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Multilevel Flow Modeling of Domestic Heating Systems

HU Junjie*, LIND Morten, YOU Shi, and ZHANG Xinxin

Department of Electrical Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

(*Tel: +45-45253487, Email: junhu@elektro.dtu.dk)

Abstract: *Multilevel Flow Modeling (MFM) is a well recognized methodology for functional modeling of complex systems which primarily focuses on the representation of their goals and functions. It has been successfully used in industrial process, e.g. nuclear power plant, chemical plants etc. to facilitate the operation on fault analysis and control. A significant improvement of the MFM methodology has been recently proposed, where the "role" concept was introduced to enable the representation of structural entities and the conveyance of important information for building up knowledge bases, with the purpose of complementing this reasoning methodology.*

Domestic heating systems, as the main resource to meet the thermal requirements of end-users, have different implementations in Europe in order to achieve various degrees of controllability and heating efficiencies. As all the heating systems serve the same basic needs i.e. supplying and transferring thermal energy, it is off interest to use MFM to investigate similarities and differences between different implementations. In this paper, three typical domestic European heating systems, which differ from each other in the number of temperature sensors and auxiliary components e.g. storage tanks, are modeled using the MFM methodology. Both the goals and functions of material and energy processes and the control functions of the heating systems are represented in the MFM models. It is found that varying the physical system setup results in only little differences among the MFM models. The 'role' concept is used to associate the relation between physical structures and functions in all MFM models. This study contributes to MFM library expansion and provides a significant test of the expressivity of MFM.

Keyword: functional modeling; heating system; physical structures; MFM

1 Introduction

Increasing environmental sustainability has led to more efficient energy supplies and rational use of energy. A distributed heating system is considered in this study, in which a micro combined Heat and Power (CHP) unit is integrated into existing residential heating system, with the purpose of providing the heat economically. Previous studies [1] have given extensive investigations on methods to obtain optimal running periods of a microCHP, i.e. the microCHP cover the demands of the heating system while running itself with the lowest operation cost. This paper explores the physical and functional structures of heating systems using the MFM modeling methodology. Heating systems have different setups in Europe in order to achieve various degrees of controllability and heating efficiencies. As all the heating systems serve the same needs, i.e., supplying and transferring thermal energy, it is valuable for MFM modelers to investigate their similarities and differences from the modeling perspective. Three typical domestic European heating systems [2], which differ from each other in the number of temperature sensors and auxiliary components, e.g. storage tanks, are modeled using the MFM methodology.

Multilevel flow modeling [3] is a methodology for representing goals and functions of process plants involving interactions between flows of material, energy and information, and this theory has been developed and enriched by Prof. Lind and his co-workers, PhD students and international researchers. MFM has been applied on a wide range of processes including nuclear power plants [4], chemical engineering plants and power systems [5]. A recent improvement of MFM theory is the introduction of 'role' concept, which enables the representation of structural entities and the conveyance of important information for building up knowledge bases for reasoning purposes. The main contribution of this study is the novel application of MFM on a distributed energy system. Besides, the relation between functions and physical structures is also explored, which provides a significant test of the expressivity of MFM.

The remainder of this paper is organized as follows. System architecture, components and assumptions are presented in section 2. In section 3, the setups of physical structures of the heating system are described in detail. Section 4 describes the MFM models of the three types of heating systems. In section 5, the relation between physical structures and functions of MFM model are analyzed. Discussion and future research plan are given in the final section.

2 Heating system description

Figure 1 illustrates the main scheme of this paper. The domestic heating system will be modeled by MFM concepts and the role concept will be utilized to connect the relations between physical structures and functions of MFM models.

