The holonic approach for controlling modern district heating and cooling systems

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***Abstract*—** This article presents the idea of distributed control methods for district heating and cooling system control. The modern concepts of distributed control are also represented by multi-agent and holonic systems that are also in this article described and compared. Up to date district heating systems integrate (are preparing to be able to integrate) many elements, such as small heat source for example in the form of renewable energy, storage tanks, surpluses form active buildings and many other. The concept of clustering of these disparate elements and their interconnection is referred as Smart Thermal Grid. This concept is analogous to the Smart Grid, which has been applied for many years in the production and distribution of electric power. Smart Thermal Grid concepts also cannot be isolated from existing concept, because heat and power production is often strongly interconnected. Effective use of all the elements forming such extensive system also requires new approaches in control. The central approach is already insufficient and the intention is to enforce already mentioned distributed concepts. This article will mainly focus on two distributed approaches - multiagent and holonic. These approaches are similar in many aspects, but still there are some differences and these will be discussed.

***Keywords*—** Cogeneration, district heating, distributed control systems, heat distribution and consumption, holarchy, holon, Smart Thermal grid.

I. INTRODUCTION

THE interest in all modern countries in the field of energetics is to behave ecologically and use its resources as effectively as possible. These ideas could be summarized as it aims to reduce primary energy means [1]:

- Modernize and improve the efficiency of technological equipment for heat production (improving the combustion process, development of modern boilers, etc.)
- Use broader engagement of energy from renewable energy sources (RES), which is not be ranked among primary energy.
- Use of secondary heat sources - waste heat from industrial processes, low-potential sources and municipal waste incineration.
- Insulation - reduce losses in the distribution network and heated objects.
- Heat management optimization.

Addressing heat management optimization together with wider use of RES and waste heat is included in the Smart Thermal Grid (STG) concept [9]. In fulfilling this concept is also trying to contribute our proposal distributed district heating control system, which should be built on the idea of holonic structure. The primary idea is however distributed concept itself, which may not necessarily be called holonic, we can understood it as a system of cooperating agents with which is usually a general reader more familiar.

This article will try to show how such a system should be designed - how to divide tasks for individual Holons, how to build a holarchy and what services must be implemented to ensure the optimal performance of the entire system. Because control, or more appropriately management of STG is a huge field and each location can also offer other possibilities, the article will not try to cover the entire field but focus on one sub-area which is CHP sources.

II. DISTRICT HEATING AND COOLING

Classical district energy systems produce steam, hot water or chilled water at a central plant [10]. The steam, hot water or chilled water is then piped underground to individual buildings for space heating, domestic hot water heating and air conditioning. As a result, individual buildings served by a district energy system don't need their own boilers or furnaces, chillers or air conditioners. The district energy system does that work for them, providing valuable benefits including:

- Improved energy efficiency
- Enhanced environmental protection
- Fuel flexibility
- Ease of operation and maintenance
- Reliability
- Comfort and convenience for customers
- Decreased life-cycle costs

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- Decreased building capital costs
- Improved architectural design flexibility

In addition, district energy systems can use the "reject heat" that results from burning fuel to produce electricity at a power plant, dramatically increasing the overall efficiency with which useful energy is extracted from the fuel.

The reject heat can be used to spin turbines and generate electricity. This arrangement, called "combined heat and power" (CHP). A CHP system may have double the fuel efficiency of an electric generation plant and can also lower the emissions typically associated with conventional fossil-fuel powered electrical production. The less energy used, the less sulfur dioxide and carbon dioxide and other emissions are expelled into the environment [2].

A. *Smart Thermal Grid*

Do not waste energy is the fact that humanity is aware for several decades. Above mentioned concept of CHP is very important, but the effort to optimize the use of energy sources must continue - as also the EU promotes in its project challenges.

