Hindawi
Complexity
Volume 2022, Article ID 2588364, 18 pages
https://doi.org/10.1155/2022/2588364

Research Article

Decentralized Coordination of Temperature Control in Multiarea Premises

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Received 26 August 2022; Revised 27 November 2022; Accepted 2 December 2022; Published 13 December 2022

Academic Editor: Hiroki Sayama

With local control of a large number of objects that mutually influence each other, the problem of coordinating local control systems to achieve the best overall result arises. If the structure of the system (the number of control objects and the parameters of interaction) can change frequently, then the process of setting up/training a centralized coordinator will take an unacceptably large part of the action time and require a significant amount of resources. In this work, the use of decentralized coordination is proposed to solve the problem. As a basic task for research on decentralized coordination control of objects that mutually influence each other, stabilizing the comfort temperatures was set in multizone rooms using movable heaters. Providing individual thermal comfort is an important problem. In particular, there are many multiarea premises with conflicting requirements for the comfort of habitats. This problem can be solved with the help of movable heaters and air conditioners. However, the presence of heat flows between areas with different specified parameters makes it difficult to adjust them. The work aims to improve the quality of thermal control in multiarea premises with a dynamic structure for the location of movable heaters. To achieve this goal, we proposed the concept of Movable Smart Heaters (MSH). A group of Movable Smart Heaters that could influence each other and exchange information forms a dynamic system with a changing structure since switching on/off or moving one MSH to another area changes the mutual influence and connections in the system. The criteria for control quality are defined and evaluated. The proposed coordination algorithms make it possible to optimize the operating modes of the system automatically when its structure and/or settings are changed. Simulation of the system is performed with the use of a worked-out modelling library in Scilab. The results of comparing the MSH system's efficiency show an increase in comfort while reducing energy consumption.

1. Introduction

With local control of a large number of objects that mutually influence each other, the problem of coordinating local control systems to achieve the best overall result arises. If the structure of the system (the number of control objects and the parameters of interaction) can change frequently, then the process of setting up/training a centralized coordinator will take an unacceptably large part of the action time and require a significant amount of resources.

Sets of controlled objects that influence each other, or multizone distributed objects, are found in many areas. Examples of such objects are multizone premises. Ensuring a comfortable and safe environment on the premises is an important task, as is energy efficiency. The complexity of the task is due to the ambiguous understanding of the concept of comfort and the presence of conflicting requirements for comfort among different occupants. In particular, there are many multiarea premises, such as “open space” offices and studio apartments, with separate areas. Comfortable conditions in such areas demand different air temperatures. Although such zones are called thermostatically controlled load (TCL) [1]; however, the static mode in them is observed only for a limited time interval. A characteristic feature of such premises is the rapid and frequent change in requirements: premises are vacated or filled, comfort requirements change following individual needs, etc. In such premises, separate means of maintaining air temperature (air conditioners, convectors, fan heaters, etc.) with local control systems are used. The mutual influence between separate areas requires the coordination of local control systems (LCS). The task of coordinating temperature settings means in connected zones when using movable devices has several general and special properties: a variable number and location of operating heaters or air conditioners; only movable heaters or air conditioners can communicate wirelessly with other devices; and a slight increase in the cost of heaters and air conditioners due to the installation of coordination and data transmission controllers on them. These special properties necessitate a new look at the task of coordinating control of TCL movable heaters/air conditioners in the context of the general problem of the decentralized coordinating control of the multizonal distributed objects.

2. State-of-the-Art

2.1. Coordination of Control Systems. Coordination tasks have a long history. Theoretical research on coordination has been going on for more than a century. H. Fayol is considered the founder of the theory of coordination [2]. However, the problem itself appeared much earlier. This is illustrated by the classic formulation of the task of Byzantine Generals [3], which is devoted to the synchronization of the states of two systems over unreliable communication channels.

The problem of coordination is very popular in scientific and practical publications. However, the approaches to the coordination of strategic plans and operational decisions of state and corporate management bodies are the main considerations. Unlike the control processes in engineering and technology, these approaches focus on the psychological, legal, and political aspects of a problem. A significant contribution to the development of coordination management in man-machine hierarchical systems was made in the series of works by Dmitry Novikov, in particular in [4].

In the control of production and technological systems, the main attention is paid to architectural, informational, and criterion aspects [5]. The problem of coordination in distributed technological systems focuses on the control of material and energy flows as well as on the characteristics of the dynamics of operations [6].

With the emergence and active development of a multiagent technology for control of distributed systems and interacting objects, the works began to be formulated mainly as the tasks of coordination of agents of a multiagent system [7, 8]. In general, coordination tasks are considered while taking into account the balance of local (individual) and global criteria. Various coordination strategies are considered: cooperation, competition, consensus, negotiations, etc. [9–11] in this direction.

Some authors consider general issues of coordination in systems with a certain structural organization of coordinated processes: parallel [12, 13], sequential [14], and serial-parallel [15].

The architecture of the system and the structure of the coordinators' information connections play an important role in the development of the coordination system. The most common approaches to the coordination of local technological process control systems (LCS) are based on a centralized or hierarchical system architecture [16, 17]. The centralized architecture is usually used for a small number of LCSs and a small distance between them, and the hierarchical one is for systems with a large number of LCSs and/or a large distance between them. Centralized coordination can be considered the special and simplest one-level case of hierarchical coordination. The theory of hierarchical coordination is based on the works of M. Mesarovich and coauthors, first published in 1970 and republished many times [18]. The advantage of hierarchical systems is the relative simplicity of matching local (individual) and global criteria and the guaranteed stability of control, which is due to the tree-like structure (without cycles) of subsystem connections. However, such systems at each level of coordination presuppose the presence of a top-level coordinator, which must be configured, administered, and maintained, and its disconnection or failure destroys the entire coordination system. Such systems have a rigid structure of connections, and they are difficult to scale. This complicates their application to objects with changing composition and/or connections between coordinated subsystems.

2.2. Individual Regulation of the Parameters of the Human Environment. An important area of application for LCS of distributed objects is to ensure the individual comfort of occupants in the various premises for collective use. Such a task requires coordination of the comfort parameters and LCS settings of the individual systems. In modern scientific and technical publications, there are many names for systems for individual regulation of the parameters of the human environment on the premises.

2.2.1. Personal environmental control (PEC). Systems were studied for a long time. There are several reviews of PEC systems [19–23]. Most existing research and review articles focus on thermal comfort with PEC systems. For example, PEC's thermal comfort was studied in [20, 21], and [22] investigated the effect of PEC on thermal comfort and energy consumption. In [23], research on ways and technologies to influence thermal comfort in multizonal premises is systematized. It should be noted that the review did not consider algorithms and technologies for coordination (group control) of movable and individual heaters and air conditioners.

2.2.2. Task Ambient Control (TAC). Systems are investigated from the point of view of the tasks to be solved. TAC systems are designed to maintain the thermal regime in a localized area and are controlled individually or by a group of people [24–27].

2.2.3. Personal Comfort System (PCS). PCS is designed both to increase the comfort of individuals and to reduce the energy consumption of heating and cooling systems. Examples of PCS are being handed out, such as spot cooling [28], personal environment module (PEM) [29], individually controlled microenvironment system (ICS) [30], and an office partition system with a radiant cooling panel [31]. Many works explore the technological and energy aspects of PCS and their impact on thermal comfort [22].

The work [32] presents a building control system that takes into account the microzones; a set of algorithms for individual control of devices in microzones was developed, and comfort information is derived from higher-level settings.

In many studies, much attention is paid to the use of communication standards for the organization of multiarea comfort systems [33]. In particular, IPv6, 6LoWPAN, Bluetooth Low Energy (BLE), ZigBee, Wi-Fi, and Z-Wave protocols are considered. Control systems, sensors, and actuators of an existing building, supplemented by the Internet of things (IoT) can be classified as a general class of “cyber-physical systems” [34, 35].

No less attention is paid to research on ways to reduce energy costs for its provision than comfort.

Occupant behaviour and activities have a significant impact on the energy efficiency of a building, and various researchers have confirmed the human role in building operation [36]. The results of studies [37, 38] show the degree of influence of user behaviour on energy consumption for heating.

The methodology for determining the most effective methods of local control focused on the presence of people and was developed in [39]. The methodology integrates a simulation model with a multicriteria optimization method. In [40], the *EnergyPlus* simulation platform was used to assess the impact of occupant behaviour on comfort and energy consumption. In [41], the authors also proposed an approach to energy control by monitoring the heating system to ensure comfort.

