Heat Production and Distribution Control System Based on Holonic Concept

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Abstract: - This article shows the idea of the application of holonic concept for distributed control systems in district heating systems. Application of the holonic concepts appear to be appropriate for requirements of modern heating networks, referred as smart heat grids, which require quality control and communication infrastructure. District heating network can be divided into the autonomous elements and consequently it is possible to define tasks and relationships between them. To build and successfully manage such systems bring many benefits in comparison with centralized approaches. The first task of this research is to analyze the behavior of each heating network element in detail and define hierarchies and mutual bindings. The preparation of this holonic application has already been started for the key elements of the distribution network. The analysis focuses on physical properties and operational data of individual heat exchanger stations and their binding on other system elements.

Key-Words: - District heating, distributed control systems, heat distribution and consumption, holarchy, holon, Smart Thermal grid.

1 Introduction

The accurate and quality management of heat production and distribution undoubtedly leads to efficient energy consumption and therefore to economical use of resource, which is currently very desirable. Heat supply in the scale of the municipality, termed district heating, means to provide the transfer of heat energy from source into the place of consumption in time when it is required and in the expected quantity and quality. Quality of supplied heat energy is expressed in the temperature of heat transferring media. Quantity and quality of heat energy must go hand in hand with minimal distribution costs [1]. It is obvious that the heat distribution is inextricably linked to heat consumption, therefore the management strategies of the heat production, distribution and consumption must be solved as one unit. Nowadays, modern low-energy, passive or even active buildings are developed, smaller local sources are set up - such as waste incinerators, extensively grows the use of renewable resources. At the same time, there are a large power plants producing electricity with potential large residual heat production. All of these factors change the view of the management strategies. Current strategy and concepts have to be upgraded or replaced by new one. Such modern concept is the Smart Heat Grid [2]. To control such complex system as smart heat grid it is advisable to use one of the distributed management methods. The method based on holonic architecture was selected and is presented in this contribution.

2 Smart Thermal Grid

Smart Thermal Grids can play an important role in the future Smart Cities by ensuring a reliable and affordable heating and cooling supply to various customers with low-carbon and renewable energy carriers like waste heat, waste-to-energy, solar thermal, biomass and geothermal energy.

Smart thermal grids allow for adapting to changing circumstances in supply and demand in the short, medium and long term, and facilitate participation of end-users, for instance by supplying heating or cooling back to the network. To do so, they need to be spatially integrated in the whole urban energy system and interact with other urban infrastructure, such as networks for electricity, sewage, waste, ICT, etc. Optimising the combination of technologies and enable a maximum exploitation of available local energy resources through cascade usage, smart thermal grids can contribute to improving the efficiency of urban heating and cooling, while increasing the cost efficiency and increasing the security of supply at a local level by using local sources of energy. The scale of smart thermal grids can range from neighbourhood-level systems to city-wide applications, depending on heating and cooling demand and urban context.

Technical elements of smart thermal grids cover thermal generation like small-scale low-carbon heating and cooling systems, CHP and new approaches for producing domestic hot water, thermal storage technologies and innovative network improvements such as new piping materials new piping layouts and non-invasive construction and maintenance of thermal networks. Network-integrated sensors and smart heat meters allow for more effective and efficient use of the separate components, supported by overarching energy management [16].

As mentioned earlier, the paper focuses on the preparation of a distributed control system, which should cover the different elements of Smart Thermal Grid. However, this is a very broad area, where it is not possible to prepare a central control system, but choose the path of distributed systems and part by part integrate the modules into a defined environment. In the initial phase, which is also described in this article, we focus mainly on the integration of existing large sources (see fig.1 for art photography) of heat to the Smart Thermal Grid and the associated control system based on holon concept.

Independent control of the central source (large heating plan) has a number of applications and has also been published many times [12, 13, 14]. Their control system is therefore fairly well described, although in different concepts. However, new challenges are assuming that the central source becomes part of the something bigger - Thermal Smart Grid. Obviously this idea requires modifying existing management systems and prepares them for much greater cooperation with the surrounding environment

Fig. 1. Coal heating plant in the Czech Rep. [15]

3 Distributed Control Systems

Distributed systems are widely known and their idea was already presented many times. For this reason, they are in the article explained only marginally, and it will be assumed that the differences between the central and distributed control method is known for the readers.