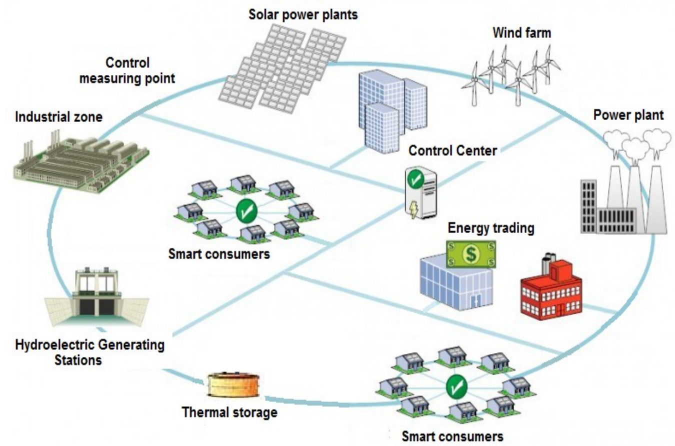
Currently it is the concept of Smart Thermal Grid (STG), which efforts to use all the energy produced but also seeks the way to make this use the most optimal. An example might be the use of the sources that are in particular moment the most efficient and also effort to accumulate energy that can be produced profitably and there is no consumer for it at a given moment. This is especially applicable for the energy produced from the sun, wind and other renewable sources.

For STG is also important the role of buildings that should not be considered as simple consumers but as the objects that are able to cooperate with sources for optimum performance of the entire smart system [3].

STG 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.

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 [4].

Possible components of STG are shown in fig. 1.



. Fig. 1. Components of the STG [5]

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III. State of the Art

According to Schmidt et al. [20], the first district heating and cooling systems with smart elements have been recently implemented in Denmark, Sweden, Austria and Germany. In comparison with Smart Electrical Grid the Smart Thermal Grid is in an early research and development phase. However, it is based on the well-known district heating technology which is widespread in Northern and Eastern Europe. Smart Thermal Grid as defined in Schmidt et al. are those thermal grids that allow adaptation to changing circumstances in heat supply and demand and facilitate participation of consumers within the network boundaries. Smart Thermal grid integrates smart meters and bidirectional communication and control devices for demand side management. Several projects on Smart Thermal Grids already exist:

- The recent large EU pilot project CELSIUS – Combined efficient large scale integrated urban systems (2013-2016) – is being carried out in the context of the European Smart Cities Stakeholder Platform. The project covers all aspects of urban heating and cooling systems.

- In [21] a prototype substation using the EISTEC's tiny wireless sensor platform Mulle was used to control the district heating load by developing a variable price scheme that guaranties indoors comfort and quality of service. The research resulted in a method described in the patent District heating substation control

(EP2394099A1) which comprise of storing a relationship between primary supply temperature and desired secondary supply temperature, detecting a primary supply temperature, using said relationship to determine a set point value for secondary supply temperature based on the detected primary supply temperature, and controlling the secondary supply temperature according to said set point value, by regulating the primary side flow.

- Project ABSINTHE (Agent-based monitoring and control of district heating systems) was a collaboration project between Blekinge Institute of Technology and Cetetherm AB. The goal of the project was to improve the monitoring and control of district heating, e.g., by increasing the knowledge about the current and future state of the network at the producer side and by performing automatic load balancing at the customer side [21]. The consumer substation contained a built-in extendable I/O platform with an expansion slot for a communication card by Siemens.

Now presented approach extends the sensor networks by using an intelligent control system located at the consumers substations with certain level of intelligence and autonomy to help balance the load during situations where there is a shortage of heat in the system, or when building up the load after a breakdown. Substations are equipped with microcontroller, sensors, actuators and communication platform to enable communication between different units of the holonic distributed control scheme.

A. *Optimization and control of DHC network*

Today, the operation of most district heating systems is based on a simple mapping between the ambient temperature and the temperature of the water in the supply network. Optimization of the supply temperature must be performed with an objective function with costs for production and with constraints given by the customers' demands. It is obvious that an optimization model of a large district heating system with many loops and more than one heat source is extremely computationally demanding. Nevertheless, there has been some research activity within this field:

- In [23] an optimization scheme based on fairly detailed physical models of the heat production units and the distribution network is proposed, where the unit commitment problem is solved by a fuzzy logic approach. Power production, heat storage and flow restrictions are not considered.
- A concept for controlling the supply temperature in a district heating system based on linearization of the detailed physical system models has been presented in [24],[25].

