditions. At the network level of the cold supply system, only cold demands are considered as a transition condition to turn the network on or off. At the subsystem level, the cold storage satisfies cold demands, while the borehole-heat-exchanger field runs as an auxiliary cold source, to protect the heat pump from low evaporator temperature in the winter, and helps supply cooling in the transition season.

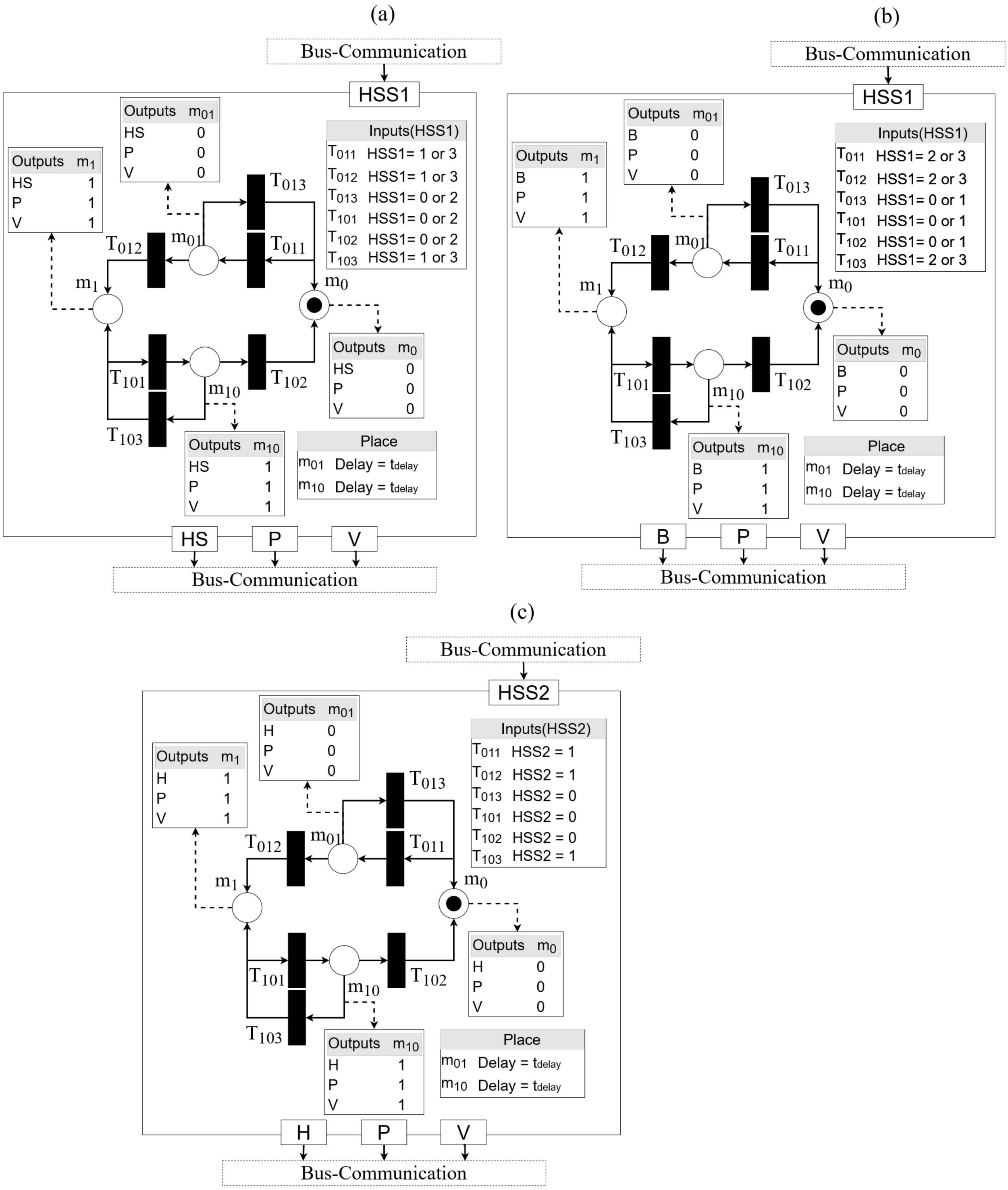


Figure 10. The control function of the heat supply system at the component level based on SIPNs. (**a**): the control model of the heat storage; (**b**): the control model of the boiler; (**c**): the control model of the heat pump. HSN: heat supply network; HSS1: heat supply subsystem 1; HSS2: heat supply subsystem 2; S: sensor data, HS: heat storage; B: boiler; HP: heat pump; P: pump; V: valve.

3.3. Results of the Simulation-Based Evaluation and Tuning

In this section, we focus on the simulation-based evaluation described in Section 3.2. As Figure 11 illustrates, we model the energy system (named system model in the following) and the controller (called control model) in the modeling language Modelica, using the Modelica Standard Library, PNlib [52], to construct the control models, as well as the