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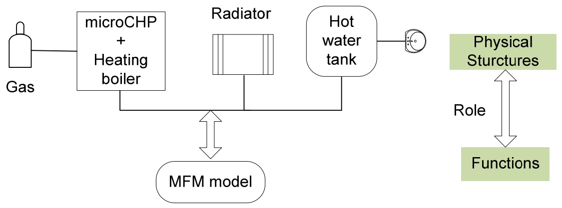

Fig. 1 Main scheme of the heating system

2.1 Physical structures of the heating system

In general, a domestic heating system consists of a microCHP unit, radiator, heat exchanger, storage tank, heating boiler, water service tank and a controller. A microCHP can produce electrical and thermal energy simultaneously. The principle of a microCHP system is similar to a traditional CHP system, which makes use of the heat produced by a small scale generating unit. This improves the overall efficiency of the generation process. Compared to traditional CHPs designed for district heating, a microCHP system is usually installed close to or inside the end users' premises, and therefore does not suffer from transmission losses. The applications of microCHP units include large single and multi family homes, condos and apartment buildings, medical clinics and small hospital facilities, health and fitness club, hotels and restaurants facilities, etc. The electricity produced by the microCHP is assumed to be either consumed by the users or absorbed by the external grid.

The heating boiler is an important supplement to microCHP unit. Natural gas is assumed to be used by both the micorCHP unit and the heating boiler. The controller of the heating system has following functions:

- Start and operation of the CHP unit
- Feeding of electric energy into the public grid or into the building.
- Feeding of thermal energy into the radiator or service water tank or storage tank.
- Monitoring the operation parameters of the CHP unit.
- Monitoring the feeding of electric energy into the grid.
- Monitoring the electric safety in case of power or phase failure (safety chain).
- Controlling the fuel intake.

Other components are not further explained. Three assumptions are made for the operation status of the domestic heating system concerning the main physical structures: (1) the CHP will be turned off if no base load is required; (2) when base load is required, the need should be first covered by the microCHP unit; (3) when base load is required and cannot covered by the microCHP unit, the heating boiler will be started as soon as possible.

2.2 Heating system operation

In this study, a laboratory DACHS [2] micro-CHP is utilized and analyzed. The controller of the DACHS micro-CHP unit is called MSR1, and controls all necessary functions for heat production and distribution. Depending on the physical configuration of the heating system, their operation can be programmed in the controller by program A, B and S, corresponding to three physical layouts 1, 2, and 3, which are shown below. Table 1 shows the controllability of the controller on the main components in each program.

Table 1 Components controlled by the controller in each program

	MicroCHP	Heating Boiler	Pump
Program A	Full control	Turn on/off	Turn on/off
Program B	Full control	Turn on/off	Full control
Program C	Full control	Turn on/off	Full control

Note: Full control means the controller can control the thermal output power of microCHP and the water circulation speed of the pump.

3 Hydraulic connection of the domestic heating system

3.1 Physical layout 1 (Program A)

As shown in Figure 2, the micoCHP unit is integrated into the existing heating system to increase the return flow temperature (measure by sensor RF: return flow temperature sensor). A rated value is fixed for the heating water temperature in the return flow. The CHP unit constantly ensures that the return flow water temperature is maintained and covers the base load. The boiler is started as soon as the thermal output of the CHP unit can not meet the heat requirement of the system.

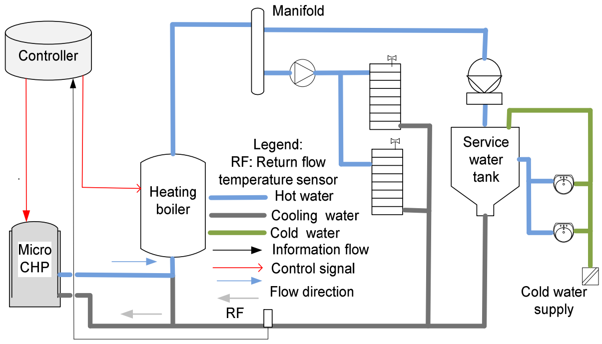

Fig. 2 Physical layout 1 of the heating system

3.2 Physical layout 2 (Program B)

Besides according to the measurement of return flow temperature, Figure 3 shows that the output flow (sensor VF) and outdoor temperature (sensor AF) are also measured and processed so that the CHP unit can adapt to changes in ambient conditions. Compared to physical layout 1 shown in Figure 2, the heat requirements of consumers can be further ensured. This is achieved by controlling the flow speed of the pump which is located above the service water tank.

