ENERGY AND FORECASTING AUTONOMOUS MANAGEMENT SYSTEM DEVELOPMENT

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Problem

The problem is – how to develop the architecture of the energy consumption management system, assessing energy consumption needs, costs and their possible forecasting methods in order to enable more efficient consumption of electricity

Object

Smart Home Electricity Self-Control Subsystem for the collection, monitoring and forecasting of power consumption data and management in the changing mobile network topology as well

Aim

To develop an autonomous *power forecasting and management system* and ***propose its architecture*** for data capture, forwarding, analysis and forecasting functions in the changing mobile network topology to increase efficiency of electricity consumption

Tasks

to propose and implement the application layer for the integration of multiple sensor networks into the smart housing architecture

to test the operation of the selected data communication protocol for collecting and analyzing electricity consumption data

to propose methods for forecasting smart energy environment data

to create a set of algorithms for prediction of energy consumption in embedded systems

to create a prototype of a self-acting, energy-efficient, control system, integrate it into a smart home services system and to carry out an experimental study, when testing in different operating modes

Relevance

Based on the literature review, it has been found that in the existing energy consumption management systems autonomous management is not based on the prediction of electricity costs *(Barnawi et al 2016; Daniela et al. 2015; Engerati, 2016)*

In this work, the forecasting methods are integrated into the energy consumption management system, which allows *to ensure greater autonomy* of the system and *to achieve the higher accuracy* of management

Relevance (2)

The advanced decision-making system integrated into ECMS (energy consumption management system) and experimental research show that it possible to more innovative control of power devices, taking into account the high power factor, maintaining its corresponding level in real time

Workflow

Firstly, the applied measures in the home energy management systems were reviewed and codified, overviewed the possibilities of the Internet of Things for intelligent housing energy saving solutions, the principles of scanning and data collection of environmental parameters of lighting and heating-ventilation systems

Secondly, home automation communication tools and technologies were chosen. Network topology used for electricity services can be applied for low-energy embedded network systems because they are described in standards that are adapted for low power systems

Workflow (2)

Thirdly, the architecture of the energy saving system was analyzed and service modules for energy data forecasting and autonomous operation of the system were developed

And finally, the forecast algorithms in the energy resource management system were made, the decision-making system and the decision-making methods for the regulation of the power-consuming equipment described. Smart energy efficiency energy saving tests were carried out and the results of forecasting and regulation were presented

Review of infrastructure solutions of the smart house management systems

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.

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)

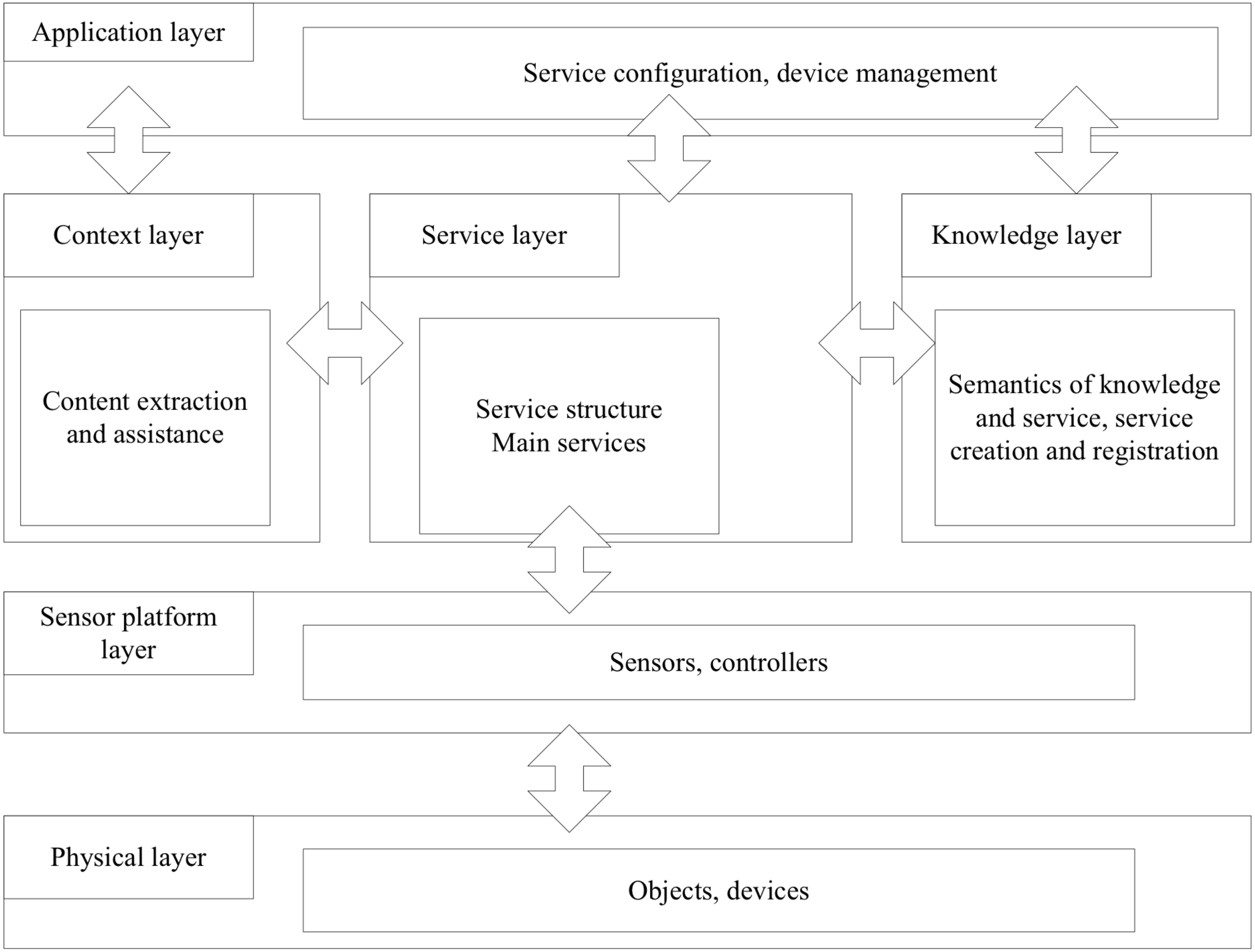
- lighting (automatic turn on and off according to the task list, lighting selection by considering the environmental conditions, etc.)

