VILNIUS UNIVERSITY

EVALDAS ŽULKAS

DEVELOPMENT OF ENERGY CONSUMPTION FORECASTING AND AUTONOMOUS MANAGEMENT SYSTEM IN SMART HOUSE ENVIRONMENT

Summary of Doctoral Dissertation

Technological Sciences, Informatics Engineering (07 T)

Vilnius, 2017

The dissertation work was carried out at Vilnius University from 2012 to 2016.

Scientific Supervisor

Prof. Dr. Dalė Dzemydienė (Vilnius University, Technological Sciences, Informatics Engineering – 07 T).

Scientific Consultant

Prof. Dr. Eleonora Guseinovienė (Klaipėda University, Technological Sciences, Informatics Engineering – 07 T).

The defense Council:

Chairman

Prof. Dr. Albertas Čaplinskas (Vilnius University, Technological Sciences, Informatics Engineering – 07 T).

Members:

Prof. Dr. Vitalijus Denisovas (Klaipėda University, Technological Sciences, Informatics Engineering – 07 T),

Prof. Dr. Saulius Gudas (Vilnius University, Technological Sciences, Informatics Engineering – 07 T),

Prof. Dr. Audrius Lopata (Vilnius University, Technological Sciences, Informatics Engineering – 07T),

Prof. Dr. Audris Mockus (The University of Tennessee, USA, Technological Sciences, Informatics Engineering – 07 T).

The dissertation will be defended at the public meeting of the Council in the auditorium 203 of the Vilnius University Institute of Mathematics and Informatics on the 29th of September, 2017 at 9:30

Address: Akademijos str. 4, LT-08412 Vilnius, Lithuania.

The summary of the dissertation was distributed on the 28th of August, 2017.

The dissertation is available at the library of Vilnius University.

VILNIAUS UNIVERSITETAS

EVALDAS ŽULKAS

ENERGIJOS SĄNAUDŲ PROGNOZAVIMO IR AUTONOMINIO VALDYMO SISTEMOS IŠVYSTYMAS IŠMANIOJO BŪSTO APLINKOJE

Daktaro disertacijos santrauka

Technologijos mokslai, informatikos inžinerija (07 T)

Vilnius, 2017

Disertacija rengta 2012–2016 m. Vilniaus universitete.

Mokslinė vadovė

prof. dr. Dalė Dzemydienė (Vilniaus universitetas, technologijos mokslai, informatikos inžinerija – 07 T).

Mokslinė konsultantė

prof. dr. Eleonora Guseinovienė (Klaipėdos universitetas, technologijos mokslai, informatikos inžinerija – 07 T).

Disertacija ginama viešame Gynimo tarybos posėdyje:

Pirmininkas

prof. dr. Albertas Čaplinskas (Vilniaus universitetas, technologijos mokslai, informatikos inžinerija – 07 T).

Nariai:

prof. dr. Vitalijus Denisovas (Klaipėdos universitetas, technologijos mokslai, informatikos inžinerija – 07 T),

prof. dr. Saulius Gudas (Vilniaus universitetas, technologijos mokslai, informatikos inžinerija – 07 T),

prof. dr. Audrius Lopata (Vilniaus universitetas, technologijos mokslai, informatikos inžinerija – 07 T),

prof. dr. Audris Mockus (Tenesio universitetas, JAV, technologijos mokslai, informatikos inžinerija – 07 T).

Disertacija bus ginama viešame Gynimo tarybos posėdyje 2017 m. rugsėjo 29 d. 9.30 val. Vilniaus universiteto Matematikos ir informatikos instituto 203 auditorijoje.

Adresas: Akademijos g. 4, LT-04812 Vilnius, Lietuva.

Disertacijos santrauka išsiuntinėta 2017 m. rugpjūčio 28 d.

Disertaciją galima peržiūrėti Vilniaus universiteto bibliotekoje ir VU interneto svetainėje adresu: *www.vu.lt/lt/naujienos/ivykiu-kalendorius*.

ABSTRACT

The smart house systems, which integrate the energy consumption management functions, are classified as technological solutions of the Internet of Things. Development of autonomous energy consumption management system requires assessment of the proposed architectures, systematization of the measures, applied in the home energy management system, and upon analysing them, one needs to identify what is missing, and what could be selected properly. Usually, the smart house management system integrates lighting and heating, ventilating and air conditioning (HVAC) subsystems, which require special devices and network capabilities for reading the environmental parameters and for data collection (Jiang X., 2010; Kaklauskas et al. 2015).

To make automated decisions on energy consumption management, the capabilities of the data collection, the communication and the analysis subsystems of the embedded systems, and their application for more efficient energy consumption are researched. The dissertation proposes to develop the architecture of the energy consumption management system by focusing on the energy consumption needs, costs, the applicable forecasting methods to enable more efficient energy consumption.

While developing the energy consumption management system (ECMS), it is essential to adapt the principle of autonomous management, and to include the forecasting-based decision-making methods in the ECMS subsystem. It should be noted that the energy consumption management system, discussed in the literature, is not based on the forecasting analysis (Barnawi et al. 2016; Daniela et al. 2015; Engerati, 2016). To ensure the system autonomy, it is required that the devices (sensors and controllers), embedded in the system, would get the purpose (working scenario) at runtime, and that this purpose could be changed.

Considering the usage of the energy management system in the architecture of the smart house management system, it is sought to analyse the current and propose other development possibilities for autonomous energy consumption management (Adinya, 2013, Kaklauskas et al. 2015). The methods, examined and applied for the developed energy consumption forecasting, are presented (Shamisi et al. 2011) in this work.

The improved and proposed network application layer allows developing a hardware solution and installing a device with sensors in the smart environment without defining the purpose of a device. Both sending and receiving devices are configured during runtime.

ECMS architecture is made up of the modules by using the solutions, proposed by the authors (Barnawi Y. et al. 2016; Jiang X. et al. 2007; Sinderen V. M. et al. 2010) for development of these service systems. However, the architecture solutions, proposed by the aforementioned authors, did not include the components for implementation of energy consumption forecasting with task schedule. Therefore, the dissertation thesis proposes to integrate the task management and forecasting data to ensure the functioning of decision support system (DSS). The proposed command management and management analysis methods are characterized by novelty because their usage is required to find out whether the solution to manage the e-service device answers its purpose.

To monitor the real-time energy consumption of device, it is necessary to monitor the power metering components in real time. The calculations require the instantaneous power, the current value, and the zero-crossing values. Along these parameters, power factor is calculated. If a power factor is too low, energy consumption is inefficient, and efficiency can be increased by improving hardware solution of controllers.

The research on the storage of the real-time experimental instantaneous data from sensors revealed that subject to the used sensor and environment parameter, data detection and stabilization of their values may vary, therefore, stabilization function should be used for data reading, in order the intermediate values would not be used instead of the final ones.

A three-step feedback structure allows to get the system response in three parts of the system: during real-time management of the device, correction is sent to the decision support system and to the database server for further analysis.

The data of the energy consumption management system can be analysed as stationary time series, and mathematical modules can be applied for forecasting (e.g., ARMA). If seasonal and trend components are not clear, the algorithms for neural networks should be used. To forecast one sample in the future, Kalman filter could be used. In any case of forecasting, the task schedule can be applied as it provides accuracy to all algorithms under consideration because the schedule for the use of the devices is assessed.

While testing the system in practice, the real-time management of artificial illumination was monitored. The system ensured a constant lighting, however, the change in power curve was observed when illumination was constant, and environment got naturally darker. To assess the process of the end of the daytime by forecasting algorithms, the cloudiness tracking should be included in the forecasting model data.

Keywords: smart house management system, energy consumption management, e-services, forecasting algorithms, mobile network topology.

INTRODUCTION

Topicality of the problem

Fast development of the digital economy leads to embeddedness and digitization of all public spheres. The modern smart house systems, based on technological solutions of the Internet of Things, are developed. Such technology-enriched and embedded for house environment allows to provide new services, adapted to the user's needs. These e-service systems are designed based on the possibilities, provided by the Internet of Things, where environmental monitoring and analysis estimates are used for decision making (Andziulis et al. 2009; Bielskis et al. 2009; Schmid et al. 2012). Sensor networks and embedded systems, interconnected to achieve one purpose, are the main components of implementation of the systems of the Internet of Things (De et al. 2012; De Silva et al. 2012; Murtaza et al. 2013). The architecture solutions of the energy consumption management and saving system are described, giving the possibility to provide the controlled services and to ensure the balance between the comfort and the energy consumption efficiency.

In case of efficient management of energy resources, dedicated for service provision, it is possible to ensure more fluent and cost-effective solution for consumption management. While developing the embedded systems, it is necessary to consider what data are needed, to obtain information from the environment, and to ensure that different system versions would function with microprocessors of various architectures with different peripheries, communication, and calculation capabilities. In this research, the architecture solution of energy data monitoring and power device management system is proposed, adapted for the heterogeneous networks. Seeking to ensure such possibility, that the system could respond to the environment not only by providing information about ongoing events, but also by proposing decisions on how to manage the subsystems, existing in the environment. The system should be able to implement the data forecasting for the future. To ensure adaptive decision making, enabling for autonomous management of energy consumption, in this system, the methods, suitable for forecasting energy consumption, should have been selected. The forecasting methods and the decision-making components, were included to ensure the functioning of the energy management subsystem. Seeking to make autonomous decisions to reduce the energy consumption, it is necessary to examine the capabilities of the data collection, transmission, and analysis subsystems of the embedded system, and to apply the methods for more efficient energy consumption. Therefore, the main objective arises – to develop the architecture of the energy consumption management system, focusing on the energy consumption needs, costs, the possible forecasting methods to enable more efficient energy consumption.

Problems of research

To ensure the integration of these sensors for monitoring of energy consumption in the smart house system, it is necessary to develop the network application layer of the interconnected sensors that would work in the environment of other standardized network layers. This application layer should ensure the proper data exchange (for service data and sensor data transmission), and provide the framework for smart management.

Seeking to develop the autonomous system for energy consumption management, it is necessary to assess the proposed architectures, which integrate the energy consumption management functions. Usually, the smart house management systems integrate lighting and heating, ventilation subsystems, which require special devices and network capabilities for reading the environmental parameters and for data collection. As appropriate methods for connection of these devices had to be searched for, the capabilities the data collection, transmission, and analysis subsystems of the embedded systems were examined. This research is devoted for following problem - how to develop the architecture of the energy consumption management system by considering the energy consumption demand, costs and autonomy using forecasting methods to enable more efficient energy consumption. Device schedule plan can be introduced to the applicable forecasting methods to manage energy consumption in a more efficient way.

Object of research

The autonomous energy management subsystem integrated in the smart house, allowing energy consumption data collection, monitoring, forecasting and management in the mobile network of adaptive topology.

Aim of research

To develop the autonomous energy forecasting and management system, and to propose its architecture, which would enable the data collection, transmission, analysis and forecasting functions in the mobile and adaptive network topology, seeking for more efficient management of energy consumption.

Objectives of research:

1. To study the methods and measures for information and communications technologies, required for development of the smart house infrastructure and dedicated to reducing the energy consumption, and to perform comparative analysis of the proposed solutions.

2. To examine the communications protocols for integration of the small-scale embedded systems in the smart house management system.

3. To propose and implement the network application layer for integration of the sensor network in the smart house architecture, and to test the operation of the selected data communications protocol for collection and analysis of energy consumption data.

4. To propose the forecasting methods of energy consumption in the smart house, to adapt a set of algorithms, allowing for energy consumption forecasting in the embedded systems.

5. To develop the prototype of autonomous, energy-efficient management system, to integrate it in the smart house service system, and carry out experimental research by testing the integrated system under different operating modes.

The research methods

Analytical review of literature resources was carried out, the key functioning principles of the smart house systems were systematized, and comparative analysis of the implementation measures of these systems was performed.