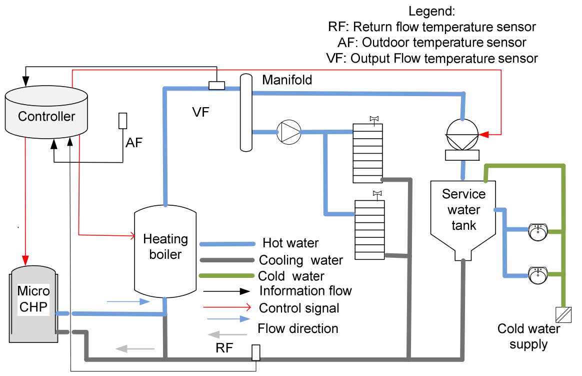

Fig. 3 Physical layout 2 of the heating system

3.3 Physical layout 3 (Program S)

In this setup, which is shown in Figure 4, a storage tank is installed between output flow and return flow which can provide the possibility of letting the CHP unit operate when no heat but only electric power in the building is required. The unused heat can be stored in the storage tank and remains in the system. This possibility is especially economically interesting for objects with high cost of power purchase.

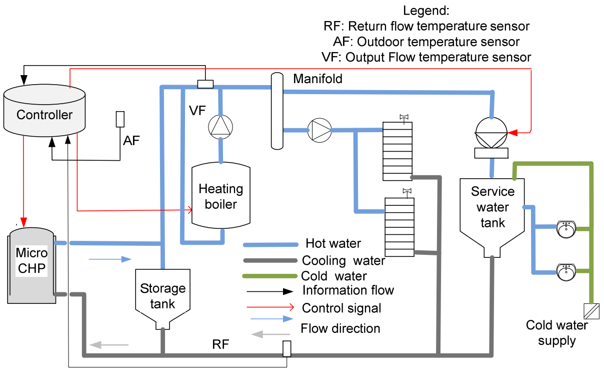

Fig. 4 Physical layout 3 of the heating system

4. Multilevel flow modeling (MFM) of the heating system

MFM represents goals and functions of process plants involving interactions between flows of material, energy and information. Functions, represented by elementary flow, and control functions are interconnected to form functional structures (including energy, mass and control structures), and those structures are related by means-end relations.

Generally, there are two main principles of building MFM models [3]; the first is top down and takes its departure in the definition of objectives of the modeling object or system. System functions provided to achieve the objectives are then identified. The second method is to associate functions with system components, i.e., the physical realization. In most cases, these two principles are combined into an iterative procedure. Besides, as it is emphasized in [6], the functional ascriptions are dependent on a predefined context of one of several goals. Specifically, in this study, the working status of the three types of heating systems are assumed to be similar, i.e., the microCHP, heating boiler and the storage tank are all used to support the heat requirement of the loads. The reason for this clarification lies in the practice, where each heating system may work in various situations, such as physical layout 3 of the heating system may have several modes of operation [8]. In a short word, the several modes of operation consist of: Spare thermal energy is stored in storage tank; thermal energy in the storage tank is used to heating the load; microCHP will be added on if the thermal energy stored in the storage tank cannot cover the demands of the load; heating boiler will be added on if both the microCHP and thermal energy in the storage tank cannot cover the demands of the load.

Bearing this in mind, we will present the MFM model of the heating system in following. In subsection 4.1, a brief introduction on the MFM symbols is given; then the MFM model of the three physical layouts are presented in each subsection 4.2, 4.3, 4.4. Considering the similarities of the MFM model, the MFM model will be explained comprehensively in the subsection 4.2. The main difference between the MFM models are discussed in subsection 4.3 and 4.4.

4.1 MFM symbols

Figure 5 shows the symbols which are used in MFM for representing functions, objectives, functional structures as well as the influence and means-end relations. The detailed definition and explanation of the symbols are introduced in [3], in which a simple example modeling of the water mill is given to facilitate the understanding.