Some efforts aimed at improving the efficiency of PEC are based on simulation. Large and complex work on the development of modelling tools and energy efficiency improvements based on this is carried out in the Building Technology and Urban Systems Division of Berkeley Lab (USA). They have developed and are developing now such products as *EnergyPlus* [42], *Modelica Buildings Library* [43], *Building Controls Virtual Test Bed* (BCVTB) [44], *Generic Optimization Program* (GenOpt®) [45], *EnergyPlustoFMU* [46], etc. The *EnergyPlus* simulation system is the most widely used. This modelling system is the basis of most other products by this developer. The study [47] showed that *EnergyPlus* makes it possible to evaluate the energy efficiency of the behaviours of residents. The work [48] introduced fuzzy-logic heating, ventilation, and air-conditioning (HVAC) controller and used the *Building Controls Virtual Test Bed* [44] to test the model using *EnergyPlus*. It is shown that the proposed technique reduces the number of uncomfortable hours by 50%, spending the same amount of energy.

The work [49] presents a system that includes predictive mechanisms and intelligent heating control algorithms based on an artificial neural network (ANN) to optimize energy efficiency while taking into account the satisfaction of residents. To do this, Berkeley Lab collected data for three years on whole-building and end-use energy consumption, HVAC system operating conditions, indoor and outdoor environmental parameters, and occupant count and created a dataset for analysis and machine learning [50].

Since 2017, the US Environmental Protection Agency has implemented the *ENERGY STAR®* [51] performance certification program for Internet-connected TCLs. The authors of the paper [52] analyzed the results of the *ENERGY STAR®* data registration and showed that HVAC systems showed stable trends in increasing comfort and energy savings. Moreover, the increase in efficiency of the systems of individual suppliers is explained by more successful algorithms and control strategies. In particular, effective ASHRAE Guideline 36 (G36) control strategies for the multizone operation of a variable air volume (VAV) system are analyzed in [53].

The abovementioned works are focused on centralized TCL optimal control systems and stationary HVAC devices. For example, the structure and principles of the *AlphaBuilding ResCommunity* system were described in [54], which uses the joint modelling of all community TCLs with the help of *EnergyPlus* and *Modelica* for optimal control. The use of such “heavyweight” systems require a lot of preparatory work for modelling and, accordingly, a developed user interface.

At the same time, it should be noted that in many cases, individual thermal comfort is provided with the help of movable heaters and air conditioners. Issues of installation and use of portable heaters are considered from the points of view of their safety, energy efficiency, and ease of use. The rules of safe use are defined in NFPA 1—Fire Code standards; ANSI/UL Standard 1278 for Movable and Wall- or Ceiling-Hung Electric Room Heaters, etc. At the same time, all studies and standards concern single heaters, and the efficiency of groups of mobile heaters is not considered.

However, when using several portable heaters in adjacent areas of the premise, the presence of heat flows between areas with different set parameters, complicating their adjustment, and when their location changes, the settings also have to be changed. The problem of prompt automatic adjustment of the group of movable heaters, which forms a dynamic system with a changing structure, has not yet found an effective solution.

2.3. Related Works.

The review and analysis of distributed systems of coordination control were made in [55].

The most generalized approaches to the coordination of local control systems are based on a centralized (for a small number of LCS and a small distance between them) or hierarchical (for a large number of LCS or a large distance between them) architecture of the coordination system [56–58]. Such systems are widely used, and they provide high efficiency when controlling the thermal regime of individual buildings and groups. In the work [43], the effectiveness of the model predictive control (MPC) HVAC system in a real office building using a *Modelica-based toolchain* was studied. It was shown that MPC saves approximately 40% of HVAC energy over the existing control.

However, centralized systems have a rigid structure of connections and are difficult to scale. It makes their application to objects with frequent and rapid changes in requirements more complicated.

A promising way to solve the problem is to use decentralized coordination with Smart coordinators in each local control system. Most often, such a coordination architecture is used with a very large number of relatively autonomous objects, for example, in the energy industry [59, 60], in collectives of autonomous robots and engineering objects [61], and in autonomous flying machines (drones) [62, 63].

Decentralized systems are the subject of many studies. Many interesting results were obtained in the research Project Control for Coordination of Distributed Systems (CON4COORD and C4C, both acronyms are used) by the Consortium of 12 Research Centers in Europe [5]. A feature of distributed, decentralized systems is significant uncertainty in the parameters of subsystems' interaction, the nonfully-connections of the system, and the absence of complete information about the state of other subsystems that are in direct connection with a separate subsystem.

Depending on the type of system, the tasks of decentralized systems control are called synchronization, decentralized stabilization, one-level coordination, peer-to-peer control [64], etc. Linear and nonlinear systems, continuous and discrete, with optimal and adaptive control, robustness, and artificial intelligence elements are considered [65].

The adaptive decentralized control with model-based coordination was proposed in 1992 by B M. Mirkin and was being actively further developed by many authors, for example, in [66]. This assumes the availability of information among local controllers about the state of the reference models of all local subsystems.

The concept of distributed optimization of control of a state of the multiarea premise was proposed in the work [67]. The paper proposes a distributed method for optimizing air conditioning that can be implemented in a parallel way.

Despite a significant number of works on the study of decentralized coordination systems, the problem of coordination control of the state of continuous multiarea distributed objects with a dynamic structure and variable requirements has not yet found an effective solution. In addition, the mutual influence of coordinated objects on each other is rarely taken into account in existing works.

2.4. Objectives and Problems. Let us formulate the main provisions of our study.

The object of this study is the process of decentralized coordination of local control systems to ensure a comfortable individual thermal environment in multizonal premises under the conditions of dynamic changes in the requirements of zones.

Considering the special features mentioned above of the concept of individual comfort and methods of coordination of local control systems, we formulate the purpose of the study as the improvement of the quality of thermal control in multiarea premises with a dynamic structure of the location and connections of heaters.

In this work, we propose a novel approach to temperature control in multiarea premises through the use of decentralized coordination of movable heaters. This provides system flexibility, i.e., the ability to change the number and location of heaters without the need to change the settings of the central control system. At the same time, the characteristics of comfort and energy consumption are not inferior to systems with centralized control of stationary heaters.

The main contribution of the research is the concept of decentralized coordination of local control systems with a dynamic structure and its implementation in the Movable Smart Heaters (MSH) system. The criteria for control quality are defined and evaluated. New algorithms for decentralized coordination are proposed. These algorithms make it possible to optimize the operating modes of the system automatically when its structure and/or settings are changed. The implementation of the concept in Movable Smart Heaters allows for an increase in comfort while reducing energy consumption.

The highlights of the research are as follows:

(i) The statement of the problem of coordination control of the state of continuous multiarea premises with a dynamic structure of the location and connections of control means is made.

(ii) The concept of decentralized coordination of Movable Smart Heaters is proposed.

(iii) Criteria for controlling the quality of temperature comfort in multizonal premises are formulated.

(iv) The basic algorithms for coordination and dynamic adjustment of Movable Smart Heaters are developed.

(v) A simulation of the MSH system was made, and its results were analyzed.

3. Proposed Method

3.1. Statement of Research. In this section, we will formulate the problem definition based on an example of the area's locations in the open space office plan, as shown in Figure 1. The plan shows a fragment of the layout of the heaters. Heaters are divided into "Ordinary Heaters" and "Movable Smart Heaters". We propose to equip each Mobile Smart Heater with a coordinator who can communicate with each other by means of a Wi-Fi mesh to optimize the operation of smart heaters in addition to conventional heater controllers.

The comfortable temperature for each area $F(k)$, where k is an area number, is set remotely using a movable device. The diagram also shows some connections between areas and between coordinators. The mutual influences between the areas are "physical," as evidenced by the heat flux

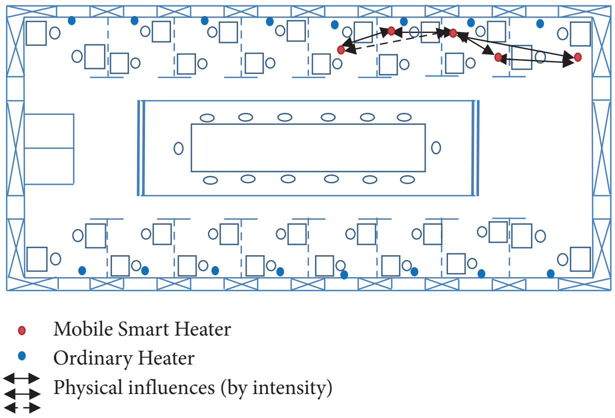


Figure 1: An example of the open office plan with heater locations.

between the areas, and following the physical influences, the information connections between the coordinators should provide optimal control of the thermal condition, taking into account the condition of the surrounding premises. In Figure 1, different arrows show that the intensity of mutual influence can be different. In this case, there may be such MSHs that are not connected by mutual influence with other devices.