- Intelligent agents for the optimization have been studied for some time. Johansson [26] has developed a distributed system with units with communication ability that controls the heating in individual buildings. The units are controlled with agents which coordinate the operation of the whole system. During the test at three major heating network systems in Sweden reduction of peak loads was achieved. The system also showed a clear ability to lower the energy usage in the participating buildings, without any noticeable difference in the perceived indoor climate. However, only one commodity has been considered. The proposed distributed system will consider both the heat, cold and electricity production in the CHP units.

- A fuzzy predictive control scheme for district heating systems was proposed and successfully applied to the test case of the Tannheim district heating system in [27]. However demand side management strategies e.g. reducing peak loads were not considered.

- A robust predictive control strategy of the district heating network was developed in [28]. Optimal scheduling on prediction time interval was applied to the whole system consisting of producers, network and consumers. The method has been successfully tested on a benchmark network created by EDF ('Electricite de France') and Supelec.

- Within an Austrian research project SmartHeatNetworks (2012), various supply and demand-side measures to reduce daytime-related peak loads were defined and assessed for the chosen model of a district heating system of a medium size village. These measures include load shifting and utilization of the capacity of district heating system.

- The INTREPID project (2012-2015) partly covers issues of DHC with focus on technologies enabling energy optimization of residual buildings.

- The synthesis of optimization of combined cooling, heating and power systems implies searching for an operation methodology that minimizes an objective function, such as economic cost, environmental load or thermodynamic efficiency. The search process is bounded by the system's model, which is expressed by a set of constraints. The optimum operation totally depends on the systems' performance and the relative demand of cold, electricity and heat. The total operation cost of the CHP system is optimized for varying electricity, thermal and cooling demands, and the changes in the fuel and electricity tariffs. There are several publications for optimization problems of CHP. Operational scheduling is solved using heuristic method based on Lagrangean relaxation [29], evolutionary programming [30] or solvers for mixed-integer [31],[32],[33] or non-linear problems [34].

- There are further research activities (Project EcoHeat4Cities) on concepts for integration of advanced information and communication technologies in DHC and modelling of new network configurations combining consumers and producers in DHC network.

The works carried out so far has primarily addressed DH systems with a one production plant usually a CHP with objective function that typically includes the production and pumping costs. In the consideration of the concept, different types of heat sources such as heat pumps, solar thermal systems will be treated in similar way to become the building blocks of the distributed control system. The novelty of proposed control system lies in the distribution of the global optimization problem into multiple intelligent, cooperating and autonomous units that solve local optimization problems. In most studies, consumers' demands were considered as given and perfectly known data, the proposed holonic distributed multi-agent system on the other hand, manages the operational decisions, e.g., reacts on shortages and performs resource redistribution in real-time. Such distributed control system will provide benefits which can be derived from multi generation options. Particular insight is expected by putting building control and grid control into relation. Currently these two systems are usually optimized separately. Control strategy for using water in the DH pipelines as a buffer to reduce peak loads is also important and must be regarded.

IV. Multiagent and Holonic Approach

From the above description of STG is obvious, that it is very appropriate to treat STG as distributed dynamic and stochastic system. For the investigation of the behavior and properties of the STG it is therefore necessary to create a distributed model of the same character, in terms of control for STG need to be addressed methods of control of distributed systems.

Distributed systems currently utilize (are based on) several concepts - bionic, holonic, fractal, multiagent etcFor application in production systems are often used holonic and multiagent concepts. It turns out that these concepts are useful for district heating systems designed as STG as well.

In the next parts of this paper, these two concepts and their use in the STG will be analyzed in detail.