Aixlib [53] and Buildings [54] for modeling of the system model. In each time step of the simulation, the system model provides state variables relevant to the control strategy, while the control model decides the used operating mode and then transfers this decision to the components and actuators in the system.

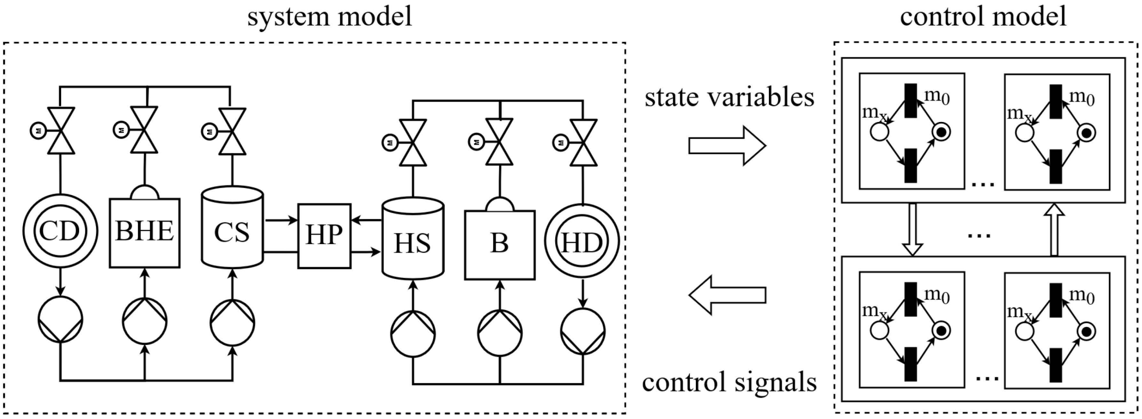


Figure 11. Modeling the energy system and the controller in the modeling language Modelica. CD: cold demand; BHE: borehole-heat-exchanger field; CS: cold storage; HP: heat pump; HS: heat storage; B: boiler; HD: heat demand; V: valve; P: pump.

The environment temperature and the heat demands are the measured data of a commercial building in Lüneburg, covering 28 days for two scenarios, respectively, as Figure 12 illustrates. We used these data for the simulation. The temperature of the evaporator and the condenser contained in the heat pump were designed with 14 °C and 60 °C, respectively. The temperature at the exit of the evaluator of the heat pump is desired to be higher than 7 °C, aiming at protecting the heat pump. The desired temperature of heat and cold supply networks are 50 °C and 17 °C, respectively. To ensure the desired temperature of the heat network, the heat storage is regarded as being fully charged with $T_{HS} > 55$ °C and empty discharged with $T_{HS} < 50$ °C.