To review the architectures of the existing energy management systems, exploratory study is applied.

Prototyping method is applied to develop the small-scale embedded systems and WSN, and to collect the environment parameters.

While implementing the energy consumption management system prototype, the methods for development (design) of the ECMS architecture were proposed.

Results

- The prototype of autonomous ECMS, enabling to connect the embedded sensor nodes under mobile and adaptive topology network conditions, was developed. The prototype is dedicated for energy consumption management, and it is integrated in the smart house service system. The prototype of this system integrates the decision support system, based on the forecasting methods, the energy consumption schedule, as well as the management algorithms. The system architecture is complemented with 3-step feedback response module.

- To interconnect the embedded devices (sensors and controllers), the mobile network application layer and communication interface was developed, allowing to configure the device management in real time without pre-defining the purpose of the embedded devices of the Internet of Things. This application layer enabled to provide the data collection module with adaptive, real-time calibration, and reconfiguration possibilities. Using existing mesh topology data transmission protocols, the network application layer for the embedded systems was developed, allowing for autonomous energy consumption management.
- The task schedule module was developed to integrate device schedule plan with ARMA model and Kalman filter, allowing to specify the results of forecasting the energy consumption.
- The results of experimental research with ECMS revealed that the introduction of the task schedule leads to more efficient operation of the energy management system. When the system operates in an autonomous manner, the real-time forecasting-based lighting management algorithm allows to save energy consumption.
- Application of task scheduling and user rules allowed to define the limitations under which the resources, used by the service system, do not exceed the set values. Seeking to adapt ECMS to the dynamic environmental changes, exceptional scenarios (regime of end of daytime, human presence in the environment) are considered during experimental research.

Scientific novelty

The proposed platforms of the Internet of Things fail to define all the components, required to implement the concept of energy management system. These development platforms (e.g., ThingSpeak, ThingWorx) are dedicated to data collection, analysis, and response to events. The use of the aforementioned platforms to save the energy resources is possible only by the development of interfaces for sensor networks and by collection of sensor data. Data transmission between devices is implemented by using the telemetry technology and M2M principle. However, the methods and measures to ensure the mobile and adaptive topology of the sensor network have not been implemented in this type of systems yet. Therefore, this work proposes the system architecture of the small-scale embedded sensors, operating in mobile wireless sensor network (WSN).

By using the smart house infrastructure (laboratory), the sensor network, allowing to capture the sensor parameters, was developed. However, the existing wireless networks still lack functionality to ensure communication of the sensor network. Therefore, the author had to expand the functionality of the sensor network and to develop the application layer of wireless network. Usage of network application layer enabled the methods for real-time configuration of the devices.

Following the literature analysis, it was found out that autonomous management is not based on the energy consumption forecasting in the existing energy consumption management systems (Barnawi et al. 2016; Daniela et al. 2015; Engerati, 2016). ARMA statistical forecasting and Kalman filter methods are integrated in the energy consumption management system, allowing to ensure higher system autonomy and to achieve higher management accuracy.

The developed decision support system was integrated in the ECMS, while the experimental research led to more innovative management of power devices, considering high power factor, and maintaining the corresponding level of power factor in real time.

In summary of the characteristics of the developed ECMS, it might be stated that in comparison with traditional energy accounting systems, it distinguishes by the fact that it can operate in mobile and adaptive network, use embedded systems for data collections, while the proposed forecasting algorithms enabled autonomous operation of the system by more efficient decision-making methods. Energy management autonomy is based on the device data analysis and command management modules that are integrated in the system.

Practical importance

The dissertation analyses the architecture of the smart house energy consumption management system. It integrates the embedded systems by using the specialized network application layer and the set of commands for describing the operation of a smart sensor or other embedded device, by configuring the commands of the master device in real time and interpreting them. Thus, low-level programming languages (e.g., assembler and C) are avoided for the functions, implemented by the embedded systems. Furthermore, this architecture solution facilitates the system implementation, since both configuration, and source code of the embedded systems are described in one centralized system node – master device. Considering the nature of energy consumption, the author proposes to divide the forecasting algorithms into the methods of forecasting one or several samples to the future. The forecasting methods (ARMA model and Kalman filter) are connected to the task schedule, thus, allowing to specify the forecasting algorithm, when energy consumption is partially deterministic. This work describes the three-step feedback response system for specification and real-time correction of the energy management decisions made by the system. The examined monitoring data of physical power parameters and reading of instantaneous values by using the small-scale embedded systems can also be used for predictive maintenance and fault detection. It would be relevant in realization of the developing smart asset management systems. When all examined functional modules are connected to the architecture, proposed by the author, the system is provided with autonomy. The energy consumption management system becomes more adaptive, i.e., able to adapt to both the internal and external changes (for example, wear of device, assessment of historical data, comfort assurance, etc.) in real time.

Defended propositions

1) For the smart e-service system, it is appropriate to develop a unified network application layer that defines the behaviour of network device without predefining the purpose of this device, and by describing only declarative interpreter mechanism.
2) When making the energy management decision, the methods of future data forecasting, covering the time interval from one instantaneous signal value to several periods, could be used. Seeking to specify the forecasting result, it is appropriate to use the task schedule, which must be integrated with the selected forecasting algorithms.
3) Seeking for higher autonomy of the system, the architecture of the existing e-service energy management systems can be supplemented with the management analysis, command management and decision-making modules. These modules are

integrated in the mobile and adaptive topology network by using decision support system with three-step feedback and forecasting data.

Approbation of the research

5 scientific articles were published on the subject of this dissertation, 3 of them in ISI Web of Science and Thomson Reuter referred scientific journals. The reports were presented, and 3 national and 3 international conferences were attended.

The publications in the peer-reviewed journals

1. Zulkas E.; Artemciukas E.; Dzemydiene D.; Guseinoviene E., Energy consumption prediction methods for embedded systems, Ecological Vehicles and Renewable Energies (EVER), 2015, p. 1-5, http://dx.doi.org/10.1109/EVER.2015.7112932
2. A. Bielskis, E. Guseinoviene, D. Drungilas, G. Gricius, E. Zulkas, Modelling of Ambient Comfort Affect Reward Based Adaptive Laboratory Climate Controller, Elektronika ir Elektrotechnika, 2013, vol. 19 (8), p. 79-82, http://dx.doi.org/10.5755/j01.eee.19.8.5399.
3. E. Artemciukas, R. Plestys, A. Andziulis, K. Gerasimov, E. Zulkas, L. Pasviestis, A. Krauze, Real-time Control System for Various Applications using Sensor Fusion Algorithm. Elektronika ir Elektrotechnika, 2012, vol. 18 (10), p. 61 – 64, http://dx.doi.org/10.5755/j01.eee.18.10.3064.
4. V. Bulbenkiene, A. Pecko, E. Zulkas, A. Kuprinavicius, A. Sokolov, G. Mumgaudis, Energy Sub-Metering Data Acquisition System, Elektronika ir Elektrotechnika, 2011, no. 5 (111), p. 99-102, http://dx.doi.org/10.5755/j01.eee.111.5.366
5. Bielskis A. A., Guseinovienė E., Drungilas D., Gricius G., Žulkas E. Development of an adaptive human friendly sustainable environment, Proceedings of 9th International Conference on Ecological Vehicles and Renewable Energies (EVER). 2014, Monaco, IEEE; p. 1-4, ISBN 978-1-4799-3787-5 (CD).

The articles in scientific conference papers

1. Žulkas, E.; Dzemydienė, D.; Guseinovienė, E. Išmanaus būsto elektros energijos taupymo posistemės projektavimo sprendimai // Jūros ir krantų tyrimai 2016 : 9-oji nacionalinė jūros mokslų ir technologijų konferencija : konferencijos medžiaga : 2016 balandžio 27-29 d. Klaipėda: [Klaipėdos universiteto leidykla], 2016. ISBN: 9789955189015. p. 244-248.

2. Žulkas E., Dzemydienė D., Guseinovienė E., An approach of designing of decision support system in smart human closed environments, International conference social technologies ’15, 2015.

3. Zulkas E.; Artemciukas E.; Dzemydiene D.; Guseinoviene E., Energy consumption prediction methods for embedded systems, Conference of Ecological Vehicles and Renewable Energies (EVER), 2015.

The scope of the scientific research

The dissertation includes introduction, 4 chapters, conclusions, references, and appendices, abstract (in Lithuanian and English) and summary.

The first chapter analyses the existing technologies of energy management systems and applicable Information and communication technologies (ICT). It reviews and systemizes the architectures applied in the home energy management system. The possibilities of the Internet of Things, dedicated for the smart house energy management decisions, are reviewed. The principle of parameter reading acquisition and data collection of the lighting and HVAC systems is described.

The second chapter discusses the communication and technologies of wireless sensor networks. Network topologies used for provision of e-services, can be applied for low cost embedded system networks, since there are described by standards, adapted for low power systems.

The third chapter presents the autonomous management and saving subsystem. The service modules, dedicated for energy data forecasting and for ensuring the autonomous functioning of the system, were developed. The decision support system and the decision-making methods for managing the energy consuming devices are described.

The fourth part examines the forecasting algorithms for the energy consumption management system. The task schedule to supplement the Kalman filter and ARMA algorithms is proposed. Finally, the smart house energy management system is tested, and the forecasting and management results are presented.

1 REVIEW OF INFRASTRUCTURE SOLUTIONS OF THE SMART HOUSE MANAGEMENT SYSTEMS

This chapter reviews and systemizes the architectures applied in the home energy management system. The possibilities of the Internet of Things, dedicated for the smart house energy management decisions, are reviewed. The principle of parameter reading acquisition and data collection of the lighting and HVAC systems is described.

1.1 Functional capabilities of the smart house management systems

The tasks of rational use of resources pose challenges for technological innovations, which would enable to develop the systems based on computer networks, and could be connected to large systems, surrounding and servicing a human being and his environment. The smart house management systems integrate smaller e-service systems, e.g., security management, heating and ventilation, lighting, and energy management system. The functions of the smart house e-service system can be divided into the following levels:

Level 1: Used communication technologies, allowing the user to communicate and be reached by other persons outside the considered environment. Possible text and voice communication methods. This level includes the communication systems, provided by telephone and computer systems, the Internet, etc.

Level 2: Response of the smart house to the user commands by specifying the tasks directly or remotely. This level includes the systems of response to management commands, for example, door locking-unlocking, window condition checking, remote turn on of lights, etc.

Level 3: Used automatic home functions. The systems, included in this level, use sensors, meters, and timers to manage air temperature, humidity. The systems can turn on and off the lights, according to the pre-set time, or automatically protect the house from intruders, etc.

Level 4: The systems of this level follow the user and look for the dependencies by analysing the templates. For example, detection of user in environment, health monitoring or consumption planning.

Level 5: Data are analysed, decisions are made, and responded to. These systems can alert the user about the events that take place in his environment, for example, about received letters, water leak or unlocked door, etc. However, the alerts, enabled by this level system communication, reach the remote personal and home care service providers, when they need to respond to the situation, for example: it is alerted about health disorders, health rhythms, etc. The system functions include presentation of reports to the residents, to the person and home care service providers. The smart house system of level 5 automatically looks at the memorized scenarios, for example: to memorize the preferred ambient temperature or lighting.

Level 6: The system provides information, reminders, and offers daily tasks, for example, exercises or homework.

Level 7: The system answers the questions. Upon assessing the environment, the system is able to answer the questions, for example, to assess the environment condition.

Level 8: The system executes the tasks, the system maintenance tasks are automatically ordered, the lists of consumption needs are made, etc.

According to the presented system functions, the smart home energy management system, analysed in this research, meets the description of level 5: by using the data of environment parameters and upon analysing them, to accordingly respond to the environmental changes.