It is only necessary to observe the requirement of nonsimultaneity in the coordination procedures of heaters to avoid the possibility of instability in coordination. Therefore, the decentralized coordination process takes more time in total than the centralized one. It is possible to reduce the decentralized coordination time if only those zones that have a significant influence on each other are taken into account at each coordination step. We will call this principle the "principle of short-range action."

Thus, the task of coordination is to find such a desired state vector (the set of temperatures) of areas $\mathbf{T}_0 = \{T_{0k}, k = 1..M\}$, which provides the minimum deviation of the state of the object from a given function $F(k)$ while taking energy savings into account. Thus, we can formulate the optimization problem that the coordinator solves either as optimization with constraints or as optimization with priority levels:

$$\begin{aligned}
&\min R = \sqrt{\int_{t_0} \sum_{k\in\mathbf{K}_S} \alpha_k \left[T_k(t) - F_k(t)\right]^2 \mathrm{d}t}; \int_{t_0} \sum_{k\in\mathbf{K}_S} E_k(t)\mathrm{d}t \le E_{\max};\\
&\min E = \int_{t_0} \sum_{k\in\mathbf{K}_S} E_k(t)\mathrm{d}t; \underset{k,t}{\forall}\left|T_k(t) - F_k(t)\right| \le \Delta T_{\max}; \qquad (1)\\
&\min\left[\beta_R R + \beta_E E\right],
\end{aligned}$$

where $k \in \mathbf{K}_S$ is the area number within the controlled area of the premise S; $\mathbf{K}_S$ is the set of area numbers of the premise; $F_k(t)$ is the desired function of change in the time domain of the k-th area state of the multiarea premise; $T_k(t)$ is the real state of the k-th area on a time t; R is an average square deviation of the temperature in the controlled area of the premise S from the preset temperature; E_k is the energy consumption in k-th MSH; $E_{\max}$ is a maximum permissible energy consumption; $\Delta T_{\max}$ is a maximum permissible temperature deviation; α_k is the priority factor of areas; β_R, β_E are the priorities for comfort and energy consumption; t_0 is the optimization time interval.

In the previous works of the authors [68–71], research and development of the principles of decentralized coordination in distributed cyber-physical systems for controlling technological processes were carried out. In particular, in [69], a model of the interaction of controlled zones of a distributed technological object was developed. The structure of the coordinator was proposed in the work [68]. Each coordinator contains the following modules:

(i) Object model;
(ii) Interface module;
(iii) Assessing uncertain parameters module;
(iv) Clustering module;
(v) Forecasting module;
(vi) Criterion optimization module;
(vii) Module for controlling the sequence of coordination;
(viii) Parameter setting module;
(ix) Communicate Wi-Fi mesh module.

The mentioned modules in the MSH coordinator must satisfy the following several requirements:

(1) *Ease of software and technical implementation.* The software and additional controller required to implement the mentioned modules should not significantly increase the cost of the heaters.

(2) *High-speed adjustment and coordination algorithms.* Despite the inertia of thermal processes in living and working premises, the adjustment and coordination processes must occur quickly enough to provide the required comfort during the occupant's stay on the premises. Additional requirements for dynamics are related to the mobility of the heaters; changing their mutual location and turning them on/off leads to a change in the structure of the coordination system and the need for additional adjustment.

(3) *Full automation.* The user purchasing MSH should not perform any complex procedures for setting up the system. It is enough to start the coordination setting process from the smartphone, set the desired temperature, and select the type of coordination criterion (1). For this, the *Connecting module* and *adjustment module* are additionally included in the coordinator.

3.2. Basic Algorithms of Coordination and Dynamic Adjustment.

The first requirement, "Ease of software and technical implementation," is provided by decentralized coordination. This is the main difference and advantage compared to Smart Home systems. Decentralized coordination does not require the existence of a central controller and the implementation of procedures for changing its software and/or hardware configuration when changing the number or location of heaters.

With increasing the distance $|\mathbf{Z} - \mathbf{Z}_i|$ of the control point $\mathbf{Z}_i$ of the Movable Smart Heater from a given area, the influence of control decreases. Thus, with decentralized coordination, each coordinator should take into account only those controlled elements that are in its immediate surrounding (Figure 2) i.e., the cluster, whose boundaries are determined by the clustering module.

In well-known works, various models are used for modelling thermal processes in premises [72], which are based on the laws of thermodynamics and certain simplifications due to the peculiarities of premises heating processes. To determine the set of elements of the environment, we used the model of the object [69]. This model is based on the equation of thermal energy transfer from an object with temperature T_1 to an object with temperature T_2:

$$\begin{cases} \dfrac{\mathrm{d}Q}{\mathrm{d}t} = \lambda \left[T_2(t) - T_1(t) \right]; \\[2ex] \dfrac{\mathrm{d}T_2}{\mathrm{d}t} = \dfrac{1}{C} \dfrac{\mathrm{d}Q}{\mathrm{d}t}; \\[2ex] \dfrac{\mathrm{d}T_1}{\mathrm{d}t} = -\dfrac{1}{C} \dfrac{\mathrm{d}Q}{\mathrm{d}t}, \end{cases} \tag{2}$$

where λ is the heat transfer coefficient; C is the heat capacity, and the known solution of the Burgers transport equation. The transfer equation is first-order concerning time and second-order concerning spatial coordinates. In particular, an instantaneous point impact on an element k is propagated to the element j according to the formula

$$v(d_k, t) = \frac{P_{0k}}{8(\pi\lambda t)^{3/2}} e^{-d_{kj}^2/4\lambda t}. \tag{3}$$

If ε is a significant factor in the surrounding of the i-th area $\mathbf{K}_{i\varepsilon}$, we will consider the set of MSH that satisfy the condition.

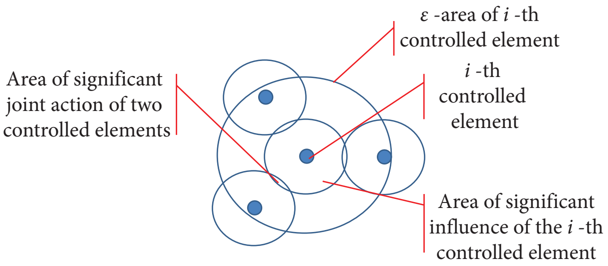


Figure 2: Determination of heaters ε-surroundings.

$$(k \in \mathbf{K}_{i\varepsilon}) \longrightarrow \left(\forall t: \quad \frac{1}{F_i} \sum_{k \notin K_{i\varepsilon}} \frac{T_{0k}}{8(\pi\lambda_k t/\tau)^{3/2}} e^{-d_{ki}^2/4\lambda_k t/\tau} < \varepsilon \right), \tag{4}$$

where $0 \le \varepsilon \le 1$; F_i is the given state of the i-th area; T_{0k} is the state of the k-th surrounding area specified by the coordinator; d_k is the distance from the specified area to the k-th surrounding area; λ_k is the heat propagation constant; τ is the heat propagation time constant.

It is difficult to use condition (4) in decentralized coordination, as this requires each coordinator to have information on the state of all MSH. This is almost impossible for large distributed multiarea premises. Therefore, it was proposed to introduce an estimation function to determine the set of MSH, which i-th MSH should coordinate.