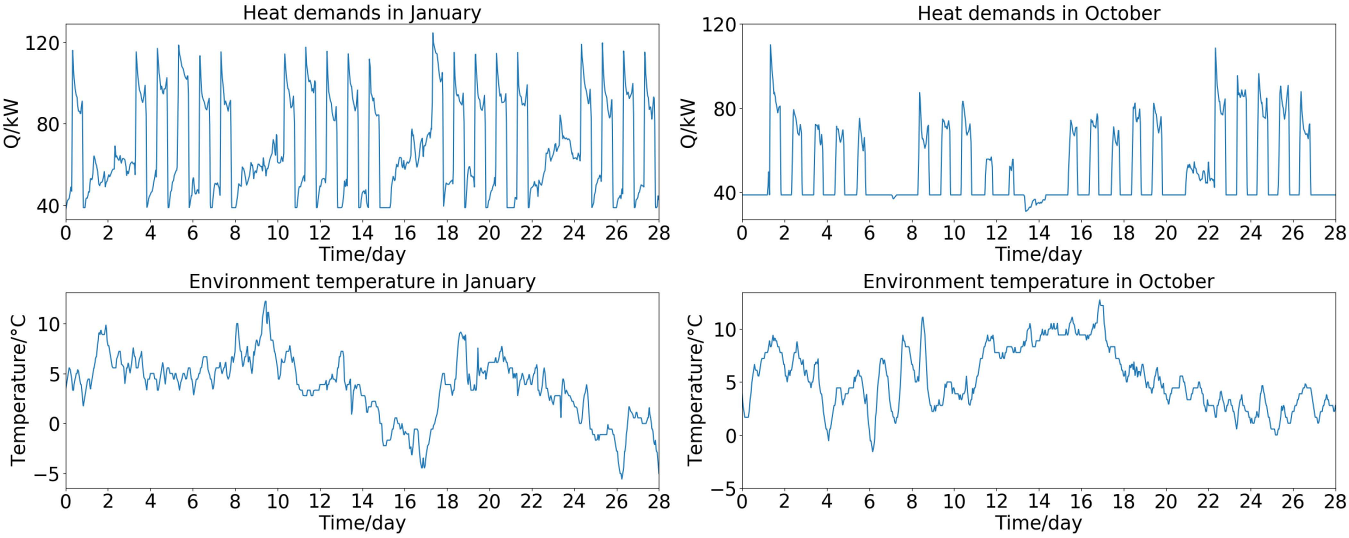


Figure 12. The environment temperature and the heat demand of January and October for the simulation.

3.3.1. Evaluation of the Mode-Based Control Algorithm Applied to the Desired System

To analyze the SIPN-based control model, the control function in the heat supply network in the winter phase was regarded as an example.

The operating of heat supply system 1 is represented in Figure 13, which illustrates the state of the heat storage, the operating modes of the boiler, and the supplied heat of the boiler. The control algorithm specifies that the boiler will operate if the heat storage is discharged. As Figure 13 shows, the control model passes the signal of 1 (M_B = 1) to the boiler, when the heat storage is exhausted (heat storage dischargeability = false). The boiler receives the signal from the control model and operates correspondingly, which is revealed by the heat power of the boiler in the bottom plot of Figure 13. In this figure, the boiler supplies heat or not according to its operating modes. How much heat power the boiler needs to supply depends on the demand in Figure 12.