It is important to understand, that controller elements of the distributed control systems are not central in location (like the brain) but are distributed throughout the system with each component sub-system controlled by one or more controllers.

Basic distribution can be described by the following figure:

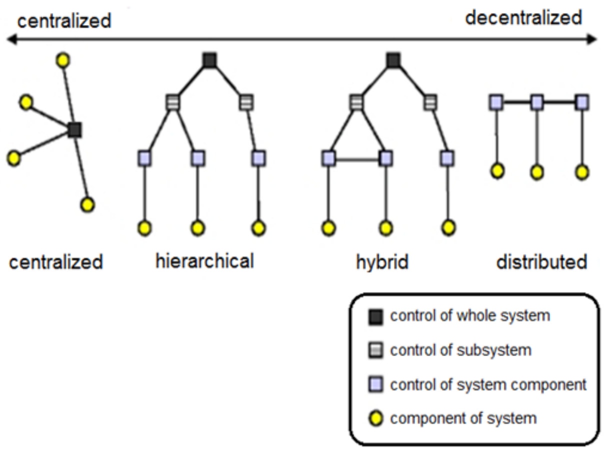

Fig. 2. Distributed Control System

4 Holons and Holonic System

The term "holon" and “holonic system” appeared more than 40 years ago, it was introduced by Herbert Simon and Arthur Koestler [4]. In recent years the concept of holonic systems expanded, elaborated and applied inter alia in the field of production systems, especially in discrete manufacturing. It is one of the concepts applicable to distributed systems and their management, but it has also potential for use in other areas.

The term holarchy refer to a set of holons including their mutual relations. Holarchy is a system of holons that can co-operate to achieve a goal or objective. The holarchy defines the basic rules for co-operation of the holons and thereby limits their autonomy [8]. The concept of holarchy is illustrated in the following fig 3.

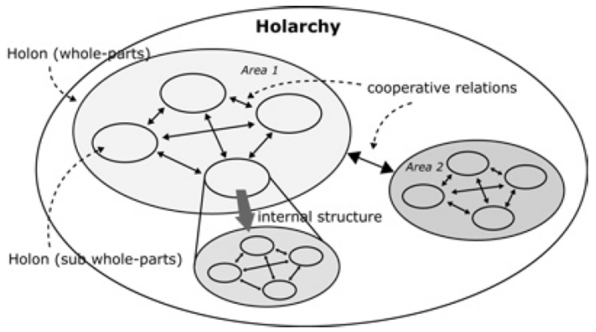

Fig. 3. Holarchy

Holon, in this context, could be defined as an autonomous and co-operative building block of a production system for transforming, transporting, storing and/or validating information and physical objects. The holon consists of an information processing part and often a physical processing part. A holon can be part of another holon. It is also possible to see it as a model of a particular element, i.e. part of the model of the entire system. In this sense is holon used in this article.

The internal structure of holons can be made up of a group of other holons, which can be described as "subholons". Any such subholon is, of course, full holon. This allows a very flexible way to define entire holonic system.

The most important features of holon are autonomy and co-operation. Autonomy is characterized by its ability of self-regulation, i.e. the capability to apply the flexible strategy which allows holon to respond differently to changes in their relevant environment. This ability to respond individually to changing conditions in which holon work, must be connected with a certain degree of intelligence to its reaction to change and adapt to the demands of the environment to be efficient and effective. Cooperation takes place between holons using the corresponding parts "subholons" of each holon - the parts that have the ability to implement relevant cooperation.

Good co-operation requires good communication between h ... ons through via a central element of the control system.

4.1 Procedure for the Construction of the Holonic Model

- Splitting model into Holons and the creation of Holarchy based on an analysis of the modeled system.
- Specification of particular properties of holons and, if relevant, also their inner structure.
- Specification of individual Holon services which are offered to all others holons

5 Holons in District Heating

This paper describes an application of this concept for the production and distribution of energy, especially heat energy.