When choosing an estimation function, we should use the following considerations:

(1) If the specified state function $F(\mathbf{Z}) = \text{const}$ and controls are located evenly in the distributed object, then the control function satisfies the optimality condition $T_0(\mathbf{Z}) = \text{const} = F_0$. Thus, from (4), the radius of the ε-area could be estimated in a next way:

(2) In the case of asynchronous work of relay heater controllers

$$d_{i\varepsilon}: \quad \left\{ d_{i\varepsilon} = \min d_k, \quad d_k: \left[\sum_{k \notin \mathbf{K}_{i\varepsilon}} \max_t \frac{T_{0k}}{8(\pi\lambda t/\tau)^{3/2}} e^{-d_k^2/4\lambda t/\tau} \right] < \varepsilon \cdot F_0 \right\}. \tag{5}$$

(3) In the case of synchronous work of relay heater controllers

$$d_{i\varepsilon}: \quad \left\{ d_{i\varepsilon} = \min d_k, \quad d_k: \max_t \left[\sum_{k \notin \mathbf{K}_{i\varepsilon}} \frac{T_{0k}}{8(\pi\lambda t/\tau)^{3/2}} e^{-d_k^2/4\lambda t/\tau} \right] < \varepsilon \cdot F_0 \right\}. \tag{6}$$

The analysis of the function $T_{0k}/8(\pi\lambda t/\tau)^{3/2}e^{-d_k^2/4\lambda t/\tau}$ to the maximum shows that the maximum is reached at $t_m = d_k^2\tau/6\lambda$. Let substitute t_m into condition (5) and obtain

$$d_{i\varepsilon}: \quad \left\{ d_{i\varepsilon} = \min d_k, \quad d_k: \sum_{k \notin \mathbf{K}_{i\varepsilon}} \frac{1.48 \cdot T_{0k}}{d_k^3} < \varepsilon \cdot F_0 \right\}. \quad (7)$$

Such a case cannot be implemented in practice since it assumes a perfectly uniform, infinitely distributed object with an infinite number of controls and an infinitely small distance between them. However, it can be considered a limiting case for testing coordination algorithms and a certain approximation of real problems.

(1) If $F(\mathbf{Z}, t) \neq \text{const}$, then more distant elements can make a significant additional contribution to the state of the considered area. This additional increase in the ε-area

$$\Delta d = \max_t 4\lambda_k \frac{t}{\tau} \ln\left[\frac{T_{0k}}{\varepsilon \cdot \Delta F 8(\pi\lambda_k t/\tau)^{3/2}}\right]. \quad (8)$$

We get by substitution $\Delta F = |F_k - F_i|$. In particular, boundary conditions (the state of the environment) are taken into account in this way.

Algorithms for determining the set $\mathbf{K}_{k\varepsilon}$ of MSH with which k-th element must coordinate are worked out. The algorithm that solves the problem based on the model of heat distribution in a multiarea premise without partitions is shown in Figure 3. The algorithm involves converting the area number to coordinates in space, calculating the distance between areas, and calculating the coefficients of mutual influence of areas depending on the distance between them.

The algorithm for determining the set of MSH in any premise based on the procedure of impact testing is shown in Figure 4. At the first MSH switch-on, a change in the comfort temperature setting, or a change in MSH position, the testing procedure is started. The coordinator sends the messages to the rest of the coordinators at MSH, and they register the temperatures in areas. After 5 heating cycles of the relay MSH, the new message is sent. After that, the correlation analysis of temperatures and the calculation of coordination parameters are carried out. Since the heat flows are proportional to the temperature difference, the correlation function was calculated as $B_{T_i,(T_k-T_i)} = B_{T_i,T_k} - D_{T_i}$, where D_{T_i} is the temperature dispersion of i-th heater.

4. Experiments and Results

The algorithm for determining the coordination parameters was studied on a model in the Scilab system. We have developed a library of modules (Superblocks) in the Scilab system for modelling distributed control systems. Figure 5 shows the part of the simulation module library and the temperature control coordination model in a multiarea premise. This model contains 9 MSH areas, each with its own on/off temperature control relay cycle. The impact of random disturbances (opening/closing doors, windows, etc.) was simulated by generators of random events. The results of the simulation of the process of parameter testing are shown in Figure 6.

Results (a) and (b) are almost identical, although result (b) is obtained at levels of random effects 10 times higher than in case a). This confirms the resistance of the correlation method to interference in determining the coordination parameters.

Results (c) are different. They were obtained at given random values of temperature in the areas in the range (20°C–24°C), but the results (a) and (b) were at the same set temperature in all areas: 22°C.

However, all the results retain the characteristic features that allow us to determine the parameters of the following coordination:

(1) The time constant τ of the heat dissipation from the MSH of another area. The simulation results show that the correlation function has some periodicity. This is due to the feature of digital simulation, in which the MSH switching frequencies in different areas have a common divider ($2^{-\mathrm{m}}$, where m is the bit depth of a binary number). The position of the first maximum of the correlation function in its first period corresponds to the time constant τ.

(2) The coefficient of heat flux influences k_{ij} from MSH in the i-th area on the state of the j-th area. Let us determine it by the formula of the regression coefficient $k_{ij} = \Delta R_{ij}/D_i$, where D_i is the heat flux from MSH i-th area dispersion. If the period of relay operation of MSH in the i-th area is Θ_i, and the time spent in the state "ON" is ϑ_i, then $D_i = p_i(1 - 2\vartheta/\Theta + \vartheta/\Theta^2 + \vartheta^2/\Theta^2 - \vartheta^3/\Theta^2)$, where p_i is the power of MSH in the i-th area. Thus, the propagation is constant $\lambda_{ij} = k_{ij}T_j/T_i$.

(3) The heat capacity of the room $C = P\Delta t/\Delta T$, where $P = \alpha c_a(T_H - T_a)$ is the heat capacity of the heater; T_H is the heater temperature; T_a is the air temperature; α is the coefficient that takes into account the design parameters of the heater (area of contact of the heater with the air, speed of airflow near the surface of the heater, etc.); c_a is the coefficient that takes into account air parameters (specific heat capacity and thermal conductivity, which depend on pressure and humidity at a given temperature).

Coordination and adjustment of the parameters of multiple heaters can be performed in different sequences. As it was mentioned, it is only necessary to observe the requirement of nonsimultaneity in the coordination procedures of heaters located in the same ε-area to avoid the possibility of instabilities in coordination. To do this, it is necessary to select connected subgraphs in the ε- area graph and solve the problem of traversing all vertices in each subgraph. At the same time, it is possible to use breadth-first search algorithms, such as Little's algorithm, Prim's algorithm, etc. To control the sequence of local system coordination, we use the wave method. The wave method can be synchronous or asynchronous. The synchronous method is implemented by using a wave generator of synchronization pulses. The asynchronous algorithm is

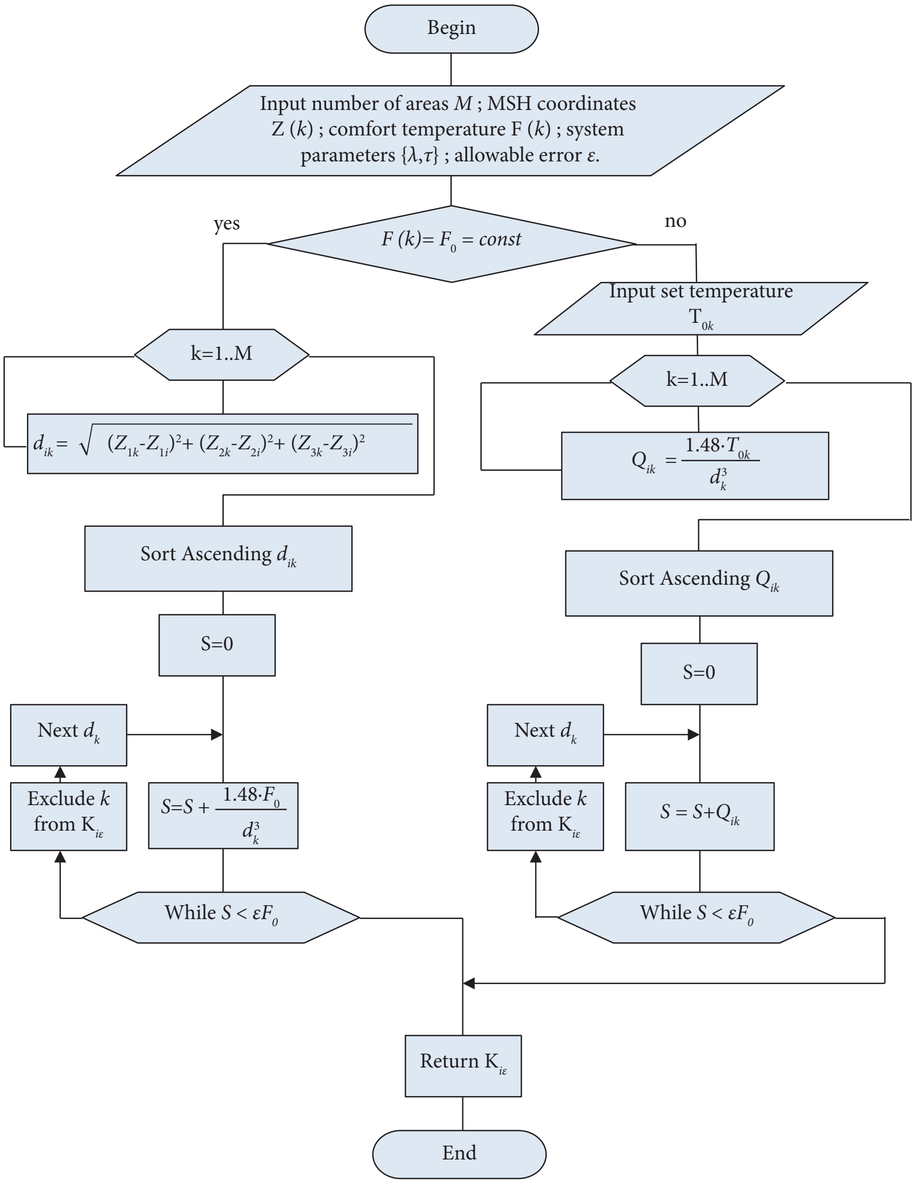


Figure 3: Algorithm for clustering a multiarea premise without partitions.