A. Agents

A MAS is made up of two or more related agents. An agent is an autonomous and flexible computational system, which is able to act in an environment [17]. Flexible means, that the agent is:

- Reactive: It reacts to the environment it is in.
- Pro-active: It is able to try to fulfil its own plan or goals.
- Social: It is able to communicate with other agents by means of some language

Some properties which are usually attributed to agents to a greater or lesser degree for solving particular problems are [15]:

- Autonomy: Agents can operate without the direct intervention of humans or other agents.
- Social ability: Agents are able to interact with other agents (human or not) through an agent communication language.
- Rationality: An agent can reason about perceived data in order to compute an optimal solution.

Lange [16] provides a more pragmatic definition that is oriented towards industrial demands: He defines an agent as a software object that has the following properties: situatedness, reactivity, autonomy with respect to its actions, and proactivity. Furthermore: an agent should be continuously executing. Option ally: an agent can be communicative, mobile, believable or able to learn.

B. Holons

The term "holon" and "holonic system" appeared more than 40 years ago, it was introduced by Herbert Simon and Arthur Koestler [6]. 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 industrial 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 [7]. The concept of holarchy is illustrated in the following fig 2.

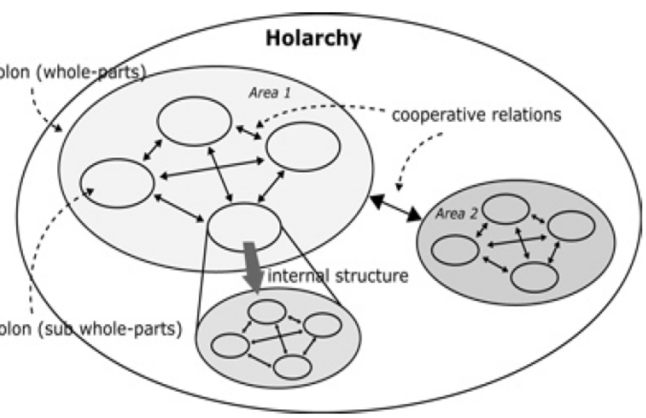

Fig. 2. Holarchy

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 its 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 holons. Holon exchange information with other holons throughout holarchy. This direct, mutual communication between holons manifests an important distinction between distributed systems management and centralized management systems. In centralized systems, all communication takes place via a central element of the control system.

C. Comparison between the agents and the Holon

Suitable explanation for HS is to liken it to multiagent system (MAS). It is therefore assumed that term MAS is for readers, at least in general terms known.

Nevertheless, semantically, an agent and a holon have very different meanings and uses. In general, the word “agent” has multiple meanings, but the following meaning from Webster’s Collegiate Dictionary is the most appropriate [12]:

“An agent is one that acts or has the power or authority to act.” In other words an agent is a singular entity with the authority that is empowered to accomplish its purpose.

The term “holon” describes self-contained elements that are capable of functioning as autonomous entities in a cooperative environment. Holon is a fusion of the Greek word “halos” meaning whole and the suffix “on” denoting a particle. In a holonic system, each holon works with all other holons to deliver an overall system objective. The underlying point here is that an “agent” has the right to make decisions for its own purpose, whereas a “holon” can only act with respect to a collective (or holarchy) of holons to which it belongs and thereby provide a collective or system autonomy, as opposed to a collection of individual autonomies. One of the most important properties of Holon is recursion. Holon unlike agents can in their structure contain other Holons with the same or a different architecture. Holons are therefore autonomous, cooperative and partly intelligent modular blocks which are functional within decentralized control. The agent is elemental decision unit that collects and processes the data and knowledge. It is not physically tied to technology.

To design a distributed software system, as with any other solution paradigm, it is useful to follow guidelines. First, let’s summarize the major differences between multiagent and holonic systems:

Scope: agents are focused on local issues while holons are focused on global issues.

Independence: holons are not independent whereas agents can exist functionally independent of other agents.

Relationships: holons cooperate with other holons, whereas agents need not be cooperative; in fact, agents can compete with other agents.