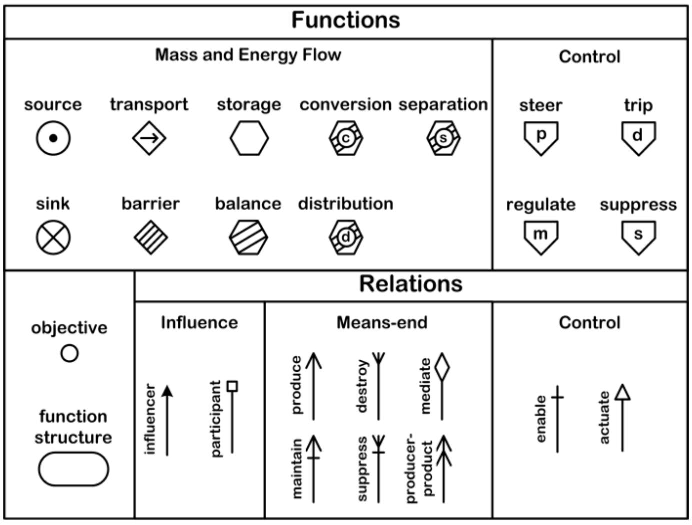

Fig. 5 The basic MFM symbols

4.2 MFM model of physical layout 1

In physical layout 1, the energy is transformed from fossil energy to mechanical energy and then to electric and thermal energy. The MFM model (Figure 6) only considers the thermal systems, which means that the transformation to electric energy is not considered. The MFM model consists of seven functional structures, energy flow structures efs1, 6, and 7, mass flow structures mfs2, 3, 4, and 5, and one control structure cfs133. These flow structures represent functions of the heating system related to: thermal energy flow (efs1), water circulation (mfs4), two similar energy flow structure represents the functions of pumping water (efs6, 7), fuel combustion (mfs2, 3) and cold water supply (mfs5). The MFM model show how these functions of the heating system can be organized in levels of means and ends. The functional levels are connected by several means end relations (producer-product and mediate) which shows that combustion of fuel and air (mfs 2, 3) are the means to produce energy (efs1) and the circulation of the water (mfs4) is the means to transfer and distribute thermal