The smart house service components are usually used for provision of the following services (Naimavičienė J., 2008):

• indoor climate control (HVAC systems, temperature and humidity monitoring systems);

• lighting (automatic turn on and off according to the task list, lighting selection by considering the environmental conditions, etc.);

• protection (video surveillance cameras, human detection, smoke, fire, water, natural gas leakage sensors and control systems).

According to the functional capabilities, the smart house system can be classified into the following levels (Fig. 1) (Helal S. et al. 2005):

• physical level;

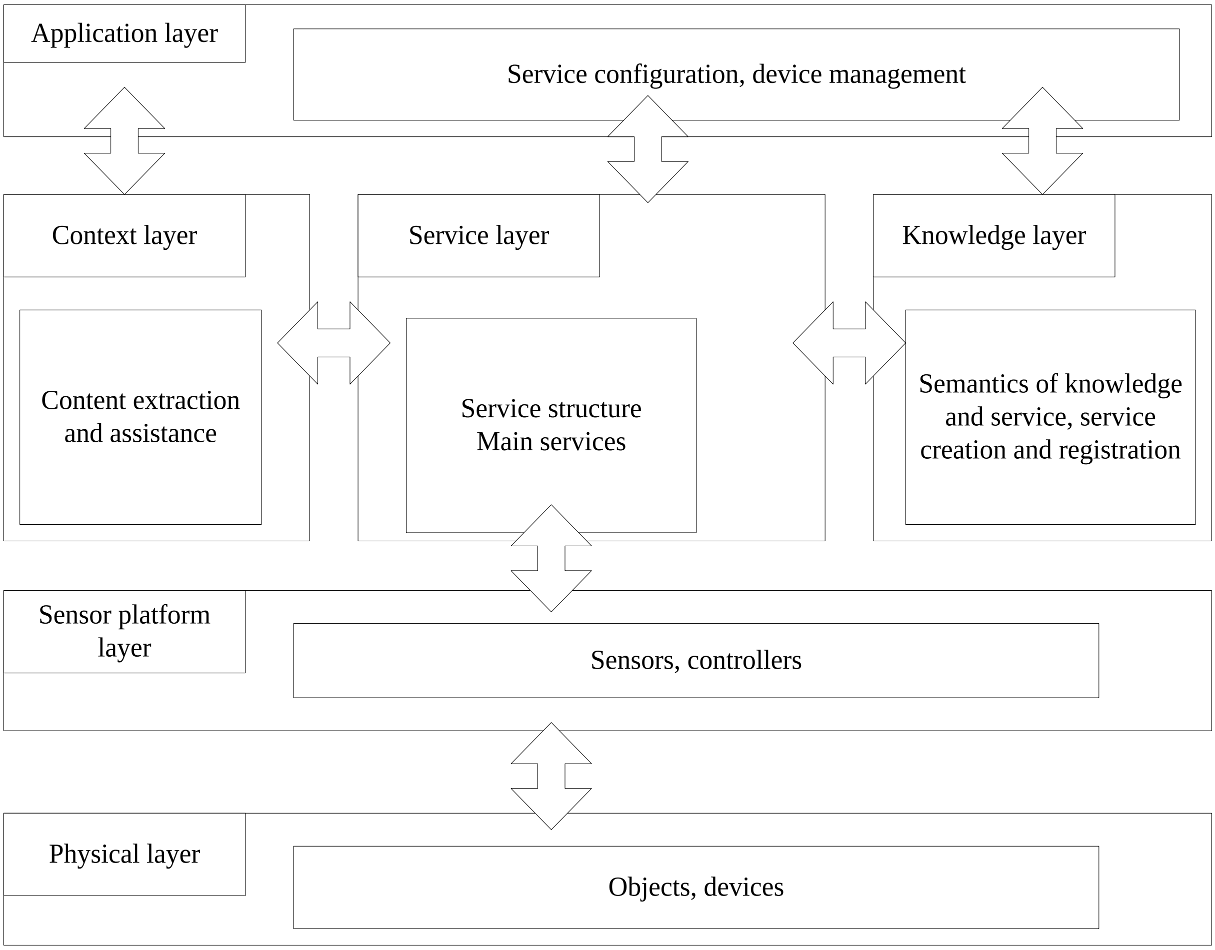
• sensors' platform level;

• service level;

• knowledge level;

• context management level;

• application level.



Source: compiled, according to (Helal S. et al. 2005, Naimavičienė J., 2008)

Fig. 1 Smart house infrastructure implementation levels

Physical level includes the embedded devices and other electronic components, facilitating the user's private life. Electronics, for example, lighting fixtures, heaters, etc. can be assigned to this level. At the sensors' platform level, the parameters are collected from environment. At sensors' platform, the sensors are connected to the network. The sensors platform is tied to the physical level. For example, considering the sensor data, the controllers respond by generating certain signal. The management level includes the services, provided in house. At knowledge level, information about the service structure and possibilities is described. This level assesses how the devices of the Internet of Things communicate with each other and what information is shared. At this level, information about what controllers and sensors enable the services in the smart house environment is stored. At the context level, it is described how the system should assess the environment condition, using defined user rules. This level is responsible to detect the unwanted condition and to attempt to restore the system to the predefined norms. At application level, the services are managed: turned on, off, configured. Various management and context view interfaces are created, in order the user would have connection with the surrounding services (Helal S. et al. 2005).

1.2 Energy consumption and data processing systems

This work develops the energy consumption data collection and processing system, allowing to forecast the needs and resources of the consumed energy. This system requires systematization of consumption data collection process. The small-scale embedded systems, adapted to read the physical power parameters and/or characterized by communication capabilities, are suitable for this task. In order to transmit the system data, sufficiently high speed (samples per second) should be ensured, considering that the power factor measurement requires measuring and collecting the data about power and current curves in real time (On Semiconductor, 2014).

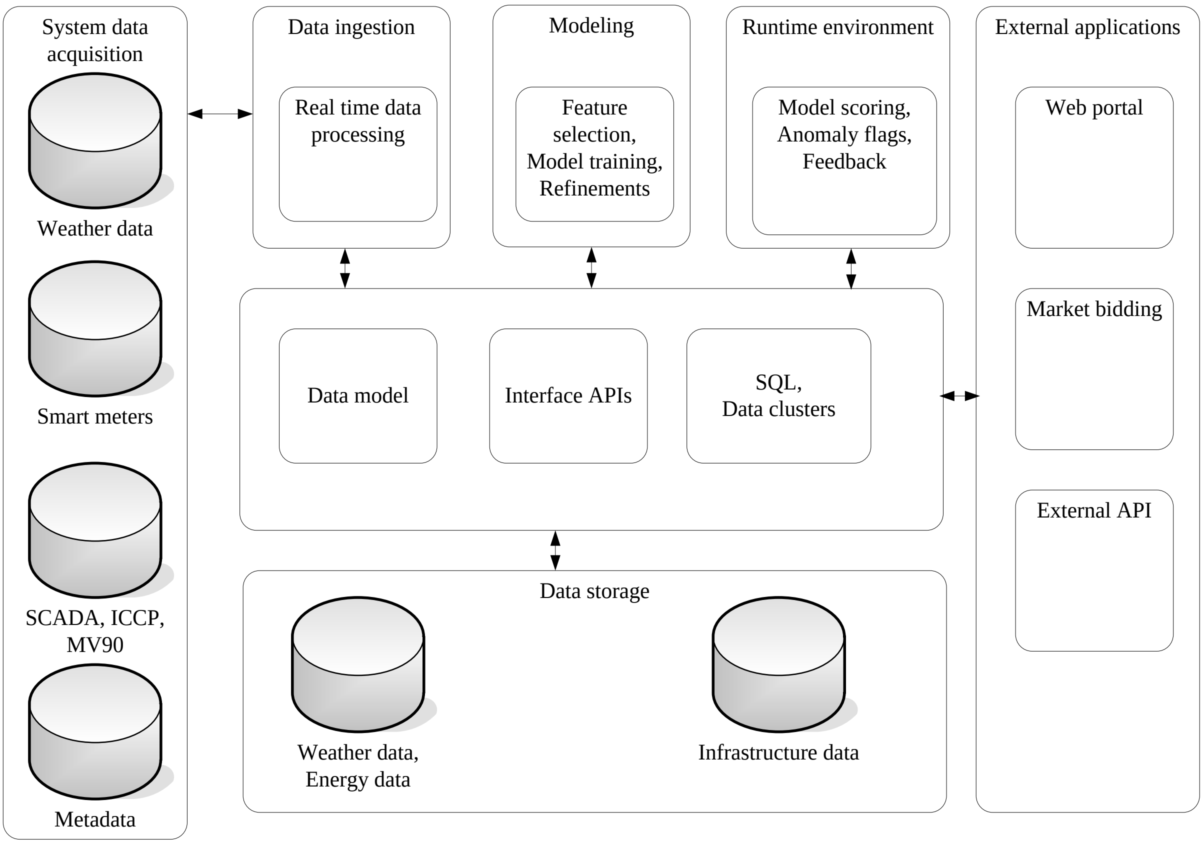
The main technologies of integrated management, consumed energy data collection and processing, enabling to forecast the energy needs, must communicate in heterogeneous network (Krawer et al. 2001). The energy consumption data are collected from the smart environment premises during experimental research. Energy consumption monitoring is performed with specialized equipment, which sends information to the web service database by standardized data protocols. SQL database is selected for data storage. The network nodes, responsible for collection of specific measurement data from specific premises, have access to electronic web service and are responsible for data integrity. The data obtained were used for energy consumption analysis and forecasting in the third part of this dissertation. During experiment, information is stored in real time, therefore, it is essential to prepare the proper structure of a relational database, adapted for analysis of large data arrays. Energy consumption analysis helps to find regularities between data records, for example, to look for regularities in time series. Data processing requires application of consumption forecasting methods and visualization (Koponen et al. 2012). It is sought to ensure the lowest measurement errors and high quality of the device control; therefore, the experimental research uses the smart digital energy meters, which microcontroller is connected to for data reading and data transmission to concentrator. Data collection network ensures data transmission and integration into the data processing system. Furthermore, it ensures consistency of data collection, since data are additionally stored on the primary data storage.

Real-time supervisory control and data acquisition systems – SCADA – are used in industry, manufacturing, energy, and other fields (GE Industrial, 2011; Rainys R., 2011). However, the functionality, proposed by these systems, is also suitable for the realization of the smart house solutions (Deshpande S. V. et al. 2014). Realizations that include monitoring (event capture), data concentration and control system functions might be found among the solutions, existing on the market (GE Industrial, 2011). The plan for sequence of task execution, used in the proposed systems, describes when and what actions must be performed by the system under certain conditions. The data, presented in the SCADA energy management systems, include the costs of production, therefore, these systems are widely used in industry for provision of services (GE Industrial, 2011).

The realizations of SCADA solutions do not provide the possibility to manage the energy of devices in smart house environment based on the results of energy consumption forecasting. The energy consumption forecasting of SCADA system is used to assess the consumption need, regardless the consumption details (uncontrolled household devices, device characteristics are not assessed) (Deshpande S. V. et al. 2014).

The solutions, proposed by the authors (Fusco F. et al. 2016), for energy data collection and analysis of consumption needs, examine the data model, defining the data to be collected and the method they must be described. The main feature of the proposed data model is to store various heterogeneous data in times series, on the database structure. The architecture (Fig. 2), proposed by the authors (Fusco F. et al. 2016), does not provide for possibility to fully automate the process to make the system run without human intervention (autonomously). SCADA systems do not have the possibility to create the algorithm during the system runtime, i.e., to define the command execution of the sensor network components from the remote device. Thus, this drawback of SCADA systems reduces the system dynamism.