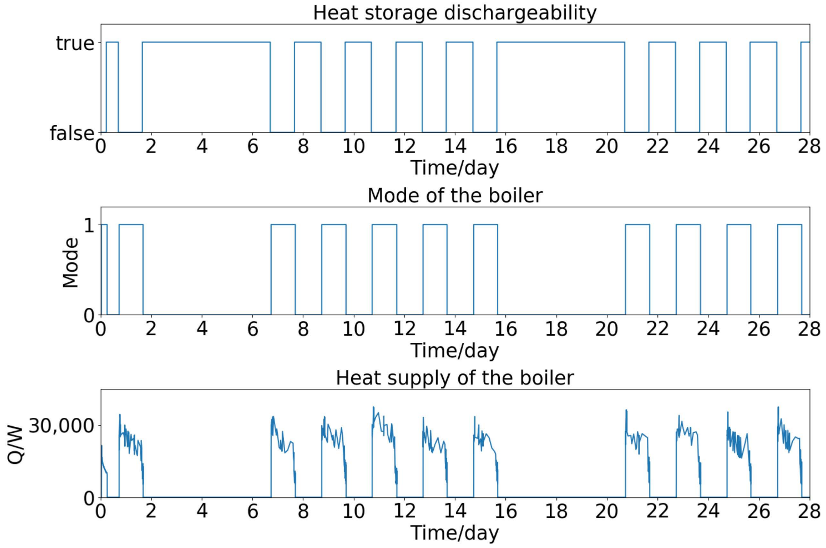


Figure 13. The simulation results of heat supply subsystem 1 containing a heat storage and a boiler as time series in the winter phase.

Figure 14 shows the chargeability of the heat storage, the mode of the heat pump, and the electrical power of the heat pump in heat supply system 2. Due to the heavy demand in the winter phase, the heat storage is never full. Correspondingly, the heat pump always runs to charge the storage, which is indicated by the electric power as a time series. The supplied electric power also runs in accordance with the demand.

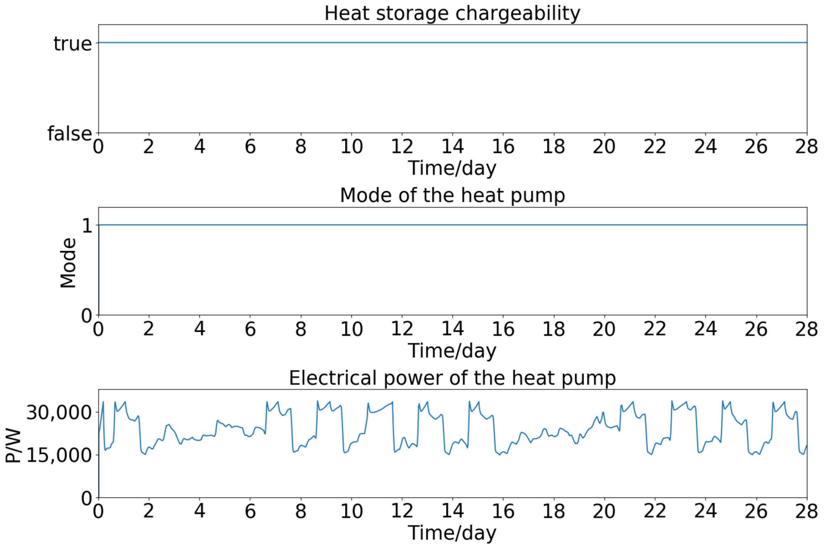


Figure 14. The simulation results of heat supply subsystem 2 containing a heat pump as time series in the winter phase.

Table 2 shows the KPI values of the energy system in the two phases, respectively. Under the control algorithm, the demands of the system are satisfied with high satisfaction rates for both the heating supply and the cooling supply. Compared to the transition season, the energy efficiency of the system will be decreased and the boiler needs to run frequently to support the energy supply in the winter with heavy heat demands. Hence, the SCOP of the whole energy system in the winter is lower than that of the transition season and P_B also increases significantly. As a renewable energy resource, the heat pump is always preferred to operate, as Figure 14 illustrates. Therefore, mode changes were detected only twice.

Table 2. The KPIs of the energy system controlled by the developed mode-based control algorithm. SR: satisfactory rate; SCOP: seasonal coefficient of performance; P: part of energy supply; SCF: signal-changing frequency; B: boiler; H: heat pump.

KPI	Winter Phase	Transition Season
SR_{heat}	99.98%	99.99%
SR_{cold}	99.88%	99.98%
SCOP	2.12	2.34
P_H	88.4%	96.6%
P_B	11.5%	3.3%
SCF_B	43	13
SCF_H	2	2

3.3.2. Tuning the Transition Conditions Applied to the Heat Supply Network

Based on the developed control function for the desired system, we present a method to improve the control function by testing different transition conditions applied to the heat supply network. We use a fitness value given in Equation (3) as an indicator for the tuning process.