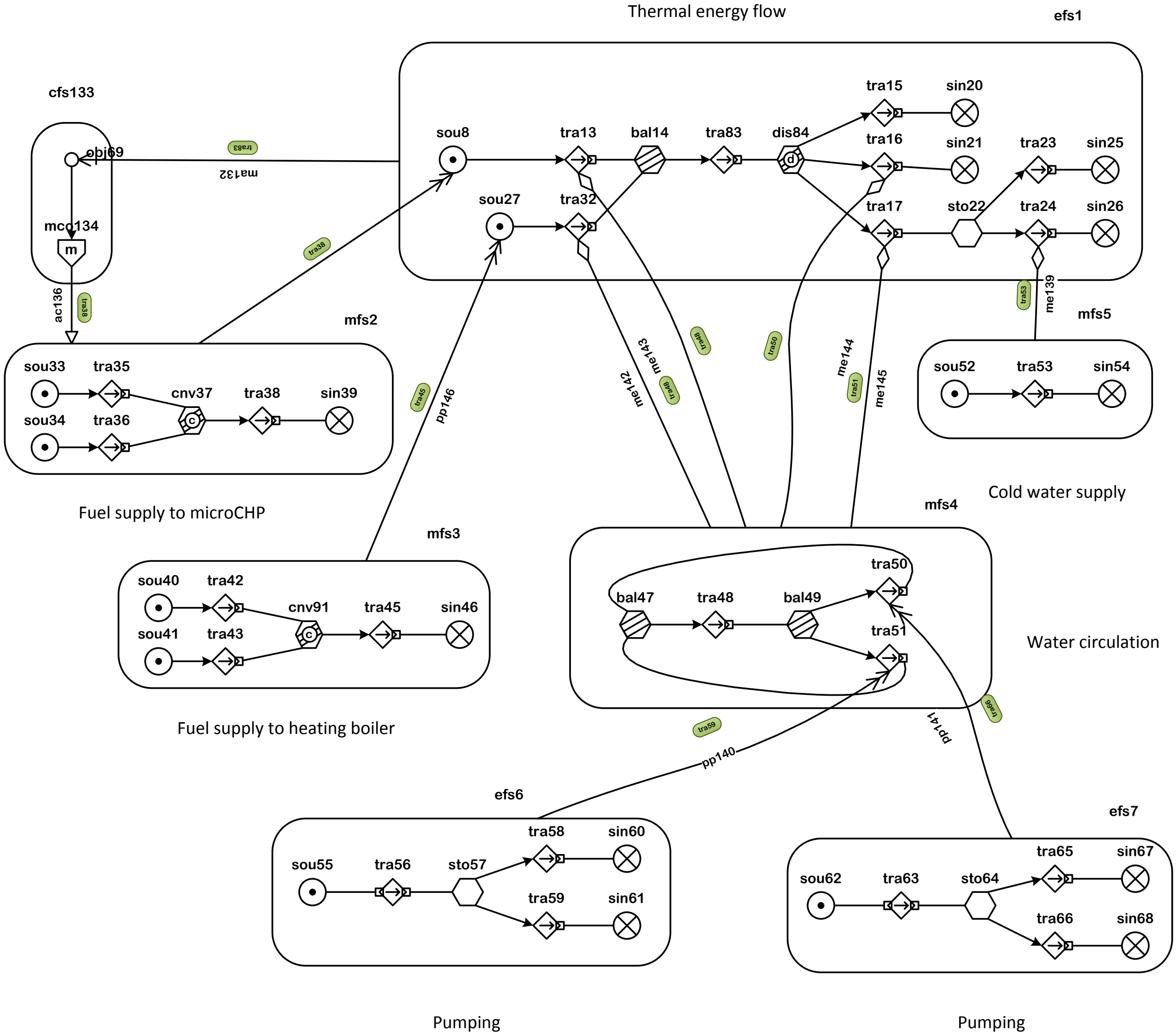

Fig. 6 MFM model of physical layout 1

The energy conversion in the pump (efs 6 and 7) is the means to circulate the water (mfs4). Within the control structure, the objective obj69 is maintained by controlling the input of fuel energy. Obj69 represents a general objective, such as the heating system should operate properly.

A: Energy conversion structure (efs1)

Within this structure, there are two source functions sou8 and sou27, which represent the thermal energy sources produced by the combusting processes of the microCHP and the heating boiler. They are supplied by two mass flow structure mfs2 and 3. The generated heat will be balanced (bal14) and distributed (dis84) by three parts: heating the home spaces (tra16, sin21), heat loss (tra15, sin20) and providing hot water (tra17, sin26). In order to provide a comfortable hot water for the users, a storage function (sto22) representing the service water tank is utilized to mix (tra24) the hot water and cold water supplied by mass flow structure (mfs 5).

B: Pumping water structure (efs6, 7)

The flow structures efs6 and 7 represent the functions involved in pumping of the water in the circulation loop when seen as an energy conversion process. The sources sou55 and sou62 represent the power supply, sto57 and 64 the accumulation of rotational and translational energy in the circuit and tra2 and tra3 represent conversion of the energy into kinetic energy of the water (tra58, 65 and sin60, 68) and friction losses in the circulation loop (tra59, 66 and sin61, 68).

C: Water circulation (mfs4)

This flow structure represents the water circulation which is the means to distribute the heat. In a closed loop, the water is circulated (tra48) and balanced (bal47, bal 49) between microCHP, heating boiler, heat radiator, service water tank etc.

D: Fuel supply (mfs2, 3)

These two functional structures represent the process of converting the fuel and air into water and CO_2 in the microHCP and the heating boiler. Within structure mfs2, sou33 and sou34 represents the fuel supply, such as nature gas and air. Cnv37 represents the chemical reaction process, and the material has been changed after this reaction. A similar process happens in heating boiler.

E: Cold water supply (mfs5)

This functional structure represents the means to exchange the heat and transfer the heat energy.

In the first physical setups, the controller can control the volume of the fuel and air into the chamber of the microCHP, which is illustrated by the control function cfs133. This controller aims to maintain (mcc134) the temperature requirements by modifying (ac136) the input (tra36) of the fuel.

4.3 MFM models of physical layout 2

Compared with the MFM model of the heating system 1, the main difference is that the transportation function tra51 here is enabled through adding the energy structure efs146, in figure 7, which has similar functional structures with efs6, 7.

Another difference lies in the controlling module on the pumping structure efs7. The purpose of the pump controller is to main pump speed at its set-point and its objective obj161 is therefore related to the accumulated rotational energy in the pump (sto64). The speed is kept constant by regulating the power delivered (tra63) to pump. The actuation relation connects therefore the control function (cfs163) with tra63 in efs7 in the MFM model.