The key component of the smart home energy monitoring systems is power measuring device (Fig. 5) as collection of physical power parameters determines the data accuracy (Elgama Sistemos, 2016; Neur IO, 2017). The energy consumption systems provide the possibility to collect the data of both each power outlet and an input meter. The system includes data storage and review functions. The monitoring systems, offered on the market, fail to define the feedback assessment and response realization (EnergyCurb, 2016; EnergyDetective, 2016). However, the realization could be possible by connecting the system to the Internet of Things, if API was prepared for the product (Sun Q. et al. 2016; ThingWorx, 2016). Power metering device (Fig. 5) consists of the power parameter (voltage, current, etc.) measuring sensors, which, seeking to connect the system to the Internet of Things, could be used as individual network nodes. Otherwise, the power meter is a complex network node for power measurement. The architecture, proposed in this work, allows realizing both communication versions (individual sensors for power parameters or a complex power meter), although the common systems on the market are not characterized by this capability (EnergyDetective, 2016; Neur IO, 2017).



Source: compiled, according to (Fusco F. et al. 2016)

Fig. 2 Architecture of the energy data collection and analysis system

Wireless power meters, designed for smart monitoring of each outlet of the house can increase the energy savings up to 12%, since it is possible to identify the specific point, where there is an electrical device (John A, et al. 2010). However, the case, when the system is autonomous and regulates the devices by using the energy consumption data, is not analysed (John A, et al. 2010; Bidgely, 2017).

Energy management can be focused on reading the energy, consumed by the user, in contrast to the above described architecture (Fig. 2) (Fusco et al. 2016). Then, not only monitoring, but also billing components are highlighted (Satec, 2015).

The proposed solution defines the concentrator devices of sensors. Other distinguished components of the energy management system architecture are related only with billing: automatic user report generating module, user accounting subsystem, technical service system. By using this architecture (Satec, 2015), it is possible to collect the monitoring data, however, it does not save energy in autonomous way, since evaluation of house devices and feedback from device control module is not provided for.

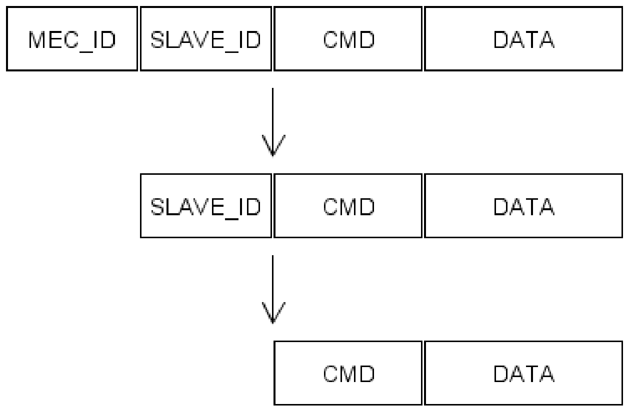
2 DEVELOPMENT OF WIRELESS SENSOR NETWORK APPLICATION LAYER AND DATA COMMUNICATION METHODS IN THE SMART HOME MANAGEMENT SYSTEM

While implementing the wireless sensor network communication, the standardized communication protocols are analysed, and functionality of the data link layer is expanded by developing the wireless network application layer for sensor communication.

The embedded systems of the home automation e-service system are characterized by the following communication features:

- Interface with user’s smart device (phone, tablet, etc.) or web access;
- Management with the system remote control to define the user rules;
- Communication with standard wired communication protocols;
- Interface with cloud technologies;
- Embedded realization of web service;
- Dynamic assignment of addresses or device connection.

When transmitting the data between the master and slave devices, the service data and application information are exchanged. The required data must be transmitted, to ensure the command interpretation, therefore, application layer data structure, that consist of command and parametric data, is developed (Fig. 3). Remote controller sends data over a network, where network structure is distributed by logical categories. For this reason, direct contact with an addressee is not always possible. Therefore, an additional identifier is required to define the logical category. Thus, each device is not addressed directly, and sensor data concentrator is responsible for data integrity.



Source: compiled by the author, according to recommendations of the standardized protocols (Heile B. et al. 2015)

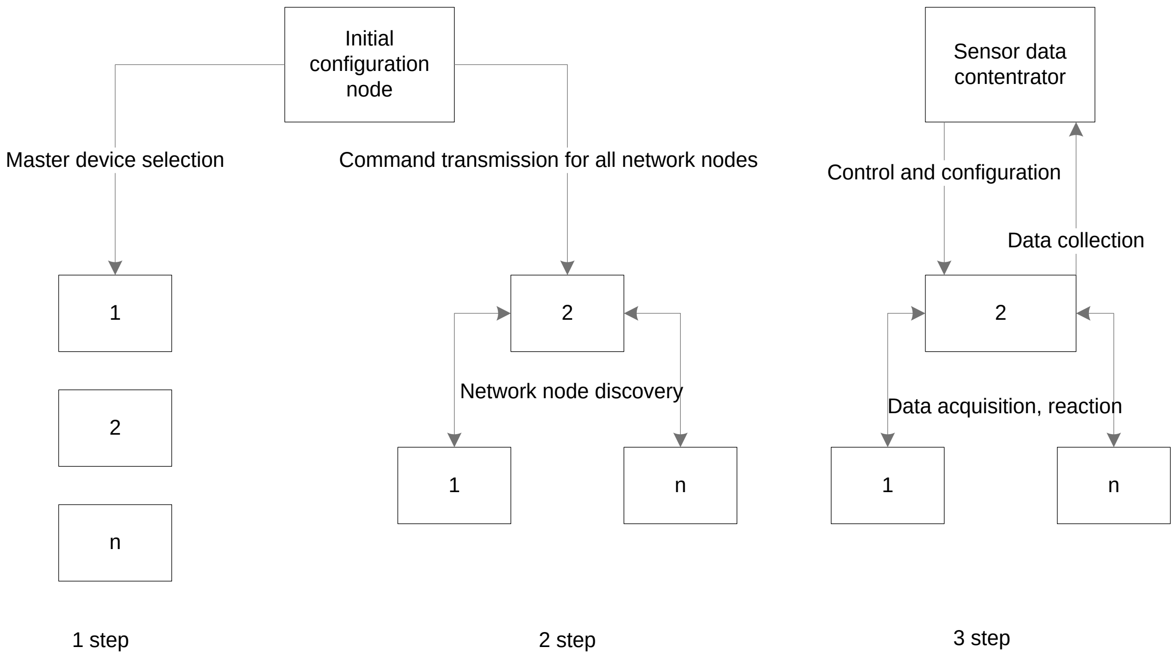
Fig. 3 Structure of the command of the master device to manage the connected devices (sensors, controllers)

Seeking to develop the network, where all devices could run in an autonomous manner, this dissertation proposes to make the embedded service network in three steps during device runtime:

1) Selection of the master device;
2) Forwarding the commands to all nodes, search for network nodes;
3) Management and configuration, data storage.

Before developing the network, the following device groups could be identified: smart sensors and controllers, primary configuration node and sensor data concentrator. The primary configuration node may be any device, able to communicate with smart sensors and controllers, for example, a computer with terminal capability. The purpose of this configuration node is to make the real-time data exchange network.

Interconnection of the embedded systems into autonomous network is shown in Figure 4. The first step is selection of the master device for management of the remaining slave devices. Several master devices can be selected, if slave devices can make a logical or physical group of hardware. In step 2, command queues are sent through the master device to all network nodes (including the master device itself). As the command queue is confirmed, it is executed in an autonomous manner, and the primary configuration node does not take part in the network – each device executes real-time commands.



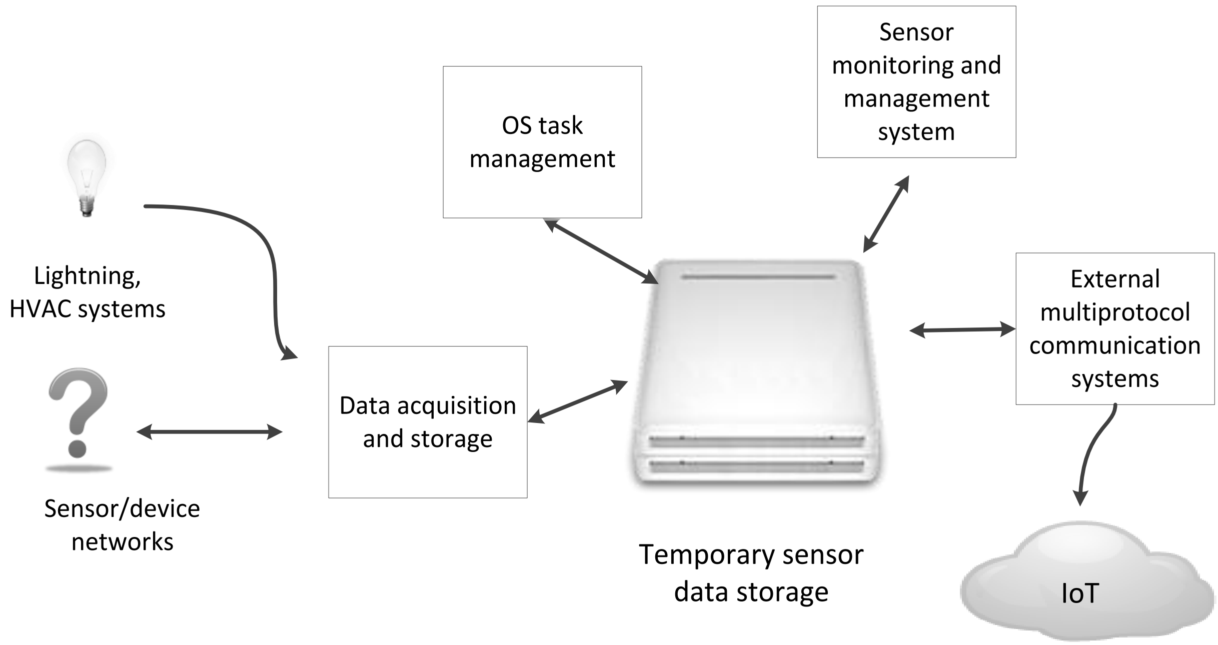
Source: compiled by the author, according to the network application layer, proposed in the dissertation

Fig. 4 Structure of combining the embedded devices into autonomous wireless network

Network reconfiguration is required to change the purpose of sensors and controllers (i.e., to send a new command queue), for example, by adding new functions for data processing. However, as the system functions in an autonomous manner, command management can also be reconfigured after initial configuration. It might be done when the system must respond to the changed environmental conditions. In this case, the command parameters will be transmitted from the management analysis module with the aim to process the feedback upon getting the response from the considered environment.

3 DESIGN AND INTEGRATION OF THE AUTONOMOUS ENERGY MANAGEMENT SUBSYSTEM IN THE SMART HOUSE E-SERVICE SYSTEM

The chapter presents the general architecture of the subsystem and gives detailed description of the individual parts of the energy management subsystem. Individual structure is described in detail for each component, and its operation in the general structure is defined. What is more, the decision support system and decision-making methods for management of the energy consuming devices are described.