The state of charge of the heat storage is used as a transition condition to enable the mode changing between $M_{HSS1} = 1$ and 3. We test five groups (G1 to G5) of values featuring the state of the heat storage for January and October, as Table 3 shows.

Table 3. Five definitions (G1 to G5) of the state of the heat storage as transition conditions.

Features	G1	G2	G3	G4	G5
Fully charged	53 °C	54 °C	55 °C	56 °C	57 °C
Empty	48 °C	49 °C	50 °C	51 °C	52 °C

Figure 15 illustrates the $KPIs$ of the five groups in January and October. With increasing temperatures, the boiler tends to handle a part of the demands, which we observe from the growing gas consumption and the decreasing SCOP of the system. Due to the heavy demands in January, the tendency is more significant than that in October. The state changing of the heat pump and the boiler are kept in an appropriate range. To reach a higher temperature in the storage, both the heat pump and the boiler work for a longer time. The state of both components changed less frequently with the increasing temperature of the fully charged state in January. In October, the heat pump can satisfy the main demands so that the boiler only needs to operate in some load peaks. Hence, the state changing of the boiler is similar in the five groups. There are only slight differences in the satisfactory rates of the five groups, which means that the heat demands are almost covered by all the five groups.

We apply the fitness values of the five groups as indicators to evaluate the results. In this case, we suppose the weights of the KPIs in Table 4. In order to obtain a higher fitness value, we define positive weights for SR and SCOP, while defining negative weights for PNR and SCFs. The weights of the SCFs (-0.01) adapt the influence of SCFs into a similar scalar as that of the SR, SCOP, and PNR. For other cases, the weights of the KPIs should be defined under specific control requirements.

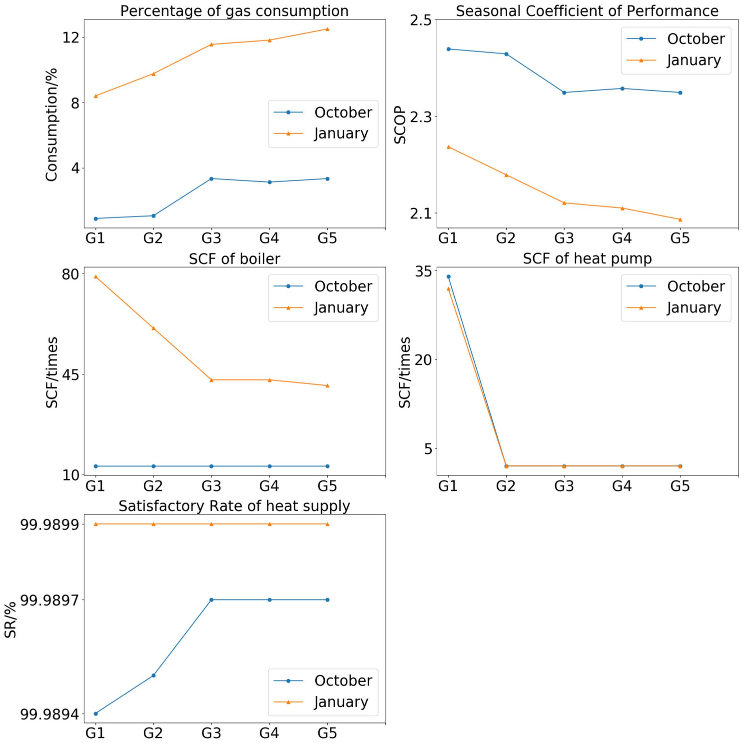


Figure 15. The key performance indicators of the simulation groups in the winter and the transition season with the charge state of the heat storage as the transition condition. SCF: signal-changing frequency, frequency of mode changing during the simulation; SCOP: seasonal coefficient of performance; SR: satisfaction rate in %, percentage of time that demands are satisfied.