implemented by passing a token [70]. The coordinator of each MSH performs the determination of the optimal control taking into account how it will affect the whole ε- environment. To avoid the possibility of instability in coordination due to the conflict between local and global optimization, we have modified the wave algorithm of Lee (1961) and introduced a compromising factor ρ_k

$$\rho_k : \begin{cases} = 1, & \text{if } k = i, \\ < 1, & \text{if } k \neq i. \end{cases} \tag{9}$$

Thus, the criterion $E(T_{0i})$ of local coordination is

$$T_{0i}: \ \min_{T_{0i}} E(T_{0i}) = \min_{T_{0i}} \sqrt{\int_{t_0} \sum_{k=\mathbf{K}_{i\varepsilon}} \rho_k \alpha_k [T(k,t) - F(k)]^2 \mathrm{d}t}. \tag{10}$$

Taking into account the model [69], we could write

$$E(T_{0i}) = \sqrt{\left[\int_{t_0} \left[w_{ii} T_{0i} + \sum_{k=\mathbf{K}_{i\varepsilon}} \rho_k \frac{w_{ki}(T_{0k} - T_{0i})}{8(\pi\lambda t/\tau_{ik})^{3/2}} e^{-d_{ik}^2/4\lambda t/\tau} - F_i + \sum_{k=\mathbf{K}_{i\varepsilon}} \alpha_k \left[w_{kk} T_{0k} + \frac{w_{ki}(T_{0i} - T_{0k})}{8(\pi\lambda t/\tau_{ik})^{3/2}} e^{-d_{ik}^2/4\lambda t/\tau} - F_k \right]^2 \mathrm{d}t \right]^2}, \tag{11}$$

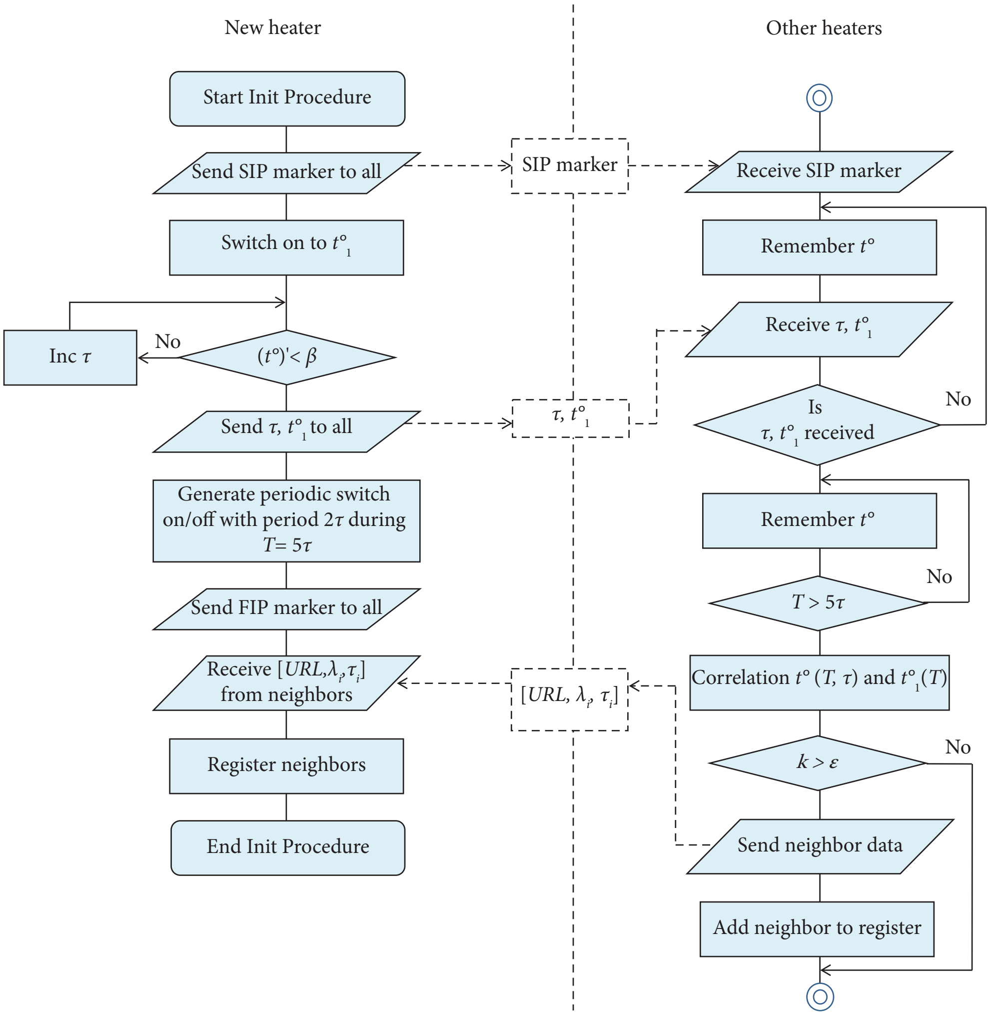


Figure 4: Algorithm for determining the set of MSH based on the procedure of impact testing.