The production, distribution and consumption of heat can be characterized as a set of individual elements of different types, which are linked together in a certain way - see Fig 4. These elements of the system can be divided into several groups and each group then into several subgroups.

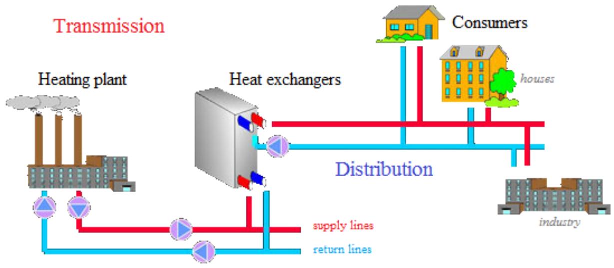

Fig. 4. District heating system [9]

Modern trend in this area is the concept of Smart Grid, respectively. Smart Heat Grids are based on the application of the distributed systems ideas and it is therefore suitable to apply holonic concept.

The fig. 5 shows designed holarchy for the district heating system.

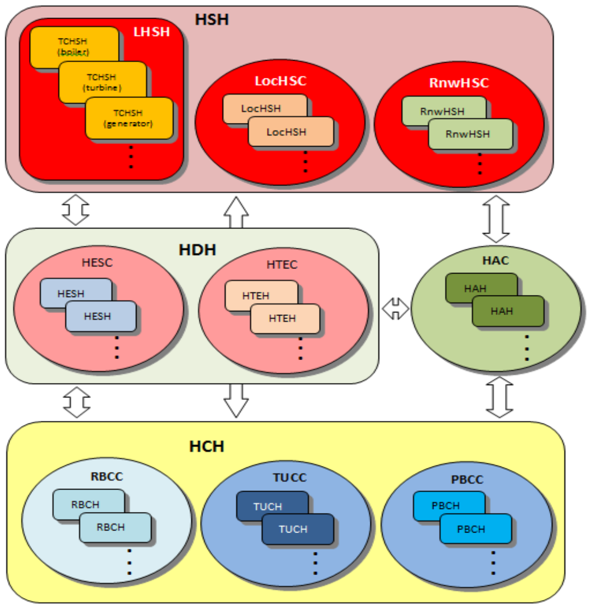

Fig. 5. Holarchy for District Heating System

The abbreviations used in the below figure mean the following:

HSH – Heat Sources Holon
LHSH - Large Heat Source Holon

HDH – Heat Distribution Holon
HAH – Heat Accumulator Holon
HCH – Heat Consumption Holon
TCHSH – Technology equipment of Heat Source Holon (Boiler, Turbine, Primary Heat Exchanger)
HESC(H) – Heat Exchanger Station Container (Holon)
HTEC(H) – Heat Technology Equipment in Heat Distribution (Pipes, Pumps, Valves, ...)
RBCC(H) – Residential Buildings Consumption Container (Holon)
PBCC(H) – Public Buildings Consumption Container (Holon)
TUCC(H) – Technology Unit Consumption Container (Holon)

5.1 Heat Sources

Structure of heat source holons (HSH) depends on the type and the structure of the source. It is important to build the structure of HSH in very flexible way to be able to match the given source. Individual subholons of HSH model the particular technological equipments of the heat source.

The resulting structure corresponds to the level of HSH intelligence. It is implemented by a set of methods, which is the union of the individual methods of subholons and HSH itself. Basic service, offered by HSH to other parts of the system, is the timing of the possible energy supplies (heat and for the case of cogeneration also an electricity) including relevant economic parameters.

Heat sources can be classified into following groups:

- Large centralized sources, which usually produce thermal and electrical energy (cogeneration systems). Their management depends on priority forms of produced energy or the ratio of their volumes. Individual variants of these resources will also differ as to the used energy technologies and source of energy.
- Smaller local sources produce only heat in the traditional way - by burning fossil fuels or biomass.
- Renewable energy sources that use different forms of renewable energy (photovoltaic sources, solar heaters, geothermal, heat pumps etc.)