4.4 MFM models of physical layout 3

Comparing the MFM model of heating system 2, with the MFM model of layout 3 in Figure 8 it is realized that the main difference is in the addition of another heating resource function sou167 and transport function tra168 in energy structure efs1, which is corresponding to the storage tank in the physical layout 3. The control function in this case is same as the control function for the MFM model 2.

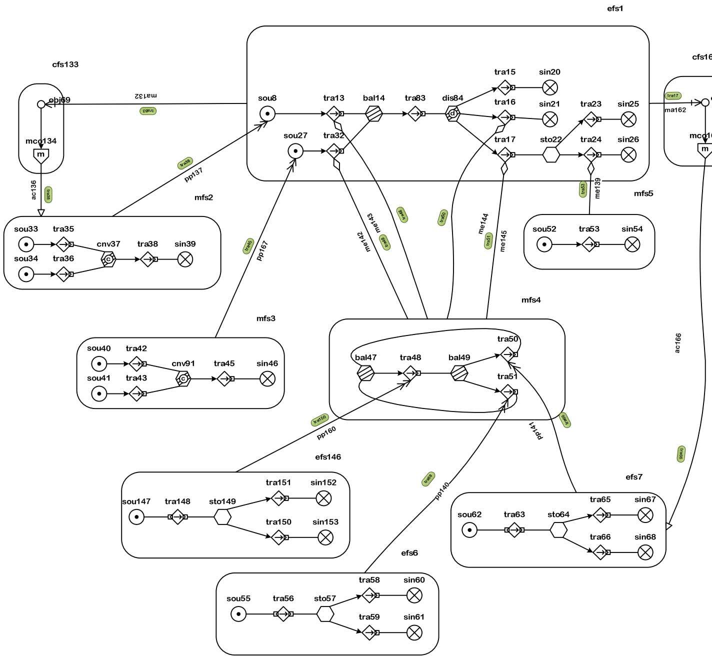

Fig. 7 MFM model of physical layout 2

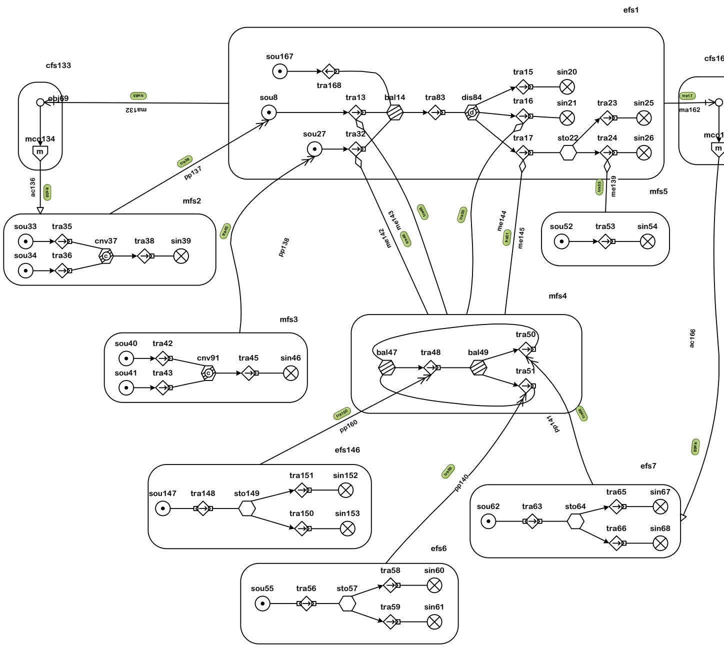

Fig. 8 MFM model of physical layout 3

5. Exploration of the connection between structures and functions

In this section, the discussion will be preceded from two perspectives. Firstly, we will show that MFM has the ability to represent generic functions common to all layouts by comparing the difference of the three physical layouts and MFM models of the heating systems. Structural information [9] is considered to include knowledge about the physical composition of plant i.e. components and subsystems such as microCHP, heating boiler and service water tank, which usually can be found in P&I diagrams. In addition we also include information about the physical objects and flows which are processed by the plant. These items are called non-solid matters in distinction to the material objects like microCHP in the system. Table 2 presents the structural information of the heating systems, in which the main differences can be seen in the bottom part of the table. General trends among these three physical layouts are the increasing complexity of the physical structures. The MFM model of each physical layout is also summarized in Figure 9, in which the differences are highlighted with orange and light blue colors.