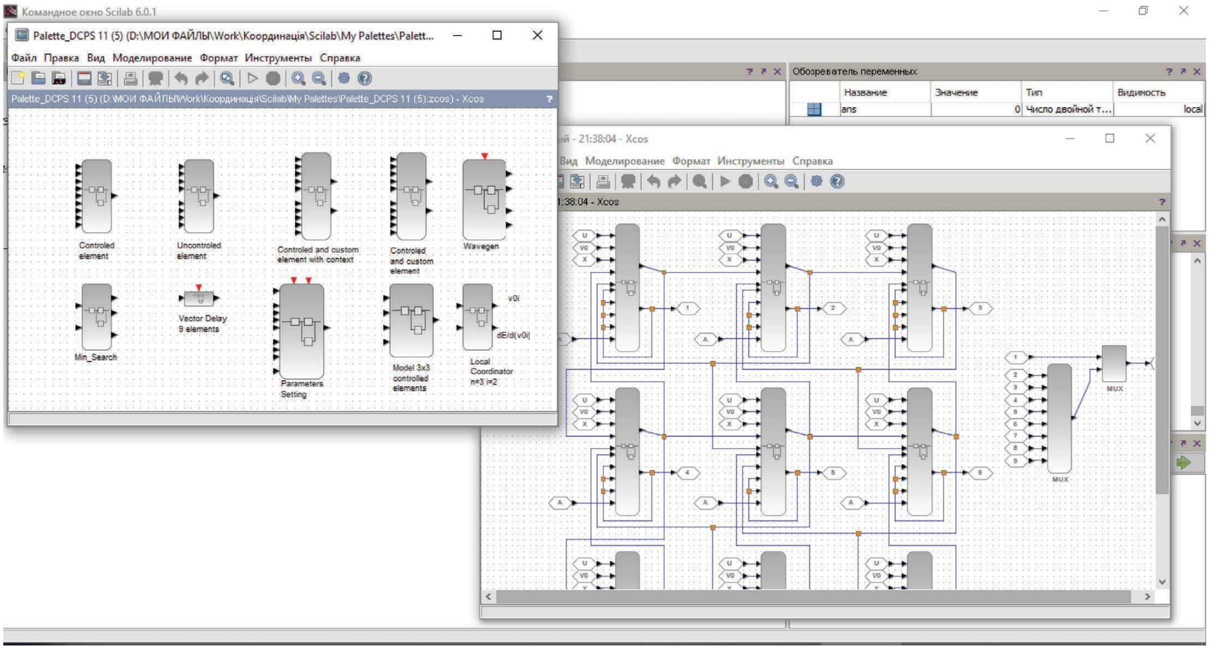
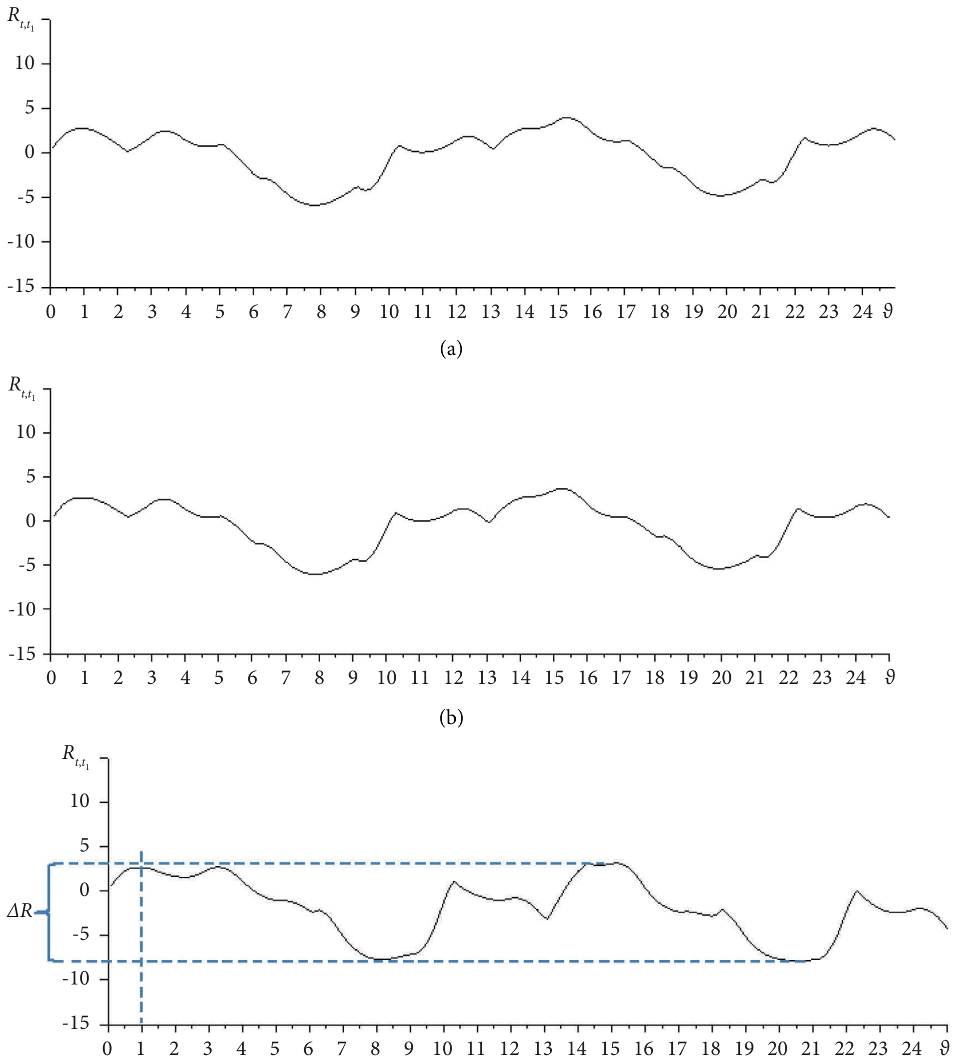


Figure 5: Simulation module library and the temperature coordination control model.



(a)

(b)

(c)

Figure 6: Results of simulation of the process of parameter testing.

where w_{ki} is the equivalent transfer coefficient of the transfer function of the system {from k-th MSH to i-th area} [69]. Since the thermal object is linear, then $w_{ki} = w_{ik}$. Obviously, in the presence of regulators $w_{ii} \approx 1$, $w_{kk} \approx 1$, and $w_{ki} \ll 1$. The form of integral function under such conditions is shown in Figure 7.

Figure 7 shows that the integrand function is bound, positively definite, tends asymptotically to zero, and therefore is integrated. So, criterion (11) may always be calculated.

The forms of dependences $E(T_{0i})$ on the parameters d_{ik} (a) and $k = \lambda t/\tau$ (b) are shown in Figure 8. The graphs show that the dependence $E(T_{0i})$ for all parameter values is smooth, at one extreme, and therefore the minimum criterion can be found by the gradient method.

The Scilab superblock of the local coordinator for the system of three elements in the ε-area is shown in Figure 9. The coordinator searches for the coordination parameter T_0 for the i-th element by finding the minimum coordination criterion (11) by the gradient method.

The correspondence of parameters of the coordinator model to the designation of criterion (11) is given in Table 1.

As the coordination wave passes through the system, the components of the coordination parameter vector $\mathbf{T}_0$ are sequentially changed to improve the coordination criterion. The convergence and stability of the wave coordination algorithm depend on the ratio of the attenuation index of the exponent $d_{ik}^2/4\lambda t/\tau$ and the coordination coefficient. γ: $\Delta T_{0i} = -\gamma \cdot (T_i - T_{0i})$.

4.1. The Estimation of Comfort. Although comfort is a complex concept, we evaluated only one of its components, thermal comfort. It was noted that thermal comfort is defined as "a state of mind that expresses satisfaction with the thermal environment and is evaluated by subjective evaluation" [73]. For a multiarea premise, the desired thermal environment in each area is determined by a given temperature distribution. A method for estimating human thermal comfort based on the predicted mean vote (PMV)

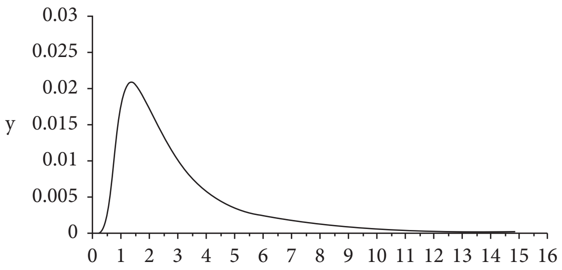
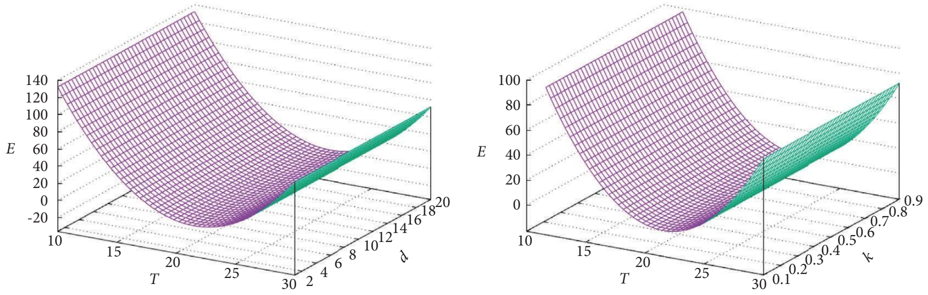


Figure 7: Integrand function.



(a) (b)

Figure 8: Dependence of the criterion on the parameters.

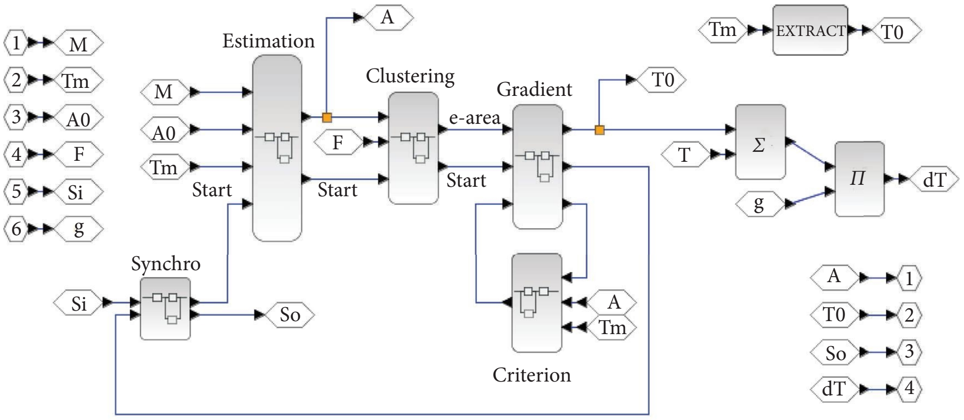


Figure 9: Superblock of the local coordinator.

was proposed in 1970 and extended in work [74]. The level of comfort in a PMV exponentially depends on the energy consumption of the occupant for self-thermoregulation. In our work, we use the PMV model constants and approximate this dependence by an exponential function:

$$C = e^{-0.29|T-F|}, \quad (12)$$

where F is the temperature of maximum comfort.