5.2 Distribution Network

Its implementation will vary depending on the heat transfer medium and it corresponds to the structure of the corresponding holarchy, which is modeling the distribution network. In this case it is not possible to talk about one holon of the distribution network but about part of holarchy. Individual holons of the distribution network holarchy correspond to elements of the distribution network, which will be listed below. The basic function of used holons is to monitor and control the hydraulic and thermal conditions in individual parts of the distribution network.

The distribution network itself consists of the following parts:

- Heat exchanger, which is used for separating the primary and secondary parts of the distribution network (transmission and distribution) and to transfer heat between them. There are several structurally and technologically different types.
- Object transfer stations - have a similar function as heat exchangers, the difference are that it serves to connect the secondary and tertiary part of distribution network.
- The components of the distribution network for the transport of heat transfer medium between the source and consumers, such as various parts of pipe (straight, forming a branch network junctions forming network nodes), valves, pumps, etc.

5.3 Appliances – Heat Consumers

The individual types of consumers vary in their technical design its properties and characteristics. This is reflected in the group of holons for modeling this part of the system. Basic characteristics, and thus offered service of modeling holons, are a timing diagram of heat consumption based on the temperatures around the appliance. This will be different for different types of consumers - heating residential building, office building, schools, retail premises or industrial building, or supplies heat for technological processes in various types of production, etc. To determine required heating diagrams, the modeling holons will use the functions for analysis of historical operating data and to update the consumption diagram will use learning process based on artificial intelligence methods.

5.4 Accumulator of Thermal Energy

Accumulators (storage tanks) allow eliminate differences in timing of the availability of heat production on the one side and timing of heat demand on the other side. An accumulator operates at certain time intervals as the source and at other time intervals as consumer. This corresponds to features and services of the relevant holons modeling accumulators of thermal energy.

Fig. 6. Heat exchanger station

6 Holonic Model of Heat Exchanger Station

An important element of the heating system - heat exchange station HES, is selected as an example. In practice, many types of heat exchangers are used which vary for example in size or purpose in the heat distribution system. However, their behavior is very similar.

6.1 Holarchy of Heat Exchanger Station

The elementary part of the heat exchanger station see fig. 7, is the heat exchanger, and the appropriate control system or mechanism. The most common types of heat exchangers are pipe, see fig. 7. and plate designed, see fig. 8. The specifics of various designs, especially their resulting characteristics must be taken into account also when the holon properties are specified.

Fig. 7. Double pipe heat exchanger [7]

Fig. 8. Plate heat exchangers [11]

The heat exchanger station holon and corresponding subholons are is illustrated by the following schematic diagram - fig. 9.

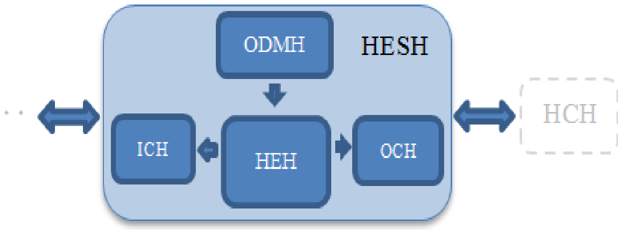

Fig. 9. Heat exchange station holon

The abbreviations used in the above figure mean the following:

HESH – Heat Exchange Station Holon
HEH – Heat Exchanger Holon
ODMH – Operation Data Measurement Holon
ICH – Inlet Control Holon
OCH – Outlet Control Holon
HCH – Heat Consumption Holon

6.2 Holons Properties

In the process of preparing a model are commonly used two approaches. The modeled object - its physical properties are described using mathematical relationships and equations. On the other hand, the properties can be achieved by the analysis of input and output information (operation data) of the explored object. Then the result is a so-called “black box”.

Our experiences show, that when possible, the best results are achieved by combination of both approaches.

Preparation of individual holons covering elements in this example of the heating supply system is assumed to be based on combination of their physical properties and analysis of operational data.

Physical properties - mathematical description

Heat exchangers work based on convective heat transfer. In this heat transfer mechanism, the transfer rate depends on many factors such as flow velocity, pipe or tube surface, flow arrangement, etc.