The choice whether the holons or agents are used for the system control will be determined by the point of view that is taken. More specifically, HS can be considered to be a paradigm for distributed intelligent control, whereas MAS is regarded as software technology that can be used to implement HS [11].

In accordance with mentioned approach of the use of holonic or multi-agent concept of distributed systems in the literature also appears concept of holonic-multi-agent system.

Arbitrary structures can be viewed as holons in Koestler's framework, where the sub-structures do not necessarily have to be of the same kind. In contrast all entities can be restrict to agents as defined above, and furthermore, it is required that sub-holons always have the same structure as the super-holon. This requirement may later turn out to be too restrictive when the fild of holonic MAS matures as for the moment this restriction makes it easier to define the merge of agents.

The essential idea is as follows: A holonic agent of a well-defined software architecture may join several other holonic agents to form a super-holon; this group of agents now acts as if it were a single holonic agent with the same software architecture [8].

The representation of a holon as a group of autonomous agents is in a sense just another way of looking at a traditional multi-agent systems. The holon entity itself is not represented explicitly. In this case, holonic structures are only a design aid for structured agent-oriented programming.

V. Considerations on the Application of Agents (Holons) for Intelligent DHC

Creating a holonic model of the system comprises a series of specific steps - for the DHC system as follows:

A. Split system into Holons and the creation of Holarchy

This is based on an analysis of the modelled system in which it is necessary to carefully and thoroughly assess the structure of the modelled system, carefully identify individual holons including their internal structure exploits the use subholons. It is also necessary to analyse the relationships and bindings between holons. All of these steps should result into a suitable split of the system into holons and creation of appropriate holarchy.

B. Specification of particular properties of holons

The aim of this step is to specify particular properties of individual holons and, if relevant, also define their inner structure.

When specifying the properties of individual holons, it is necessary to take into account the nature of the modelled system, i.e. what characteristics of the behaviour of the system will be with the support of the prepared model analysed. For each of these characteristics must every holon associated with such characteristic contain a set of methods, techniques and algorithms that allow to quantify this characteristic as accurately and completely as possible.

In the case of the DHC will be typically monitored and analysed the ongoing processes on both, the technical and economic terms.

From the technical point of view the model, and thus holons modelling the individual elements of DHC, will usually contain mathematical and physical description of the involved processes. On this basis will be determined the characteristics of the individual elements. Also will be determined the operating ranges limits of various physical quantities associated with these characteristics. These are e.g. limits of the thermal energy delivered by the source, depending on factors affecting the production (e.g. irradiation with solar thermal energy), or limits for the amount of thermal energy transferred by the distribution elements.

In terms of economy, the model will include a description of the economic variables and their calculation, depending on the value of the influencing factors. It is e.g. the determination of prices of produced thermal energy unit by the source (of course as time function), determination of the heating costs for the particular consumers (also as a function of time), etc.

C. Specification of services

This step focuses on the specification of individual holon services which are offered to all others holons.

Each holon performs within the system some specific, clearly defined activities and the results of these activities are offered to other holons as a specific services. Supply and use of these services is closely related to the implementation of essential holon characteristics - autonomy and a cooperative.

To guaranty administration of these offered services is a need to be developed and used appropriate communication system. Such system has to allow holonic model to: Communicate between any holons which may be located anywhere on a computer network.

Initiate communication between two holon, can any of them. This is due to the requirement of strict compliance with the principles of distributed systems, where all elements are "equal", at the same level. Each holon, which provide particular service can make offer to others holons either on its own initiative (e.g. when it is able to carry it out) or on demand from the potential user of the service.

One possible solution is to use a standardized mechanism for Web services, respectively semantic Web services or WCF framework.