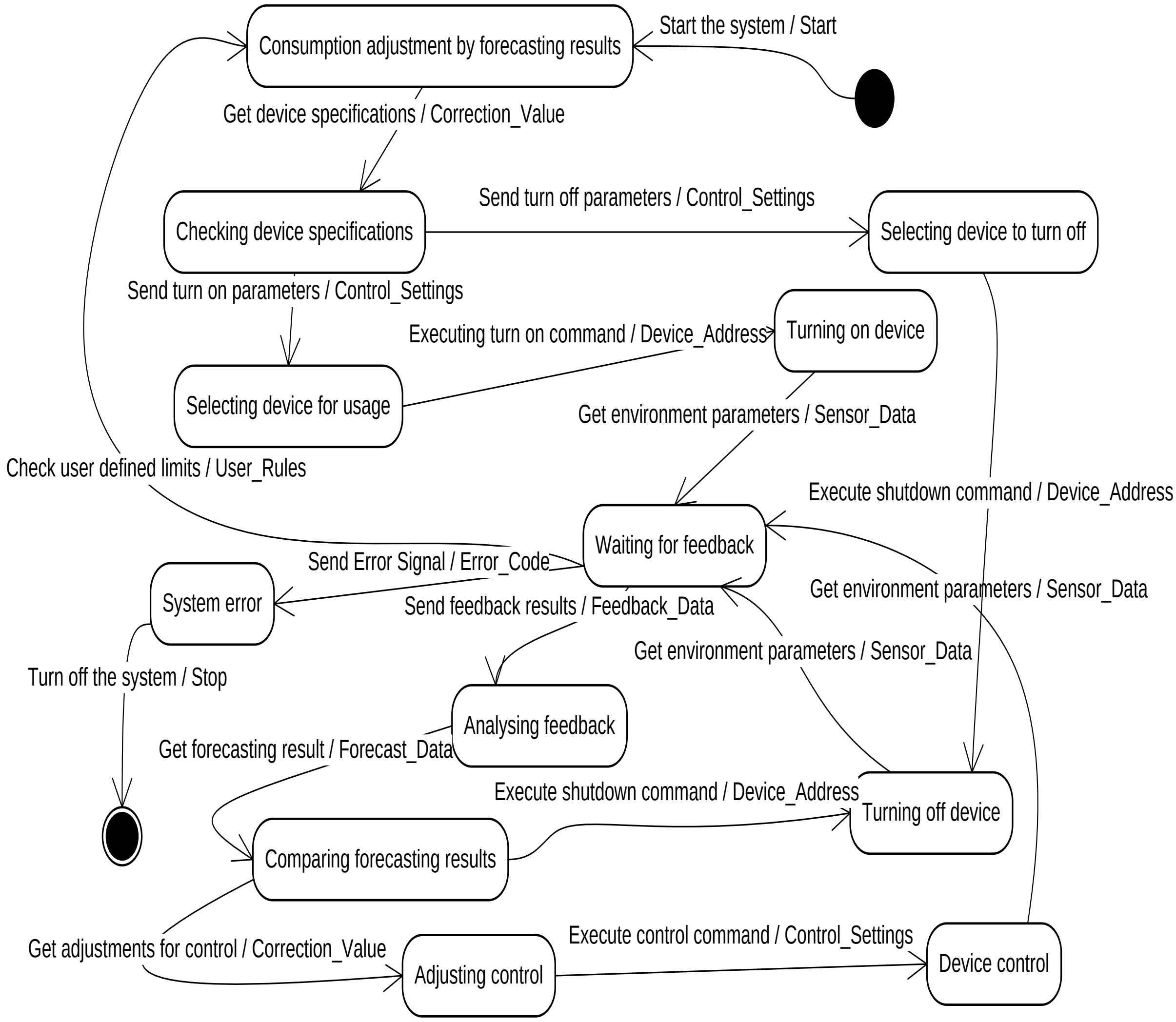
Source: compiled by the author.

Fig. 5 Sensor concentrator

The energy consumption monitoring subsystem consists of the sensors, which collect data about the energy consuming devices. The purpose of the smart object/ sensor – to collect the required data from the environment and turn them to the structured digital information (Alipp et al. 2006; Jiang et al. 2010; Sabit et al. 2012). It includes the primary storage, data filtering subsystem, as well as communication with data concentrator. In the designed system, the sensors are used to identify the energy consumption by power devices and to forecast the energy consumption. This work analyses the architecture of the energy consumption management system, covering the following processes: from reading the environment parameters to responding to environment by making autonomous management decisions.

3.1 Decision-making methods and decision support system

To automatically identify and correct the system status, this work uses the formalism, based on the Mealy finite-state machine (Fig. 6). Its statuses – possible situations, arising in the system, and the received decision-making variants, where the transitions between statuses show the transition to another decision making. In case environmental conditions change or fail to meet the user rules, different decision can be made. Thus, by describing the device management module, the power device can be controlled in a dynamically autonomous way.

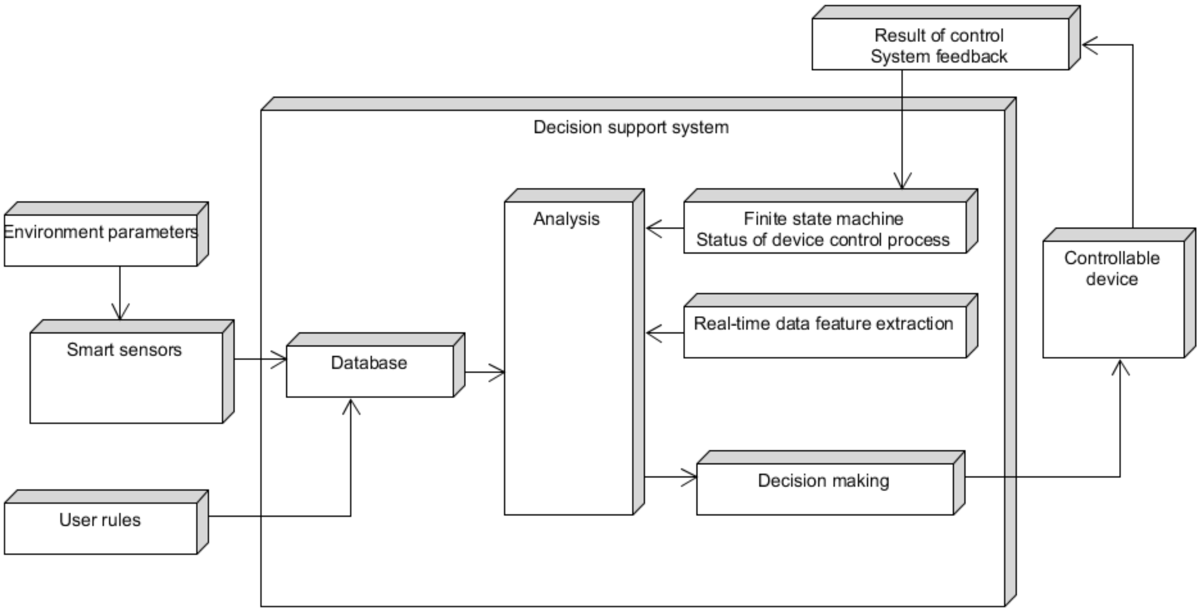


Source: compiled by the author, according to energy management DSS (Sicilia A. et al. 2015)

Fig. 6 Finite-state machine of the energy management decision support system

Realization of the decision support system with managed configuration is characterized by the fact that the sequence of actions can be managed by using the user-described rules and technical, as well as logical limitations of e-services. To define real-time configuration dynamically, it is necessary to assess the following parameters of specific sensor: minimum value, maximum value, mean value, and target result(s).

The described structure of the decision support system (Fig. 7) might be integrated in the e-service environment of the embedded system to solve various type of tasks, for example, to save the house energy consumption or to reduce vehicle fuel consumption.



Source: compiled by the author.

Fig. 7 Structural scheme of energy management decision support system

The decision support system is a part of e-service system and is analysed in this work by adapting the decisions made to save consumption and ensure comfort. When the system is used with the forecasting results, the decisions might have several uses:

- Decisions are made subject to forecasting results;
- Decisions are made upon prompt assessment of situation, i.e., without assessing the forecasting data.

The self-regulated finite-state machine for model configuration is implemented in the core of the microcontroller embedded systems and ported to the higher-level programming language management subsystem, which is adapted to ensure autonomous operation of the system. Seeking to make the energy management decision, the following methods might be followed:

- Management command is performed, according to historical data,
- Management command is performed upon making comparison with neighbour (sensors, controllers) data,
- At random decision, according to normalized data.

Management command, performed, according to historical data, presents decision on the basis of collected data, and follows the user rules on how to manage the system correctly. In case of comparison of neighbours, the made decision is specified considering the data from other, similarly functioning systems, for example, from those, installed in another smart house. Finally, the random decision is based on the consumption value of the controlled device, and can be used without historical data, however, it is most dependent on instantaneous management result. The decision is adjusted in real time based on the obtained result. Random decision requires that the system response would be received in real time and fast (insufficient time for forecasting analysis), therefore, the status of forecasting feedback analysis is impossible.

In the architecture of the energy consumption management system, it is essential to determine how data transmission will be managed, how management decision will be executed, and what response will be received from the system to confirm the management decisions. For this purpose, the task, management, and analysis modules are proposed.

3.1.1 Artificial lighting management subsystem

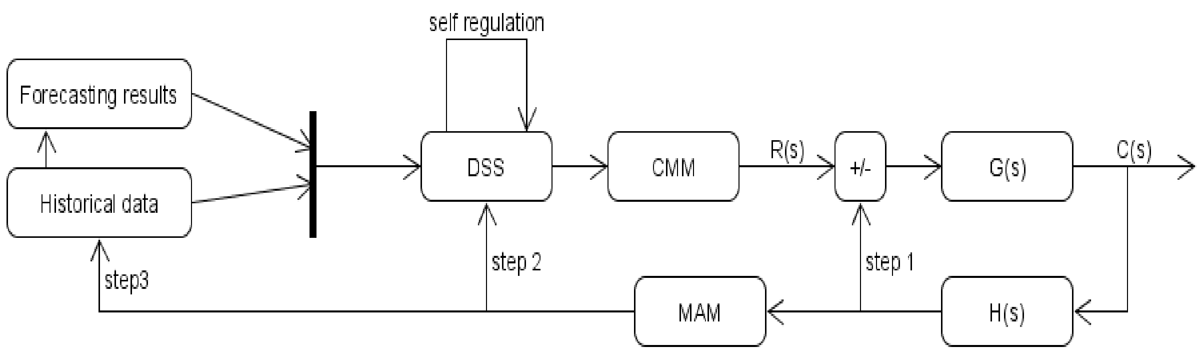
Lighting in human environment must meet the defined norm. Otherwise, the comfort problems as eye fatigue or eye irritation are faced (Azmoon et al. 2013; Bielskis et al. 2013; Quarto et al. 2011; Zanoli et al. 2012). Smart e-service system must include the lighting control subsystem, which would be able to provide the lighting management services by ensuring comfort with lowest energy consumption. In human environment, lighting can be described by various modules. For example, the case when human environment is limited, e.g., one room, can be considered; in this case, lighting depends not only on artificial light source, but also on natural illumination of the room in specific space point $E_a(P)$. To study the model (Zanoli et al. 2012), the software, able to capture lighting in the specified points, perform lighting measurement and adjust the lighting of artificial light source was developed.

$$E_a(P) = \sum_{j=1}^{2}\left[\left|C_{c_j}\cdot E_{(ND_{gl})_j} + C_{r_j}\cdot E_{(NR_{gl})_j}\right| + \frac{\tau_j + V_j\cdot A_{gl_j}\cdot \sigma_{weighted}}{sum_{AREA}\cdot(1-\sigma_{weighted})}\cdot E_{NAT_{gl_j}}\right] + \frac{I_L\frac{Lumen}{1000}\cos(\gamma)^3}{d^2} + \frac{Lumen\cdot\eta\cdot M\cdot P}{Sum_{AREA}\cdot(1-\sigma_{weighted})}$$

Where $E_a(P)$ – environment lighting at the considered point $P(x,y,z)$ (lx), $E(ND_{gl})_j$ – natural diffusion lighting through window (lx), $E(NR_{gl})_j$ – natural window-reflected lighting in window (lx), $E(NAT_{gl})_j$ – natural direct lighting through window (lx), C_{mc}/C_{mr} – diffusion and reflection illumination at the point $P(x,y,z)$ (lx), I_L – artificial illumination source (*cd/klm*), *Lumen* – light flow (*lm*), γ – light radiation incidence angle *P(x,y,z)* (°C), d – distance between lighting source and considered point (*m*), $\sigma_{weighted}$ – wall reflection coefficient, sum_{area} – total area of reflecting walls (m^2), η – light source efficiency, M – environment maintenance factor.