Table 2 Physical structures of the heating systems

Nr.	Physical layout 1	Physical layout 2	Physical layout 3
1	MicroCHP	MicroCHP	MicroCHP
2	Heating boiler	Heating boiler	Heating boiler
3	Manifold	Manifold	Manifold
4	Radiator	Radiator	Radiator
5	Service water tank	Service water tank	Service water tank
6	Pipe	Pipe	Pipe
7	Water	Water	Water
8	Air	Air	Air
9	Fuel	Fuel	Fuel
10	Controller	Controller	Controller
11	Return flow temperature sensor	Return flow temperature sensor	Return flow temperature sensor
12	Basin	Basin	Basin
13	Pump besides manifold	Pump besides manifold	Pump besides manifold
14	Pump above service water tank	Pump above service water tank	Pump above service water tank
15		Outdoor temperature sensor	Outdoor temperature sensor
16		Output flow temperature sensor	Output flow temperature sensor
17			Storage tank
18			Pump above heating boiler

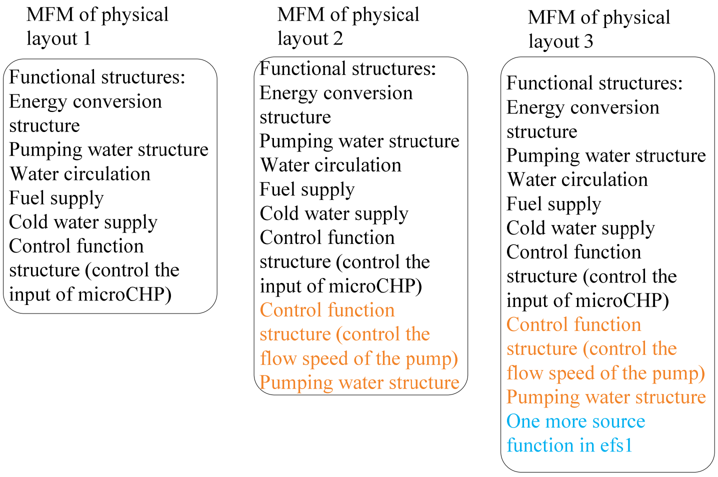

Fig. 9 Summaries of the MFM model of each physical layout

The difference between physical layout 2 and 1 of the heating system exists on the adding of two more temperature sensors and a control signal on the pump, which is shown through the red arrow between controller and the pump. With this set up in physical layout 2, the controller can monitor the temperature of water more accurate and thereafter further achieve the goals. As one can see, there is no major change between physical layout 2 and 1, while the difference of the physical layout reflected in the MFM model shows many changes, which can be seen from Fig. 6 and 7. Further on, comparing physical layout 3 and 2 of the heating system, it can be observed that significant changes have been taken place to the set up of the heating systems; however, minor changes have been made when comparing the MFM model of physical layout 3 to 2. Only one more source function is added in MFM model of physical layout 3. This is because MFM can represent the system in a very generic way. A typical illustration is the storage tank in the physical layout 3. The storage tank can be represented as various functions in MFM model. In this study, based on predefined context; the storage tank is seen as a source function in the MFM model.

Secondly, the ‘role’ concept is introduced to connect the functions of the MFM model and structures of the systems. With this introduction, more information of the system will be conveyed when doing reasoning work, i.e., fault analysis of the system. Lind [9] has extended MFM with ‘role’ concepts to represent relations between plant structure and functions in MFM models. By the study [9], the information of structural entities and their relations to functions can be used for reasoning in future developments of the MFM workbench which currently is only based on the goals and functions of the material and energy processes.

In this study, we utilize the ‘role’ concept to explore the relations between structure and functions of the MFM model of the domestic heating systems and present it in a matrix. The purpose is to investigate the use of the ‘role’ concept. It is currently assumed in the MFM reasoning process that when a function is found to be the fault cause, the corresponding physical structures will be analyzed. Therefore, with this table matrix, it is clearly stated which physical structures are related to the functions, which further relieve the dependence on the experience of engineers or system operators and enhance the automation level.

In order to facilitate the understanding, part of the MFM model of physical layout 1 is extracted and shown in Figure 10.