The heat duty can be defined as the heat gained by cold fluid which is equal to the heat loss of the hot fluid. It can be calculated as (heat loss in heat exchanger is ignored):

$$Q = m_c * C_c * \Delta T_c = m_h * C_h * \Delta T_h \quad (1)$$

In equation (1), the subscript c indicates the parameters related to cold flow and h relates to hot flow. m is the mass flow rate of streams, C is the specific thermal heat capacity and ΔT is the difference of the flow input and output temperatures [5].

According to Newton's Law of Cooling heat transfer rate is related to the instantaneous temperature difference between hot and cold media. In a heat transfer process the temperature difference vary with position and time. The rise in secondary temperature is non-linear and can best be represented by a logarithmic calculation. Typically the calculation of convective heat transfer the LMTD (logarithmic mean temperature difference) is used:

$$LMTD = \frac{|T_c - T_h|}{\log(T_c/T_h)} \quad (2)$$

With definition (2), the LMTD can be used to find the exchanged heat in a heat exchanger:

$$Q = U * Ar * LMTD \quad (3)$$

Where: Q is the exchanged heat duty (in watts), U is the heat transfer coefficient (in watts per kelvin per square meter) and Ar is the exchange area. Equations (1) – (3) describe main rules for HES. Detailed analyses of the relationships are in [5, 6, 9]. Used equations are also for HES models – i.e. holons. The parameters in model will be determined from operational data analysis.

Operation Data Analysis

The following analysis is based on data from the heat exchanger station supplying several apartment buildings. This heating exchanger is part of the district heating system connected to the large heating plant in Czech Republic.

The following charts show the similarities, but also differences in the values measured in two working days with similar characteristics of outdoor temperature.

Fig. 10 shows the outdoor temperature courses, which in the afternoon of both days rather resembles. Next figure presents consumption of the heat energy, which should reflect the progress of outdoor temperature. Fig 12 shows mass flow and the following figures present temperature in inlet and the return line.

This measured operational data and their evaluation are a source of information for determining the necessary characteristics of the individual components of the system, so also holons, forming the model.

As expected, pattern of consumption of heat are quite similar - the nature and quantity (orange curve shows the day when night and the morning temperature were slightly cooler and therefore higher compliance in external temperatures would probably mean even greater compliance in the consumed heat). The used control strategy of the HES is based on the use of heating curve for determining the water temperature in both, the primary and the secondary circuit.