General comfort level in multiarea premise:

$$\text{comfort} = \sqrt{\frac{1}{M}\sum_{i=1}^{M} C_i^2}, \quad (13)$$

where M is the number of areas of multiarea premises, and i is the area number.

4.2. *The Estimation of Energy Consumption.*

MSH is a relay system with automatic control. The method of estimating energy consumption in stationary and transient modes in thermal control systems of multiarea premises was proposed in [71].

4.3. *The estimation of coordination.*

Many sources consider the concept of the "index of coordination" as the opposite of coordination and chaos. So, there are two understandings of the index of coordination:

(1) As a qualitative characteristic of the coordination of the activities of the enterprise, project executors, etc.;

(2) As a quantitative characteristic of the location in space (the origin of the concept "coordinates" of molecules in chemical processes or mechanical elements of devices and structures).

Table 1: Correspondence of the symbols of the analytical and simulation models.

Criterion	Model	Contents
Input		
M	M	Number of areas
$d, \lambda, \tau, w, \rho, \alpha$	A0	Initial matrix of parameters
$\mathbf{F}$	F	Vector of set comfortable temperatures
$\mathbf{T}$	Tm	Vector of temperature in the areas
γ	g	Coefficient of coordination
	Si	Start marker
Output		
	So	Finishing marker
ΔT_0	dT	Coordination step
$d, \lambda, \tau, w, \rho, \alpha$	A	The matrix of parameters is specified
T_0	T0	Optimal area temperature
Internal		
T	T	The temperature of the i-th area

We can assume that the state of the system changes from completely chaotic to fully coordinated during the process of coordination.

Recently, chaotic processes are increasingly attracting the attention of researchers [75]. In their works, different names are given to this phenomenon, such as dynamic chaos, deterministic chaos, and complete chaos. A characteristic feature of chaotic processes is their unpredictability. The name "deterministic chaos" is used to emphasize that the collective behaviour of many dynamic objects, each of which is deterministic, becomes unpredictable with a certain number of them and a rigid nonlinear model that creates instability in the behaviour prediction algorithm.

Chaos theory identifies the properties of the system, in which it can be chaotic processes [76]:

(1) It must be sensitive to the initial conditions. Sensitivity to initial conditions means that small changes in initial conditions can lead to significant changes in the state of the system. This is typical of a rigid system model. An indoor temperature control system with a sufficiently large propagation constant can become nonminimum-phase, so its model is rigid.

(2) It must have the property of topological mixing. Topological mixing means such a scheme of expansion of the system that one of its areas, at some stage of expansion, is superimposed on any other area. While the radius of the ε-area of the element expands with increasing state parameters of the elements, the system corresponds to the condition of topological mixing.

(3) It must be nonlinear. According to the Poincare–Bendixson theorem [77], a continuous dynamic system on a plane cannot be chaotic. A discrete dynamical system can exhibit chaotic behaviour even in one-dimensional space.

To assess the potential for coordination of a system, we introduce the concepts of norm and measure of coordination/chaos. On the metric scale shown in Figure 10, states of complete chaos and complete coordination form the boundaries of the range of values of the index of coordination.

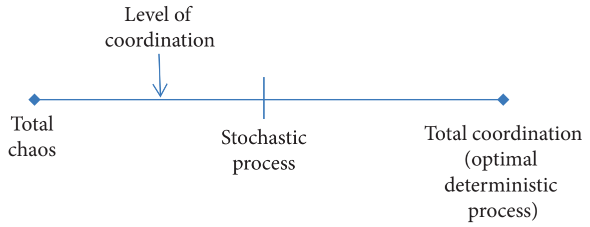


Figure 10: Scale of coordination.

However, the use of the index of coordination as an assessment of the consistency of the control subsystems of the distributed system elements is almost nonexistent. An exception is the use of the Lyapunov index to characterize the chaotic motions of a dynamic system [77]. However, for distributed environment control systems, this index is inconvenient because such systems, with the presence of relays and logical conditions, could not be represented by a system of differential equations, even with the linearization of the characteristics of the elements.

Let us use the inverse normalized RMSE of the vector of the system state as an estimation of the coordination index. If the reduced error is $\delta_{\mathbf{T}} = \sigma_{\mathbf{T}}/\max\|\mathbf{T}\|$, where $\max\|\mathbf{T}\|$ is the maximum metric distance between the state vectors of the system (the range of values of the state vector $\mathbf{T}$), then the index of coordination:

$$\mathrm{coor} = 1 - \frac{\sigma_{\mathbf{T}}(\tau)}{\max\|\mathbf{T}\|}, \qquad (14)$$

where τ is a research time interval. Since the deviation of the RMSE cannot take a value beyond the possible range of values of the state vector, then $\mathrm{coor} \in [0; 1]$.

This indicator allows us to determine which of the following three types of systems it belongs to:

(1) For a deterministic system $\mathrm{coor} = \lim_{\tau \longrightarrow \infty} [1 - \sigma_{\mathbf{T}}(\tau)/\max\|\mathbf{T}\|] = 1$;

(2) For a chaotic system without attractors $\mathrm{coor} = 0$;

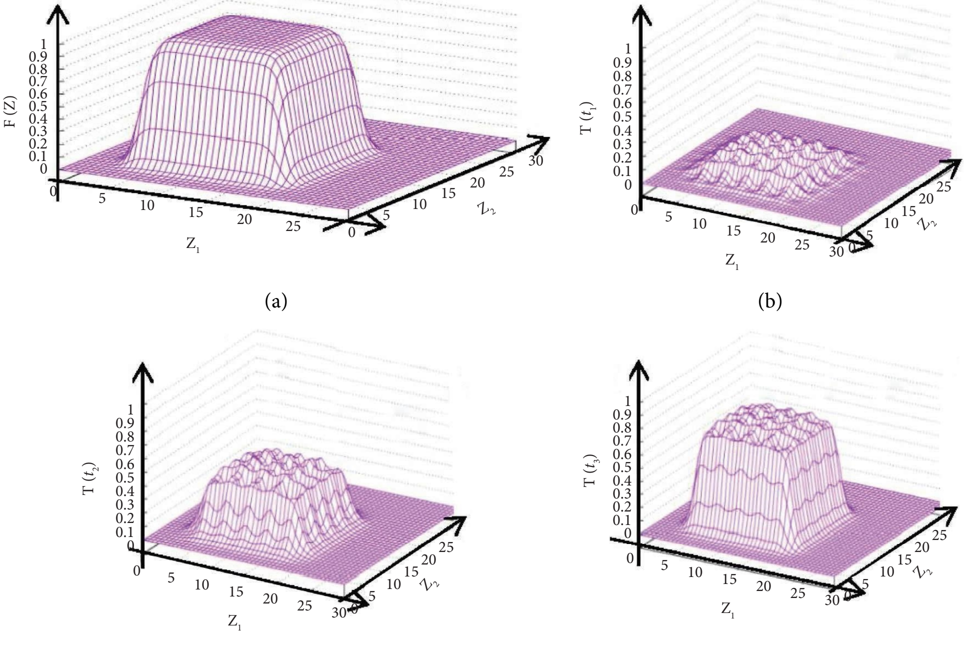
(3) For stochastic system

$$\mathrm{coor} = \lim_{\tau \longrightarrow \infty} \left[1 - \frac{\sigma_{\mathbf{T}}(\tau)}{\max\|\mathbf{T}\|}\right] = \lim_{\tau \longrightarrow \infty} \left[1 - \frac{\sqrt{\sum_i \sigma_{T_{0i}}^2 \left|W_{T_{0i} \longrightarrow T_i}\right|^2}}{\max\|\mathbf{T}\|}\right], \qquad (15)$$

where $W_{T_{0i} \longrightarrow T_i}$ is the transfer function of the regulator MSH.

Sources of reduced coordination were analyzed in [69]. For the case of periodic wave coordination, expression (9) becomes the following form:

$$\mathrm{coor} = 1 - \frac{\sqrt{\sum_i \sigma_{T_i}^2(\tau)}}{\max\|\mathbf{T}\|}. \qquad (16)$$



(a) (b)

(c) (d)

Figure 11: Evolution of the state of an object, $t_3 > t_2 > t_1$.

The effectiveness of MSH coordination was studied in models of the Scilab system and the *EnergyPlus* system. The evolution of the state of the system from switching on to achieving stationarity is shown in Figure 11 (Figure 11(a) shows the given temperature function **F**; Figure 11(b) shows the state after the first cycle of simulation; Figure 11(c) shows the state at the middle of the simulation process; and Figure 11(d) shows the state at the end of the simulation process).