Table 4. The weights of the KPIs applied to evaluate the mode-based control strategy. SR: Satisfactory rate; PNR: Percentage of non-renewable energy consumption; SCOP: Seasonal Coefficient of Performance; SCF_B, SCF_{HP}: Signal-changing frequency of the boiler and the heat pump.

KPI	$w_{\mathbf{SR}}$	$w_{\mathbf{PNR}}$	$w_{\mathbf{SCOP}}$	$w_{\mathbf{SCF\_B}}$	$w_{\mathbf{SCF\_HP}}$
Weight	1	-1	1	-0.01	-0.01

Figure 16 presents the calculation results with the corresponding weights defined in Table 4. In Figure 16, group G2 shows a remarkable fitness value integrating all KPIs in both scenarios. The system benefits from the transition conditions of G2 through low gas consumption and a high SCOP, which overtakes that of G3, G4, and G5. Compared to G1, which results in lower gas consumption and SCOP, the system using G2 presents a reduced frequency in the state changing of the boiler and the heat pump. Based on the defined weights of the KPIs, G2 could be an optimum of the transition condition in the control algorithm.

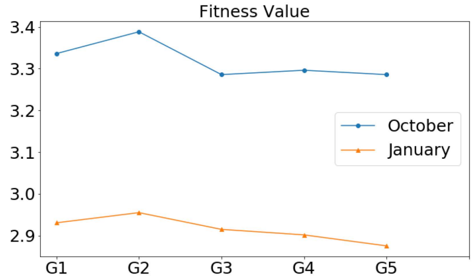


Figure 16. The fitness value of the simulation groups.

3.4. Comparision with a Reference Control

To further evaluate the developed mode-based control strategy, we used the alternative/parallel bivalent operation as a reference control for the heat supply network compared with the mode-based control strategy. In practice, the bivalent operation is a conventional control strategy used in a heating system of a heat pump and an auxiliary heating plant [55]. In the reference control, the heat pump is designed to be preferred to work. If the supply temperature cannot be achieved, i.e., the heat storage is empty, the heat storage will stop supplying heat and the auxiliary heating plant (i.e., the boiler) will run to cover all demands. We used G2 to define the state of the storage. If the heat output of the heat pump is not sufficient, the boiler will work in parallel. In the consumption subsystem, the throttling circuit transports necessary water to cover demands. Hence, the water mass flow rate in the hydraulic circuit will be matched to the required demands. We defined 98% of the heat pump power as the upper boundary and 60% as the lower boundary as an example to switch the boiler on and off, respectively.

Table 5 shows the simulation results of the MODI approach and the reference control. The demands could be satisfied by using both control strategies. However, for the same demand, the energy system represented a better SCOP and appropriate energy consumption, with a higher percentage of renewable energy and less fossil energy by using the mode-based control strategy in both scenarios. In the transition season with lower demand, the operation of the energy system is efficient with less application of the boiler. The state changes of the heat pump and the boiler are allowed by using both strategies. The heat pump in the mode-based control strategy took over more load, therefore the heat pump kept running and the state of the boiler was changed frequently, while both components ran symmetrically by using the reference control.

Table 5. The KPIs of the energy system are respectively controlled by the tuned mode-based control strategy (MC) and the reference control (RC). SR: satisfactory rate; SCOP: seasonal coefficient of performance; P: part of energy supply; SCF: signal-changing frequency; B: boiler; H: heat pump.

KPI	Winter Phase		Transition Season	
	MC	RC	MC	RC
SR_{heat}	99.98%	98.77%	99.98%	99.73%
SR_{cold}	99.98%	99.91%	99.99%	99.95%
SCOP	2.18	2.09	2.43	2.25
P_H	0.9	0.87	0.99	0.93
P_B	0.1	0.13	0.01	0.07
SCF_B	61	43	13	13
SCF_H	2	40	2	12

3.5. Discussion

The results in the case study demonstrate a complete procedure to apply MODI for developing a mode-based control strategy for the desired energy at the early stage of the building planning process. The whole procedure includes the design, the modeling, the testing, and the improvement of the control strategy.