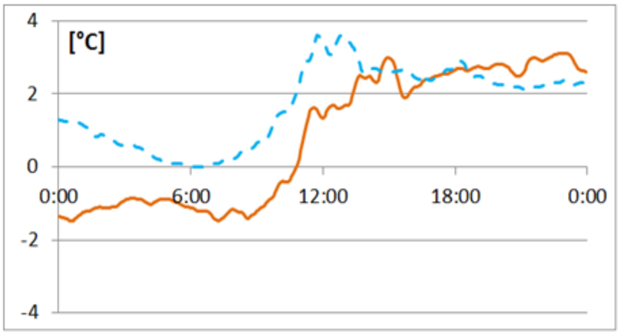

Fig. 10. Heat consumption

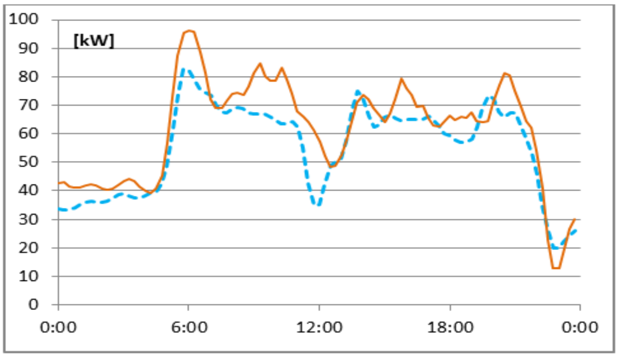

Fig. 11. External temperature

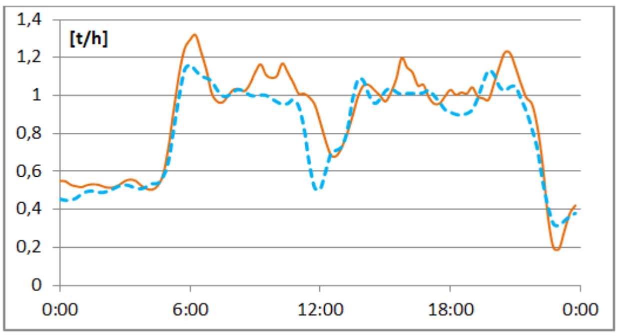

Fig. 12. Mass flow - primary circuit

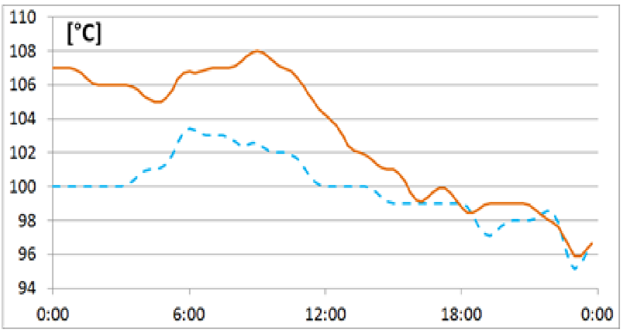

Fig. 13. Temperature of the inlet water - primary circuit

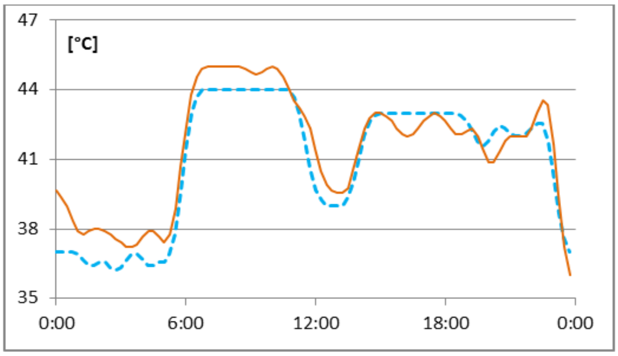

Fig. 14. Temperature of the output water from the primary circuit

In the above described method of control is also necessary to consider the transport delay. Generally this delay for the primary circuit is several hours, in the secondary circuit it is a few minutes.

Looking at the pictures presented above is also necessary to consider traffic delays. For the selected heat exchanger station and selected days was a delay from four to five hours, depending on the time of day. Mentioned delay is the time taken when the hot water send form the source reaches the consumer (heat exchanger stations). In in the field of heat supply is sometimes traffic delay considered as a time necessary for the medium to leave a source and return back there in the form of the return water.

The analyses of the presented data are the basis for defining the properties of the Holon. Apparently, it is binding on the outdoor temperature, time - day period.

For this analysis, it will be appropriate to also use modern methods, which are able to work with incomplete, inaccurate and often ambiguous data – the example of such a method could be Paraconsistent logic.

6.3 Application of Holonic Model

The holonic model, formed also by Holons whose behaviour will be based on data analysis, has the character of a simulation model and can be used in two ways:

- To determine the suitable strategy for district heating system management. From the measured data is apparent, that the selected and applied control strategy results in relatively significant variations in the operating state of the system. This may not always be appropriate – e.g. cogeneration electricity production has to achieve the desired course of electricity supplied is crucial to have a stable behaviour of the whole system, therefore also its thermal part. This can be achieved by changing the management strategy.
- As an aid for the control process in specific conditions - to allow verify the suitability of control actions by the simulation, especially when dealing with unusual situations - what-if analysis.

The task for the future holons (group of holons), is to solve above described deficiencies of classical HES control strategies. Based on the knowledge gained from the analysis of HES operational data, and in cooperation with others holons in entire system, dynamically select appropriate strategies and parameters for HES control.

7 Conclusion

The holonic distributed system for the modeling and control of production, distribution and consumption of heat has been designed and initiated its development. This concept is fully consistent with modern structures used recently in power systems - Smart Heat Grid and Smart Grid.

The holarchy system of production, distribution and consumption of heat was created and different types of holons, including their basic features were specified. The work also focuses on methodology for the design, specification and implementation of individual holons.

Acknowledgment

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