VI. Methods For Controlling DHC

The processes associated with the production, distribution and consumption of thermal energy in DHC, especially if the system included a large dominant source, have in terms of their timing a specific behavior. They are reacting relatively slowly and between their individual parts is quite various and non-negligible delay - traffic delays. This significantly affects the way of control of the entire DHC. On the one hand this simplifies the implementation of control actions (there is "enough time" to make it), but on the other hand it complicates the control strategy - it is necessary extensively to predict the behavior of system (e.g. when the heat is produced, it is already necessary to predict its amount, what will be needed in order a few hours, which will last transfer of heat media to the point of its consumption).

In view of the above, it is possible to specify a three-stage process of DHC control:

A. Prediction phase

At this stage, applies inter alia, the technical characteristics of the individual parts of the system. For their determination is usually used a combination of the above mentioned mathematical and physical models, and analysis of historical operational data. Prediction context must be understood sufficiently broad, because it involves all parts of DHC:

a) The most important is the prediction of heat consumption in individual consumers in time and depending on a number of external factors - climatic conditions, the nature of the operation of individual consumers, etc.

b) Very important is also the prediction of the amount of heat possible to be produced by individual sources, again depending on the time and range of internal and external factors - energy from renewable sources, depending on the sunlight, wind strength, the configuration of the technological equipment and the dynamics of their changes in the classical sources using combustion processes, etc.

c) It is considerable important to predict time possibility of the heat distribution, respectively its ability to transfer the required amount of thermal energy in required time.

B. Optimization phase

At this stage, it is necessary on the basis of the whole complex of predicted data to determine the best division of supply of heat between different producers and consumers. Here are mostly applied above mentioned economic variables. The objective function to optimize is the cost function whose minimum is searched.

At this stage of the control considerably appear the benefits of the holonic concept, i.e. distributed system. Optimization can be very easily divided into solutions at different levels - individual holon, suited holons groups and for the entire holarchy. For the optimization in higher level it is possible to use results from lower level, which are easily calculable.

Algorithm optimization calculations is based on the fact that individual consumers are demanding at all (technically possible) producers whether they are able to meet its requirements for heat supply in quantity, or even the quality spread over time. Quality means the temperature of the heat transfer medium - however, this option is very limited by distribution network layout. Contacted suppliers will evaluate and weigh their possibilities and make an offer to consumers - under what conditions, usually economic, or with which restrictions may be quoted energy supplied. In the simplest variant, the consumer compares each relevant offer and chooses the one, which is most suitable for its needs. Suppliers then have the opportunity to influence their profit through their offerings. In more complicated cases, the optimization is conducted with respect to the specified groups of holons or to whole holarchy. Disclosed algorithm in this case is supplemented by iterative procedures for finding the optimal value of the more complex formulated objective function.

The relation between the consumers and the producers is not only based on the laws of the market (supply and demand), but it can be understood as cooperation on a common goal. For example CHP plant may address the consumers with a request (offer), that it has opportunity to assign their production capacity at a certain time into peak load electricity (good price on the market). Consumers for some time may voluntarily give up their consumption (utilizes accumulated energy). The profit from well sold electricity is the result of mutual cooperation.

C. Coordination - implementation of control actions

At this stage of the control process has been ongoing for quite classical approach when control interventions determined by the prediction and optimization phase are applied using the appropriate technical means.

For the practical implementation of DHC control is necessary to resolve the issue of time synchronization of the phases of the control process. This is relates to the fundamental specific problem, that prediction, eventually optimization takes place at a different time of the controlled system long before the application of control interventions. The time difference, which is due to the time needed to transfer the required amount of heat exchange medium from the point of production to point of consumption. This is the dynamic variable that has a large divergence, depending on the number of internal state variables of the system.

VII. Conclusion

Building and deploying Smart Thermal Grids into practice requires a number of steps. Besides upgrading hardware and improve communication and measurement is necessary to ensure that elements of the system together and collectively came to the efficient use of resources. The article tried to show that in such a heterogeneous environment, it is advisable to implement a distributed system management. Representative of this approach, are for example holonic or multiagent systems. A brief description of these approaches and explanations of differences focused wanted to show this article. The article also presented a possible application of such a control system and the elementary steps necessary for its implementation.

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