We decomposed the desired system and aggregated the operating modes based on the standard decomposition structure of MODI. A complex energy system containing two networks was stepwise decomposed successfully, as Figure 6 shows. At each level, we only need to consider the operating modes at that level, while no overview of the total system is required. With the limited amount of operating modes, the complexity to organize mode changing is reduced significantly (see Figure 7). Furthermore, the rules that we used to identify permissible operating modes showed reusability for similar components. For example, we used similar rules to identify permissible operating modes for the four components at the component level. Based on this, developing a rule base of identification rules might support an efficient and automatic identification process.

Then, the hierarchical SIPN framework was utilized to model the developed control strategy in the modeling language Modelica. Since the structure of the framework corresponds with the decomposed energy system, the modeling process is facilitated by reducing the control function complexity and uncertainties in this process. Moreover, it provides a hierarchical overview to check the system behaviors. In the verification process, we could follow the signal transfer from the network level to the actuator level to identify suboptimal system behaviors resulting from the control design and failures in the modeling. Due to the disambiguation of SIPN as a formalized descriptor, the mistakes and misunderstandings brought by textual function descriptions will be avoided. We could even develop a software method to implement SIPN-based control algorithms in a PLC automatically [50,56]. Hence, the digitization of the control design will be finally achieved and the information loss between the planning and the implementation will be solved.

In the simulation phase, we evaluated and tuned the control strategy based on the KPIs. Compared to the original strategy, the energy consumption after tuning is more efficient and more appropriate with a larger part of renewable energy resources. The system also runs without frequent state changes. An example showed that the performance of the control algorithms can be improved by tuning transition conditions. However, the tuning results may be different with different weights of KPIs. Therefore, the definition of KPI weights was proposed to consider design requirements individually in future work. A sensitivity analysis of KPI weights on tuning results will be able to support determining KPI weights. The process of finding proper transition conditions could be further improved and automated by using optimization algorithms, e.g., a genetic algorithm [57]. Compared to the reference control strategy, the mode-based control strategy in the case study achieved a more efficient and stable performance. It indicates the potency of applying mode-based control algorithms for energy systems in practice. However, in the planning process, simulation models of energy systems are not available in general or are not validated, since modeling physical systems is time-consuming and the operation data of buildings are largely missing [58]. These can result in a performance gap between the predicted and the actual energy performance of buildings [13,14,59–62]. For this problem, this work [63] demonstrates an automated modeling approach for energy systems with mode-based control algorithms in Modelica, which can provide a simplified energy system model. In Modelica, a model allows validatation by importing the operating data. We can validate the Modelica model of an energy system in the life cycle of the system. Furthermore, the tuning of the control algorithms can proceed based on the operation data of the life cycle of the system. A real-time calculation of KPIs will support the optimization process.

Based on the use case and the discussion, we can demonstrate that the MODI method can be used not only for the planning process of a new building project but also for an existing building. If the operation of an existing building is suboptimal, a suitable control strategy can be developed by using this method. The operation data of the existing building can further support the improvement of the control strategy. The above-mentioned contributions of the MODI method to digitize the planning and implementation of building control functions are summarized in Figure 17. According to these mentioned works, it is possible to automatically perform the MODI method in both the planning and implementation processes of MODI control algorithms. Implementation of these works in a toolchain can facilitate the application of the MODI method and significantly contribute to the digitization of the planning and implementation of building automation.