3.1.2 Three-step feedback system

Usual feedback solution is made of input R(s), direct route G(s), feedback route H(s) and output Y(s) (MatLab, 2016). More precise management takes place when input is as close as possible to the output: $R(s) - Y(s) < \varepsilon$. Here ε is an estimate of error. Upon adapting the solution to control the devices in the energy management system, the data communication between command management module (CMM) and usual feedback mechanism input R(s) appears. MAM – management analysis module.



Source: compiled by the author.

Fig. 8 Structure of three-step feedback

Upon adapting the feedback management structure (Fig. 8), the decision support system parameters can be adjusted, to find out more specific solution. In the third step, the correction values are transmitted to the web service database and entered in corresponding historical data records. Second and third steps are management through the management analysis module (MAM), designed to analyse the output of the decision made.

3.1.3 Power monitoring and management system modules

If the smart house management architecture is analysed in practice, regardless the software and hardware, it might be stated that the monitoring and management systems are similar. The system focuses on the user. It is a person, located in the smart environment and receiving services, seeking to get more comfort, to achieve effective energy consumption (fig. 9). The house parameters, collected by environment, are the technical characteristics, which include smart objects with the integrated sensors and controllers that are characterized by the impact on the system outputs. Furthermore, the knowledge base uses the smart object layout, house dimensions, and other parameters, which also can be included to make a more precise decision. Environment, i.e., smart house, monitoring – real-time measurements, received from the environment at certain time interval. The user may introduce the device usage, budget restrictions, as well as to specify the desired level of comfort.

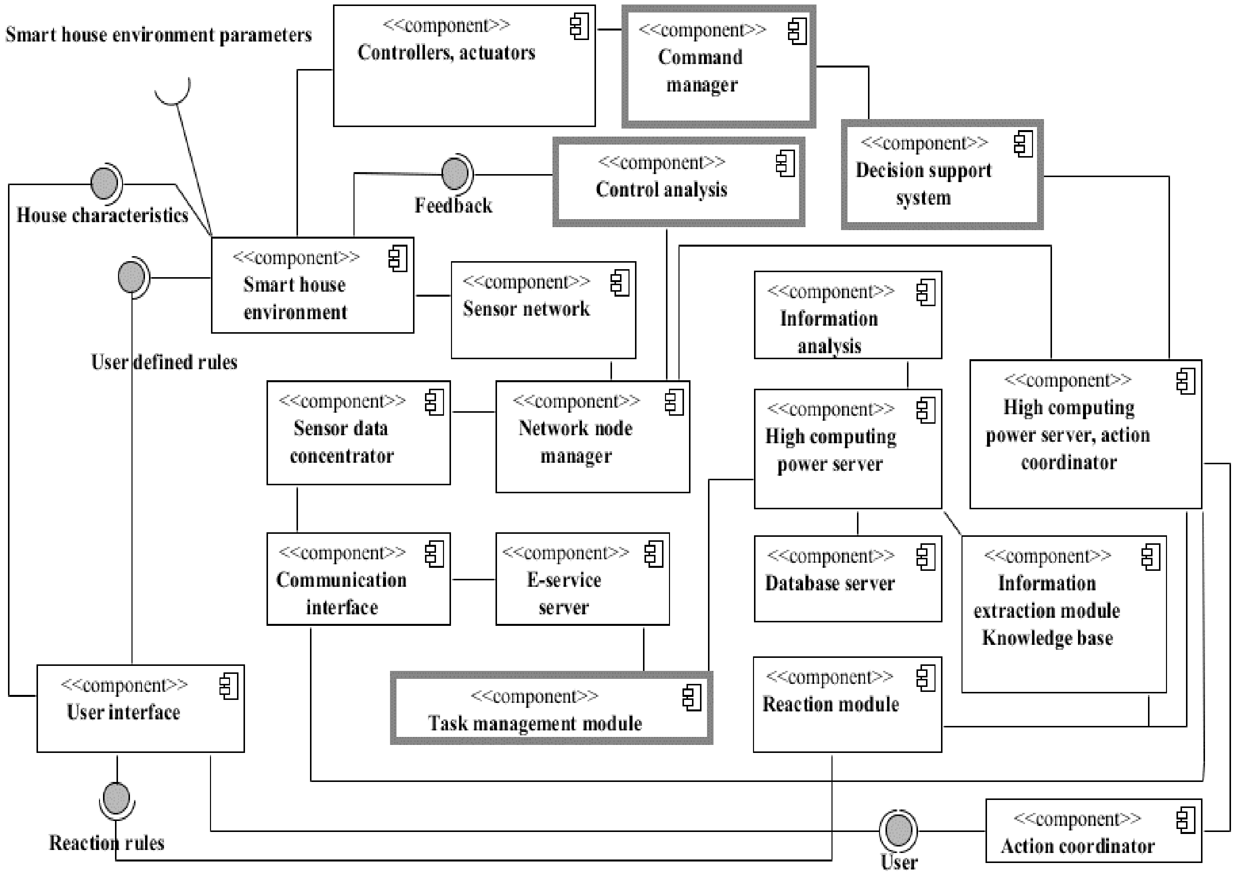
The user rules are made by assessing each monitoring. Importantly, user rules are defined upon assessing each monitoring. While assessing, fuzzy logic is followed. It should be noted that smart e-environment is the place, where monitoring, measuring takes place, and where the system response, selected according to real-time parameters (situation), is received. Monitoring task is executed by using the sensor networks – small-scale embedded systems, dedicated for measuring or instantaneous observations. These small-scale systems are connected, according to their position in the space, physical address of network node, following the logical structure. Their data are collected by network node controller, coordinator – dedicated to ensure that the sensor network would be effective. This device monitors the sensor network, manages the data streams. Sensor data concentrator is an intermediate primary data storage point between the node controller and communication interface. Its purpose is to ensure the data storage until sending them to the web services. As data are concentrated, they must be transmitted through gateway – embedded system network and cloud technology service gateway (router). The data from concentrator go to the web service – cloud technology-based service system, dedicated for servicing the clients of the energy management system. Seeking to ensure sufficient data bandwidth in the network, the task management module could be used. It is flow controller, coordinator of network tasks. Importantly, it prioritizes and makes the task queues to ensure the uninterrupted customer data communication.

In case of large data quantities from sensor networks and when the forecasting algorithms are used, a high-performance computing device – computer – is required. Computer should have the capability to use information analysis software: statistical tools, mathematical environments, and other computational tools (DB server, recognition algorithms). Information is analysed in the module, which uses statistical tools, mathematical computing environments, and other computing software. The module for information extraction from the data, the knowledge base is used in the energy management subsystem, where it extracts the required information to make decisions for more efficient energy consumption.

The main data storage – database server, where the service database is stored. This database stores not only the data from sensor networks, but also the future forecasting results.

Response module determines the conditions for response to the energy consumption analysis results with the possibility to select the response method. Furthermore, this module is responsible for transmission of the extracted information for automatic energy consumption management. The response module parses the user-defined response rules. These must describe the conditions and actions these conditions must be responded to. In fact, the e-service management architecture requires high-performance embedded system, action coordinator – communication node for information collection from response module, dedicated for coordination of actions (from response module, action controller). Seeking to make an autonomous decision for device management, the knowledge-based decision support system is employed. Its parameters and information from the energy consumption results allows to programmatically consider the specific instantaneous scenario of device and energy consumption management. The device management is carried out in the command management module –embedded system – when the module receives the result from the decision support system, which specifies the method and measures to achieve the required consumption regulation. For controlling environment e-services, various devices are used: digital signal, PWM controllers, relay based controllers – technical equipment that receives interpreted commands from the command management module (Song et al. 2008). While managing the environment parameters, feedback – object management monitoring – is received, which is transmitted to the management analysis module.

The management analysis module ensures a fast response (without web service and high-performance analysis servers) to the feedback. By using this module, unforeseen situations may be avoided. In case of unforeseen situations, information about scenario can be transmitted to the sophisticated embedded system, action coordinator with the aim to specify the analysis and forecasting algorithms.



Source: compiled by the author.

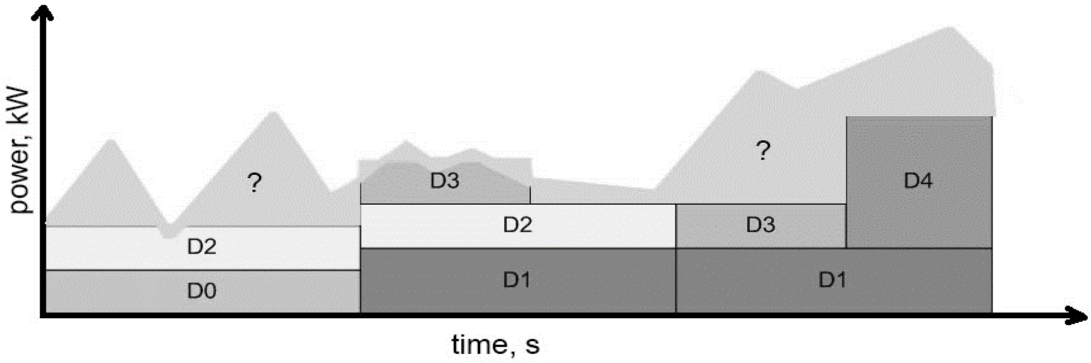
Fig. 9 Energy monitoring and decision support system

4 THE RESULTS OF EXPERIMENTAL RESEARCH OF THE AUTONOMOUS ENERGY MANAGEMENT SYSTEM

The instantaneous values of dynamic process monitoring data can be obtained at different time or in different locations. ARMA models can be applied for analysis of time series and data forecasting. ARMA model includes two parts: the main principle is to combine autoregressive and moving average models. Autoregressive process explains new data based on previous monitoring data. The process of moving average explains the time series monitoring by using Y_t model errors.

Kalman filter is a powerful tool for managing the noisy systems and is widely used to predict, control the object trajectory, to alert about collisions, in image processing, sensor fusion, and other fields. Furthermore, this filter is used for forecasting tasks in various fields (Long J. et al. 2012; Xie Y. et al. 2007).

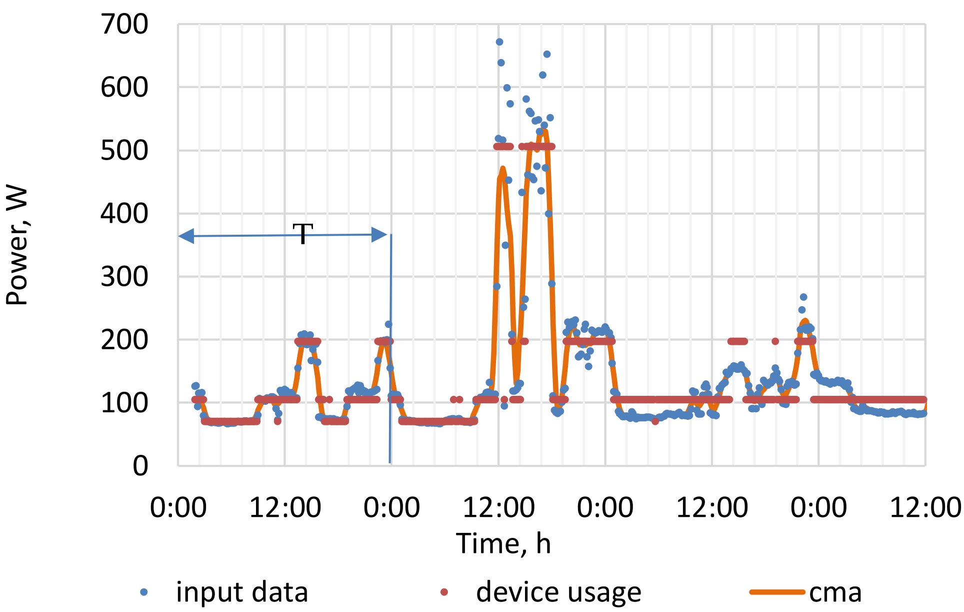
Subject to the plan of device usage, the device schedule plan (Fig. 10) can be made. This plan can be adapted to the forecasting algorithms not only for energy data, but also for other type of tasks (traffic calculation, fuel consumption calculation). Importantly, algorithms can be used for energy consumption and generation forecasting, when the energy is generated not only by electrical power grids, but also by different alternative sources of energy: solar, wind, geothermal energy. While analysing the management of power devices in the energy management system, it is essential to consider the fact that it is impossible to forecast the usage and consumption of all devices. In this case, the use of resources can be divided into deterministic D[n] and non-deterministic, marked as “?”.