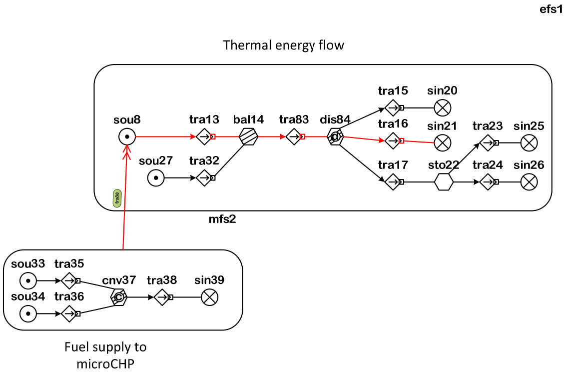

Fig. 10 Partial MFM model of physical layout 1

Two structures (energy structure efs1 and mass structures mfs2) are included in this partial MFM model. These two structures involve the main heating resources (microCHP and heating boiler) and the thermal energy flow of the heating system. The red path in the figure illustrates a hypothetic situation, in which, a ‘disturbance’ is observed in ‘tra16’. According to the reasoning principle in [10], this disturbance can then be traced to its cause. This means that each function on the red line could be the ‘cause’ for the ‘disturbance’ at ‘tra16’. As mentioned before, the physical structures information is not represented in this model. However, with table 3 (see appendix, agent and object roles are used to connect the functions of the MFM and the physical structures), more concrete information is conveyed in the MFM model and then supports the reasoning because each function has associated various physical structures based on the two roles, ‘agent’ and ‘object’.

6. Discussion and Future research plan

This study serves also to understand the application of MFM to an ongoing project [11] dealing with control policies for future distribution system consisting of many fluctuating renewable electricity production units as well as large scales of new consumptions. It is expected that a generic understanding can be achieved on the development of control policies for maximal utilization of renewable energy resources while reducing congestion problems due to the large penetration of electric vehicles.

In this study, we mentioned various modes of operations for each physical layout system, this is important since the clear distinction of different modes of operations can set up a predefined context before modeling the system with MFM methodology. Pioneering work using MFM for modeling of operation modes for the MONJU nuclear plants has been done by Lind et al. [7]. In the future, we are going to further investigate the operation modes for the domestic heating systems.

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Appendix

Table 3 'Role' concept as a glue to connect the Functions and physical structures

Functions	*Notes for the Functions*	**Agent role**	*Notes for agent role*	**Object role**	*Notes for object role*
sou8	Thermal energy source for the heating system	MicroCHP	Combusting of microCHP	Thermal energy	Heat is generated
tra9	Thermal energy is transferred to the loads	Water circulating	Circulation of the water	Thermal energy	Heat is transferred
bal14	Thermal energy input is equal to the output	Mainfold	Collect heat	Thermal energy	Heat is collected
tra83	The energy is transferred to be distributed	Water circulating	Circulation of the water	Thermal energy	Heat is transferred
dis84	The energy is distributed to radiator and service water tank	Mainfold	Distribute heat	Thermal energy	Heat is distributed
tra16	Partial energy is transferred to radiator	Water circulating	Circulation of the water	Thermal energy	Heat is transferred to Radiator
sin21	Partial Energy is used by the radiator	Radiator	Heat source to home space	Thermal energy	Heat for home space
sou33	Providing fuel to mircoCHP	Gas storage tank	Inject fuel to the microCHP	Fuel	Fuel for MicroCHP
sou34	Providing the air to microCHP	MicroCHP	Flowing of the air	Air	Air for MicroCHP
tra35	Transfer the fuel to microCHP	MicroCHP	Spraying fuel into the chamber of microCHP	Fuel	Fuel for combustion
tra36	Transfer the air to microCHP	MicroCHP	Inject air to the chamber of microCHP	Air	Air for intake
cnv37	Converting the fuel and air into water and CO2 etc	MicroCHP	Compressing and powering	Mixed material	Including fuel, air, water, waste air
tra38	Transferring the water and CO2 etc	MicroCHP	Exhaust stroke	Water and waste air	By product of microCHP
sin39	The place where the condensing water and waste air goes	Sink	Place for deal with waste air etc	Water and waste air	By product of microCHP