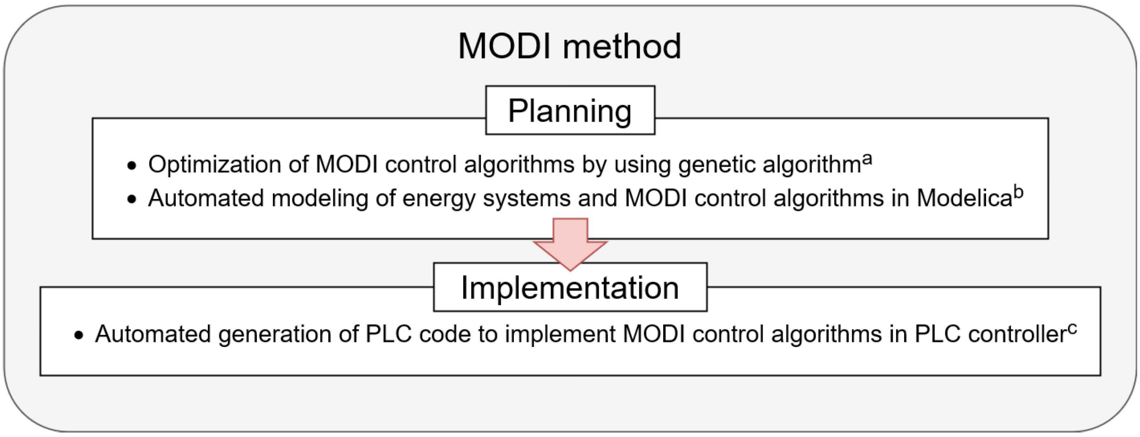


Figure 17. The further investigations of the MODI method to enable a digitized planning and implementation process of building automation, a: [57]; b: [63]; c: [56].

4. Conclusions

This paper presented the MODI method to systematically develop mode-based control algorithms for building energy systems and to evaluate the control algorithms in the simulation phase. A standard hierarchical structure was introduced to decompose energy systems and aggregate operating modes. Corresponding to it, a hierarchical signal-interpreted Petri net framework was also presented to model mode-based control algorithms in the modeling language Modelica. Furthermore, a simulation-assisted evaluation approach was performed based on several key performance indicators as well as an improvement approach of mode-based control algorithms by tuning the corresponding transition conditions. In a case study, we applied the MODI method to an energy system containing both heating and cooling supply networks. The control strategy for the system was developed step by step by decomposing the system in the standard hierarchical structure, which indeed reduced the complexity of the control design for such complex energy systems. After modeling the control algorithm, a verification of the control model proved that the control model organized the system behaviors based on the operating modes and the corresponding transition conditions. Moreover, the key performance indicators were regarded as critics for the evaluation and integrated with individual weights into a fitness value as an indicator for the tuning of transition conditions. The results showed that the energy system presented an improved performance in satisfying energy demands and with an appropriate energy consumption structure under the control model. Frequent state changing was also avoided. The tuned controller showed improved KPIs and thus a better performance than the original one. Compared to the conventional strategy, the desired control algorithm also performed advantageously in terms of the efficiency and the energy consumption structure.

Therefore, the MODI method was proved to enable a systematical design process for control algorithms. Following this method, the complexity of an energy system can be decomposed step by step in the early stage of the planning process. Correspondingly, the challenge of the increasing complexity of building energy systems can be reduced. The designers, in practice, are not required to grasp complex control relations for the whole system at the beginning of the planning process and can describe their control functions in a formalized way, which can avoid ambiguities from other planners and programmers. Designers might further benefit from the automated application of the MODI method. Furthermore, the simulation-assisted evaluation and tuning of control algorithms can be performed in the early stages of the planning process. Nevertheless, the operation data of the desired system are unavailable in the planning process, which might result in a performance gap in the energy system. Regarding this problem, we can primarily test the mode-based control algorithms to avoid faulty designs in the planning process and then tune the transition conditions during the operation after validating the model with the operation data.

Henceforth, we derive future research activities: we aim to develop a method to automate the application of the MODI method. This method is proposed to obtain the building information from a digital data source and process the information to automatically perform the MODI method in the planning and implementation process. To simplify the control design, we can develop a library containing the signal-interpreted Petri net-specific mode-based control algorithms for typical energy systems, which are generalized and can be used repeatedly. Furthermore, the integration of an advanced control algorithm into the MODI method is also intended to aim at optimizing the performance of the control algorithms.

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