Source: compiled by the author.

Fig. 10 Non-deterministic input

By using the algorithms, described in this work, it is possible to develop the energy consumption and data processing system, ensuring the energy need and consumption forecasting (Žulkas et al. 2015).

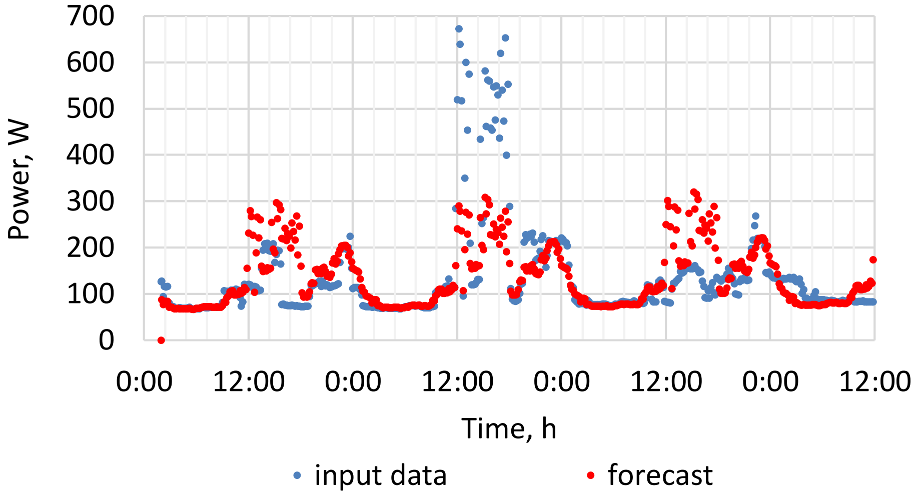


Source: compiled by the author.

Fig. 11 Device schedule plan and real energy consumption

Here: input data – consumption data, device usage – device schedule plan data, cma – centered moving average.

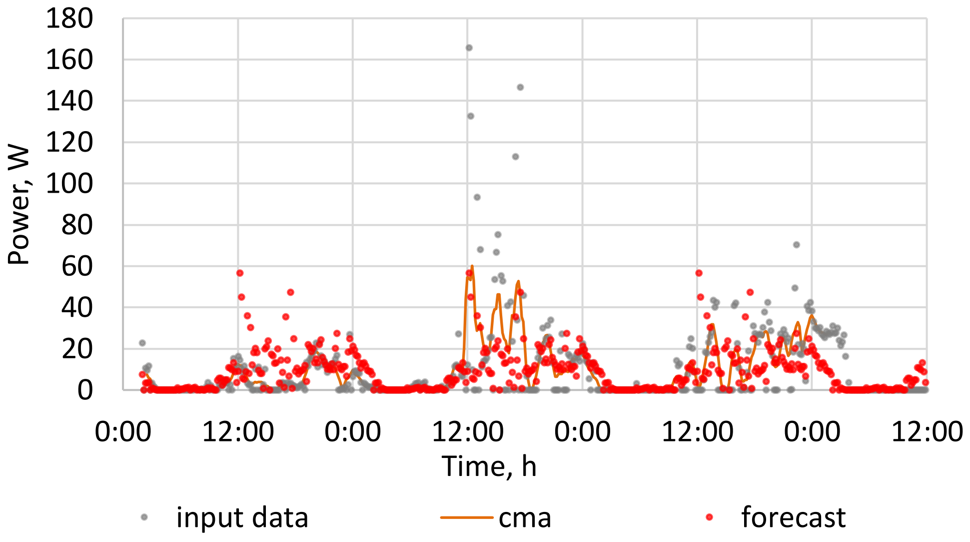
The data was collected each 1s. However, the analysis uses the averages of 10 minutes. The quantification period of 1 day was selected. One period included 144 average values for 10 minute intervals ($\Delta t = 10$). 6 averages are obtained each hour. Upon assessing the data monitoring scale, it might be stated that forecasting should be performed not further than one period ahead – in case of T. Monitoring, the values of time series will consist of deterministic and stochastic parts. Device schedule plan and real-time measured energy consumption (Fig. 12).



Source: compiled by the author.

Fig. 12 Forecasting with ARMA model

Two different tests were performed with ARMA model: Fig. 12 – forecasting by using only energy consumption data; Fig. 13 – forecasting, which depends on the device schedule plan.

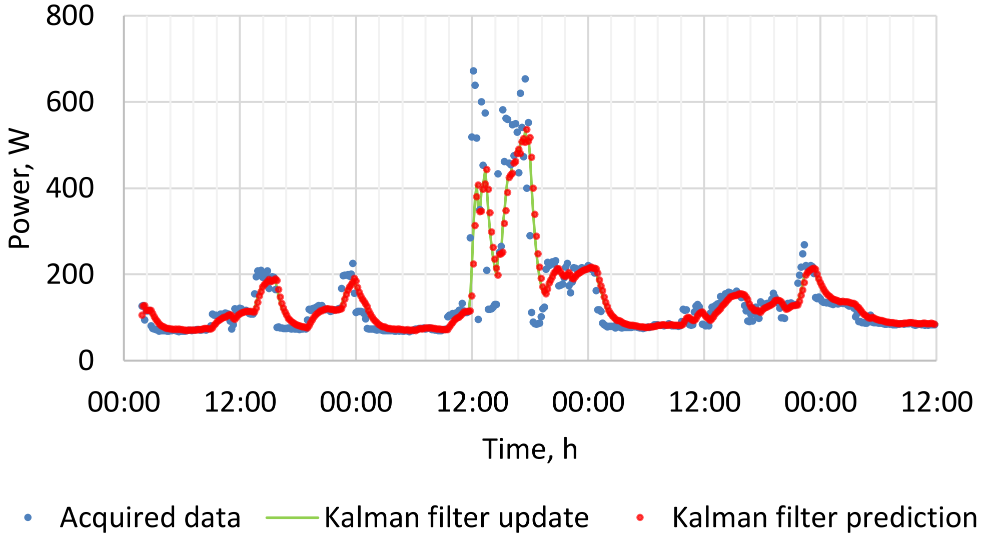


Source: compiled by the author.

Fig. 13 Forecasting with ARMA model by applying the device schedule plan

Input data – consumption data, cma – centered moving average, forecast – forecast data

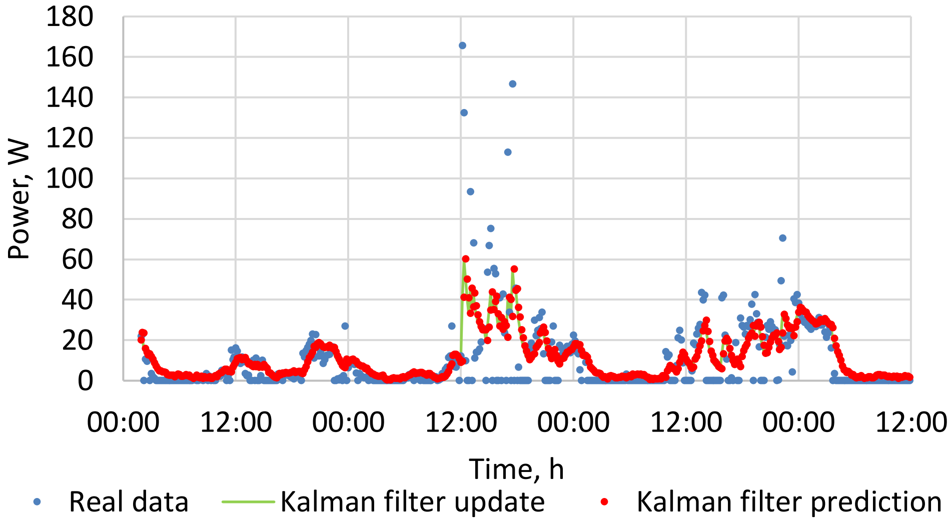
Monitoring data are normalized, when the device schedule plan is applied. The values used are higher than the average device consumption, assuming that the energy consumption will be equal or higher than the measured average. Newly obtained values are equal to the difference between the actual monitoring values and average consumption of the device. The results of Kalman filter experiments are shown in Figure 14 and 15.



Source: compiled by the author.

Fig. 14 Forecasting with Kalman filter

Figure 15 demonstrates the forecasting by using differences between energy consumption and device schedule plan.



Source: compiled by the author.

Fig. 15 Forecasting with Kalman filter by using the device schedule plan

The root mean square (RMS) value is used to summarize the forecasting results.

RMS value for the energy consumption data in the space of time is the square root of distance of all observations from the sum of forecasting squares. If there are n observations, RMS formula for observations $\{x_1, x_2, \dots, x_n\}$ can be expressed as:

$$x_{rms} = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + \cdots + x_n^2)}$$

Additional estimate was calculated, in order to obtain the average percentage distance between real points x_i and values of the device schedule plan p_i on the same time moment:

$$E_d = \frac{1}{n}\sum_{i=1}^{n}\frac{|x_i - p_i|}{\max(x_i, p_i)}$$

4.1 The results of Kalman filter and ARMA model

The results, obtained by using different forecasting algorithms, are given in Table 1.

Table 1: Energy consumption forecasting results

	ARMA	ARMA + plan	Kalman filter		Kalman filter + plan	
			Forecasting	Update	Forecasting	Update
RMS	84,534	29,251	62,115	49,681	31,537	29,267
E_d	0,203	0,120	0,031	0,113	0,114	0,106

The higher the RMS value or percentage distance E_d, the lower the forecasting accuracy.

Kalman filter and ARMA model for forecasting tasks may be applied in different situations as algorithms have different advantages and disadvantages. Kalman filter is better for modelling the current data, however, forecasting is limited to the one sample to future (Δt). Meanwhile, ARMA model reflects the features and seasonality of the regression curve. Furthermore, forecasting can be implemented for one period T ahead (in contrast to forecasting with Kalman filter). However, ARMA model has stricter requirements for the time series (requirement of being stationary), therefore, algorithm adaptation is limited.

4.2 Summarization of training and neural networks of the system

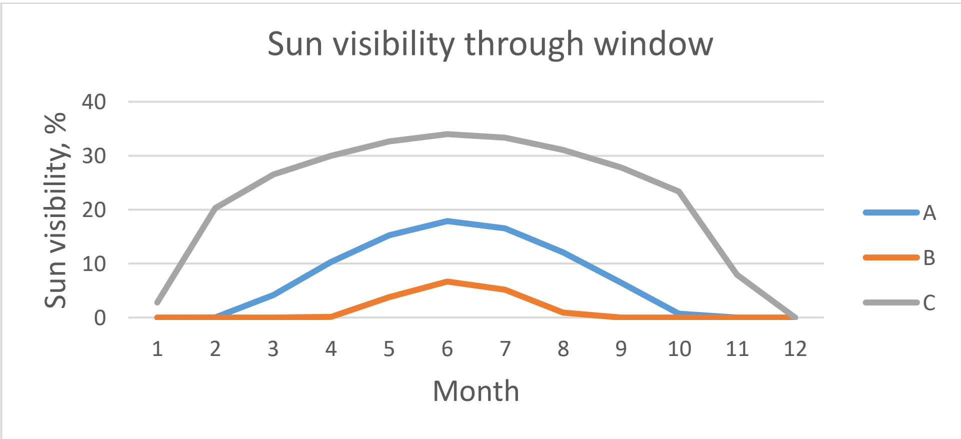
Unlike ARMA and Kalman filter, neural networks are based on nonlinear algorithms and artificial intelligence. Subject to the selected neural network and data frequency characteristics, the corresponding forecasting result may be different, therefore, it is hard to obtain a strict error estimate. Each time, the trained network has new weights and shifts.