The results of comparing the efficiency of the system with 9 areas with coordination and without one according to the results of modelling in different modelling systems are shown in Table 2 and 3. The plan of the premise with the location of MSH is shown in Figure 12. The stabilization factor of MSH regulators is 25. Indicators are given in relative units. As a basis, we took the *EnergyPlus* simulation results without coordination at the same comfort temperature in all areas $\forall k$: $F_k = F_0$ and external influence (ambient temperature) $u = F_0$, i.e., the ratios of the scatter of external influence on the area to the power of MSH are $\sigma_u / p_0 = 0$ and $\sigma_F / p_0 = 0$. The simulation data in the *EnergyPlus* system is used as a dataset to adjust the parameters of the Scilab model.

When studying the dependence of characteristics on the spread of comfort temperatures, the distribution of comfort temperatures by areas was generated in the following ways:

(1) Random distribution by size and by area number without sorting;

(2) Random values are sorted by area number in one direction;

(3) Random values are sorted by area number from the centre to the sides.

Table 3 shows the average results for all studies.

The results of comparing the efficiency of MSH system show an increase in comfort by an average of 3% while reducing energy consumption by 1.5%.

The results of the simulation of the system of 16 controlled elements with centralized coordination, decentralized coordination, and without it are shown in Figure 13.

Decentralized coordination was carried out cyclically. It can be seen from the diagram that, with each cycle, the value of the criterion gradually approached the global optimum, which is ensured by centralized coordination. The speed of the approach depends on the size of the ε-area and the parameter γ.

5. Discussion

Ensuring individual thermal comfort is a difficult task in the conditions of mutual influence between individual zones of the multizone premises. The task is further complicated by frequent changes in the set comfort parameters. Usually, this problem is solved with the help of movable heaters and air conditioners. However, you have to reconfigure the heaters in all areas adjacent to the change in comfort settings in one zone or the move of the movable device in one zone.

The proposed concept of decentralized coordination of local control systems with a dynamic structure and its implementation in the Movable Smart Heaters (MSH) system with algorithms for coordination and automatic detection of the set of adjacent areas makes it possible to simplify the solution of this problem and increase the efficiency of the system.

This approach differs from existing approaches to decentralized control of distributed systems for providing

Table 2: The results of comparing the effectiveness of the system with and without coordination under the influence of external temperature and F = const

σ_u/F_0, %	*EnergyPlus* without coordination			Scilab without coordination			Scilab with coordination		
	Comfort	*coor*	Energy consumption	Comfort	*coor*	Energy consumption	Comfort	*coor*	Energy consumption
0	1	0.98	1	0.98	0.83	1.10	0.98	0.83	1.12
20	0.66	0.89	1.01	0.62	0.80	1.09	0.64	0.81	1.10
50	0.49	0.74	1.01	0.48	0.73	1.06	0.52	0.76	1.04
80	0.40	0.68	1.02	0.41	0.66	1.03	0.45	0.79	1.00
100	0.31	0.63	1.02	0.30	0.61	1.01	0.38	0.78	0.97

Table 3: The results of comparing the efficiency of the system with and without coordination.

σ_F/F_0, %	*EnergyPlus* without coordination			Scilab without coordination			Scilab with coordination		
	Comfort	*coor*	Energy consumption	Comfort	*coor*	Energy consumption	Comfort	*coor*	Energy consumption
0	**1**	0.88	**1**	0.98	0.83	1.10	0.98	0.83	1.12
5	0.63	0.81	1.03	0.91	0.76	1.11	0.92	0.80	1.12
10	0.45	0.73	1.08	0.81	0.69	1.12	0.82	0.77	1.13
15	0.35	0.65	1.12	0.63	0.62	1.13	0.66	0.74	1.13
20	0.26	0.57	1.18	0.28	0.54	1.14	0.33	0.71	1.13

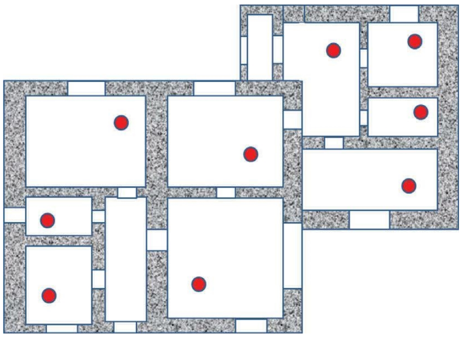


Figure 12: Plan of the premises with the location of MSH.

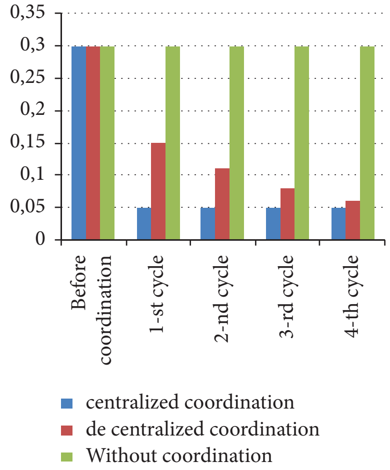


Figure 13: Comparison of the results of centralized and decentralized coordination.

individual thermal comfort in rooms. Recently, blockchain technology has been used to build decentralized systems [78]; however, this technology involves only decentralization of data collection, storage, and primary processing, while optimal coordination is performed centrally. The main advantage of MSH and their decentralized coordination is the possibility of their independent production and use at one premise in unlimited quantities without much effort to reconfigure the system.

In our work, we have not yet been able to conduct full-scale experiments, but only experiments on a simulation model. This is due to the lack of serial MSH, which are currently at the stage of advanced development. Field experiments are planned for the next stage of work. For simulation experiments, the authors have developed a specialized palette (library) of typical blocks on the Scilab platform. The problem of obtaining a dataset for setting up the model was solved using the *EnergyPlus* modelling system for building thermal processes, which is recommended by the US Department of Energy and well-tested in practice. The library of models developed by the authors is a good addition to the *EnergyPlus* system for the tasks of automatic control of processes to ensure individual thermal comfort.

The conducted studies of the system model and optimization criteria depicted in Figures 7 and 8 confirmed the possibility of achieving optimal global comfort. However, the process of adjusting system settings when changing its configuration has limitations. The authors used the correlation method of data processing under the influence of external random influences. This requires the accumulation of some minimum dataset. Numerical experiments have shown that 6 cycles of operation of the MSH relay control are sufficient. However, for internal zones and small comfort temperature differences in the zones, these 6 cycles can take a long time. During this time, new changes to the system configuration may occur, and the configuration process cannot complete. At the same time, the fact that the results of comparing MSH system efficiency using the simulation model have shown an increase in comfort by an average of 3% while reducing energy consumption by 1.5% indicates that the development is promising.

6. Conclusions

With local control of a large number of objects that mutually influence each other, the problem of coordinating local control systems to achieve the best overall result arises. If the structure of the system (the number of control objects and the parameters of interaction) can change frequently, then the process of setting up/training a centralized coordinator will take an unacceptably large part of the action time and require a significant amount of resources. In this work, the use of decentralized coordination is proposed to solve the problem. As a basic task for research on decentralized coordination control of objects that mutually influence each other, stabilizing the comfort temperatures was set in multizone rooms using movable heaters. Providing individual thermal comfort is an important problem. In particular, there are many multiarea premises with conflicting requirements for the comfort of habitats. This problem can be solved with the help of movable heaters and air conditioners. However, the presence of heat flows between areas with different specified parameters makes it difficult to adjust the movable heaters. To improve the quality of thermal control in multiarea premises with a dynamic structure for the location of movable heaters, we have proposed the concept of Movable Smart Heaters. A group of MSH that could influence each other and exchange information forms a dynamic system with a changing structure since switching on/off or moving one MSH to another area changes the mutual influence and connections in the system. The criteria for control quality are defined and evaluated. The proposed decentralized coordination algorithms make it possible to optimize the operating modes of the system automatically when its structure and/or settings are changed. Simulation of the system is performed with the use of a worked-out modelling library in Scilab. The results of comparing the MSH system's efficiency show an increase in comfort while reducing energy consumption. The study has shown the promise of using decentralized coordination to control a system of interacting objects with a variable structure.

Further research is planned to investigate the stability and dynamics of the decentralized coordination in control of a system of interacting objects with a variable structure, in particular the MSH system, taking into account the change in the operating modes of stationary comfort devices and the influence of heat flows from people and equipment in the premises.

Data Availability

Most data is contained within the article. All the data available from the first author upon request.

Consent

Informed consent was obtained from all subjects involved in the study.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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