Assessment and forecasting of energy consumption with neural networks and ARMA model is possible with historical data storage and module for information extraction from the data, which requires high-performance computing hardware. Otherwise, the quantities of processed data are limited.

4.3 Assessment of solar illumination in the energy management system

The sun position behind the window is assessed as the ball in two-dimensional space, however, the window slope influences the system configuration, while obtaining the data about sun position. The lighting model can also assess the window diffusion and wall reflection parameters. If the window is sloped, it is necessary to adjust the system and assess this slope in degrees relative to the floor. What is more, it is essential to consider the angle between the analysed environment point and the source of natural light.

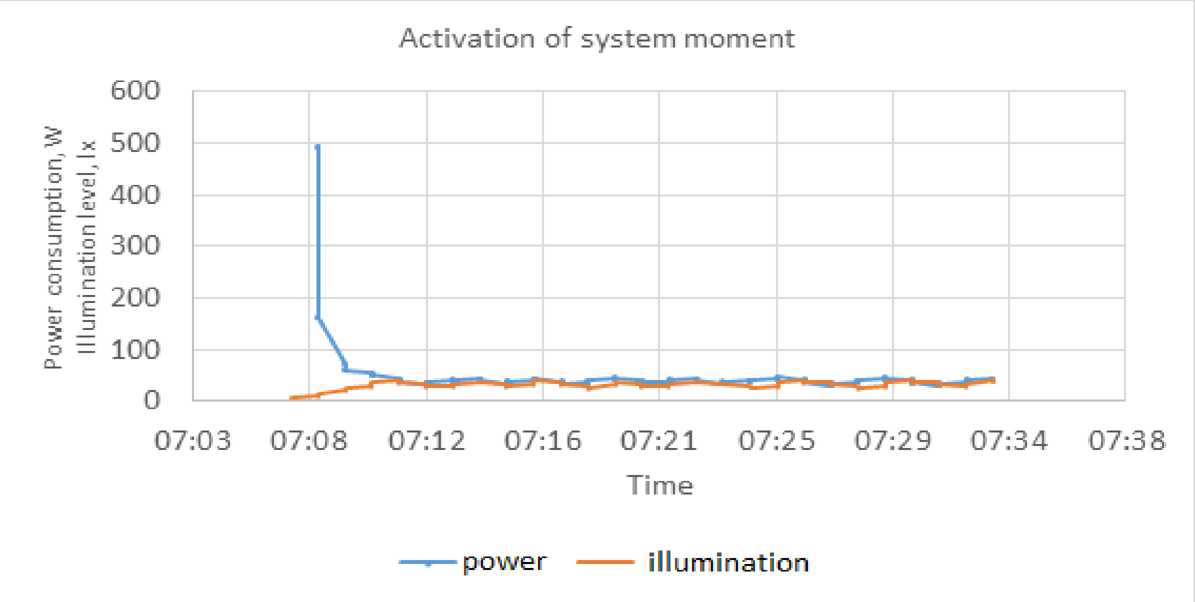
The sun position is calculated for specific coordinates and specific point in environment. The method for sun position calculation has the following parameters: examined date, in coordinates 55.7000 latitude, 21.1306 longitude, to calculate sun position, when the window area is defined in degrees from the north direction, and the altitude is defined in the vertical line. When visibility is blocked by other objects, the window is considered as the visible part of the window by crossing the invisible areas with vertical and horizontal curves. One of the results, obtained, while calculating the sunlight visibility, when the visibility is blocked by objects of different sizes A, B and C, is given in Fig. 16.



Source: compiled by the author.

Fig. 16 Sun visibility through window over a month

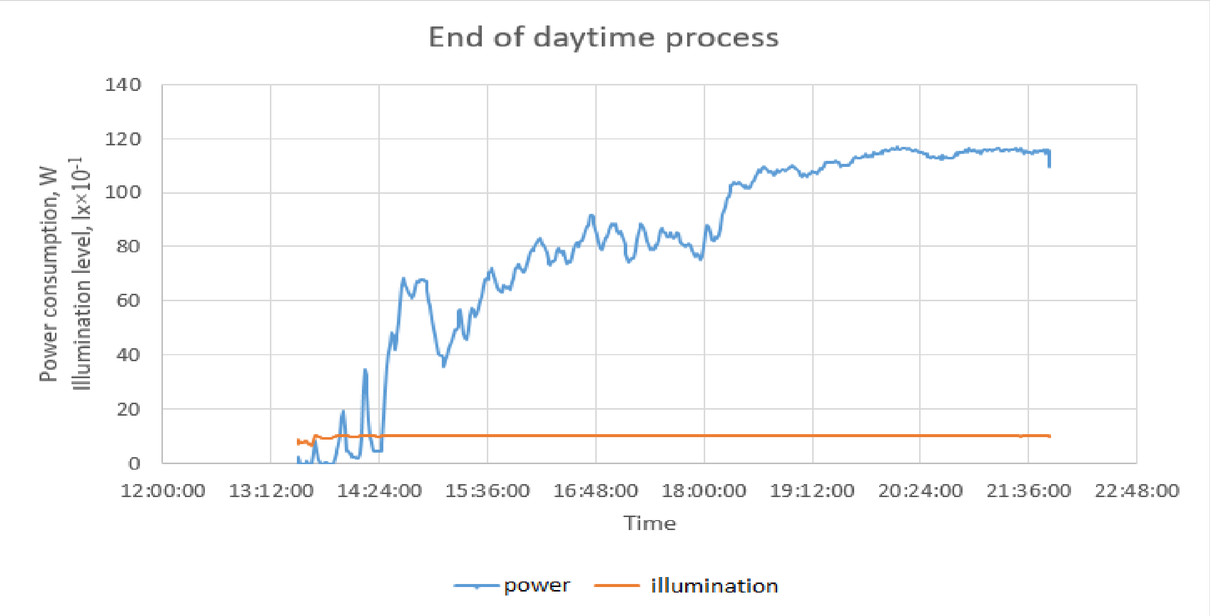
The prototype of the energy consumption management system was tested under real conditions. Figure 18 presents the process, when the system starts operating. The graph depicts time as mm:ss (minute:second). First, the system captures a completely dark environment, however, lighting is stabilized at the same time. If upon turning on the lighting subsystem, it becomes clear that it is too light, the system performs automatic balancing until minimum power is found to ensure the required comfort level.



Source: compiled by the author.

Fig. 17 Activation of the energy system prototype

During the process of the end of the daytime, it is visible that the system usage power increases gradually. Time in axis x is given as HH:mm:ss (hour:minute:second).



Source: compiled by the author.

Fig. 18 Monitoring the process of the end of the daytime and autonomous management of illuminator

The system captures a few jumps, which are visible, while analysing the mean values. This data section (Fig. 18) presents the average values of a minute.

Lighting is stable over time, however, high deviations in the power system indicate that natural lighting changes dynamically behind the window. Therefore, when the system runs only on the basis of the task schedule, these jumps will not be taken into account in advance. Seeking to assess them, the cloudiness forecasting algorithms should be realized in the system.

4.4 The features and possible improvement of the energy management system architecture

The architecture of the proposed autonomous energy management system allows not only to collect the environment parameters data, to perform analysis, but also to manage the service devices, and receive feedback. The features of this system are summarized in Figure 19.

Efficiency	To improve energy consumption forecasting accuracy, a task schedule plan was proposed, which is integrated to statistical mathematical and non-linear forecast methods. System provides a feedback communication, to evaluate when system control does not match required consumption. In such case system can adjust control decisions.
Control and automation	Developed interpreting mechanism for sensor networks enables to describe a device purpose during system runtime. Decision making system controls devices in the network autonomously, by using history and forecast data. Command control and interpretation is executed in embedded systems, which allows to control device energy consumption by evaluating power coefficient.
Communication	Network application layer was developed to enable mobile and adaptive network topology. This layer accepts various types of sensor data, so that one system can collect single and multidimensional environmental data.

Source: compiled by the author.

Fig. 19 Features of ECMS architecture

With the precise sun visibility forecasting (considering the cloudiness), it is possible to supplement the existing database and decision support system to be able to assess the need of lighting, when sun position and cloudiness schedule parameters are forecasted and real-time checked, seeking to verify the results of the later forecast. By using these parameters, it would be possible to correct the natural lighting forecasting model.

The system has not been tested, however, it is adapted to operate, when a fast response to the changing dynamic environment characteristics is required. However, it is hard to find or make these conditions in smart house. Thus, the aforementioned system function could be experimentally used and examined in mobile vehicles based on power energy or other resources (e.g., piloted and non-piloted, and road vehicles).

GENERAL CONCLUSIONS

1) The solutions and technologies offered by other authors for the management of smart home energy resources was systematized and main components of the energy consumption management system were described.
   a) Existing electrical energy consumption management systems do not integrate household appliance management, according to the electricity cost forecast with the goal of autonomously managing the smart housing environment.
   b) IoT platforms cover only part of the components intended for the autonomous management of electricity consumption: only the communication between the devices is defined and the feedback from the system after the acquisition of the monitoring data is offered.
   c) The solutions developed focus on the billing of electricity, but the analysis components remain non-automated.
2) When designing autonomous home energy management system, remote access, data analysis, and environmental response to events must be ensured by using the technological capabilities of the Internet of Things and the mobile adaptive network topology. This work proposes to use the mesh topology communication network in power management systems, adapting to the mobility characteristics of the network for embedded system.
3) The proposed network application layer allows to define the purpose of the device at runtime. Creation a hardware solution is independent from installation. Configuration of the embedded devices and controllers in a smart environment is implemented ad hoc. The author's proposed sensor network devices are configurable during runtime. This ensures not only a mobile but also a real-time adaptive network topology.
4) Energy resource consumption management system data can be considered as a stationary time series and methods of mathematical and statistical models for forecasting (for example, ARMA) can be applied. If the components of the seasonality and trend are unclear, filter type or non-linear algorithms are suggested. When there is a need for prediction of one sample ahead, the Kalman filter prediction can be applied. In any cost prediction, you can create a task execution plan that corrects any of the algorithms under consideration, because an estimate of the device usage schedule data is available. During the research, it was observed that the forecast accuracy could be increased up to 7%.

5) Author proposes to complement electricity resource consumption management systems by a decision support system based on the Mealy state machine, when making a decision of household appliance energy management, incorporating the results of the environmental parameter monitoring into the state-of-the-art automation system. The autonomous management decision is adjusted using the author's proposed 3-step feedback logical structure. The system prototype was tested investigating the monitoring of the real-time control of artificial illumination. The system ensured a constant illumination, but there was a change in the power consumption curve because the environment darkened naturally.

Evaldas Žulkas

DEVELOPMENT OF ENERGY CONSUMPTION FORECASTING AND AUTONOMOUS MANAGEMENT SYSTEM IN SMART HOUSE ENVIRONMENT

Summary of Doctoral Dissertation
Technological Sciences (T000)
Informatics Engineering (07 T)
Editor Gytė Jermolina

Evaldas Žulkas

ENERGIJOS SĄNAUDŲ PROGNOZAVIMO IR AUTONOMINIO VALDYMO SISTEMOS IŠVYSTYMAS IŠMANIOJO BŪSTO APLINKOJE

Daktaro disertacijos santrauka
Technologijos mokslai (T000)
Informatikos inžinerija (07 T)
Redaktorė Sandra Čiužienė