- 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 (includes the embedded devices and other electronic components)
- sensors' platform level (the parameters are collected from environment)
- service level
- knowledge level (information about the service structure and possibilities is described)
- context management level (describes how the system should assess the environment condition)
- application level (the services are managed: turned on, off, configured)

Smart house infrastructure implementation levels



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

Energy consumption and data processing systems

The energy consumption data were collected from the smart environment premises during experimental research. Energy consumption monitoring was performed with specialized equipment, which sends information to the web service database by standardized data protocols. SQL database is selected for data storage

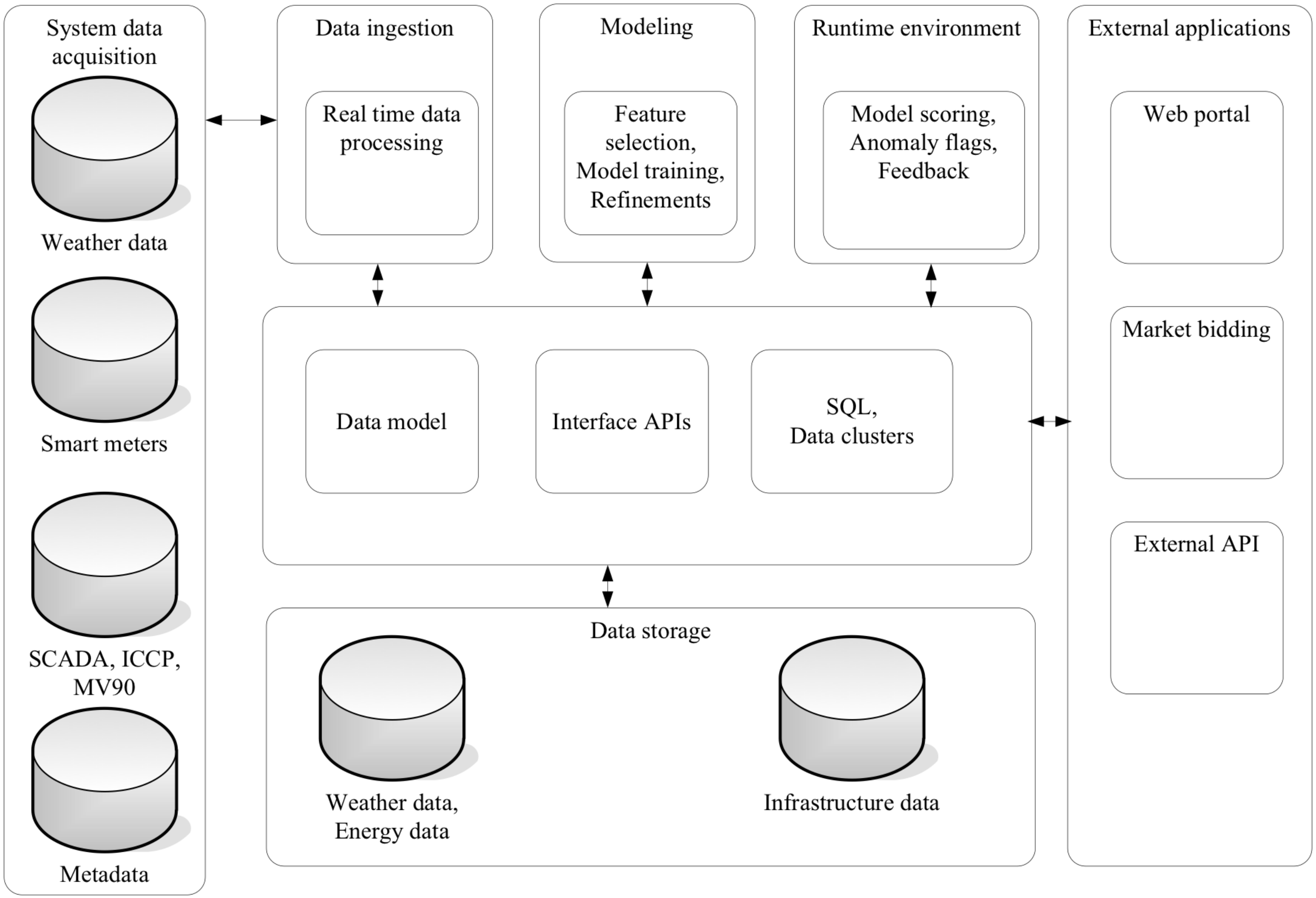
Energy consumption and data processing systems (2)

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. Within 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

The key component of the smart home energy monitoring systems is power measuring device (sensor concentrator) as collection of physical power parameters determines the data accuracy. 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

Power metering device (sensor concentrator) 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

Architecture of the energy data collection and analysis system



Source: compiled according to (Fusco F. ir kt., 2016)

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*

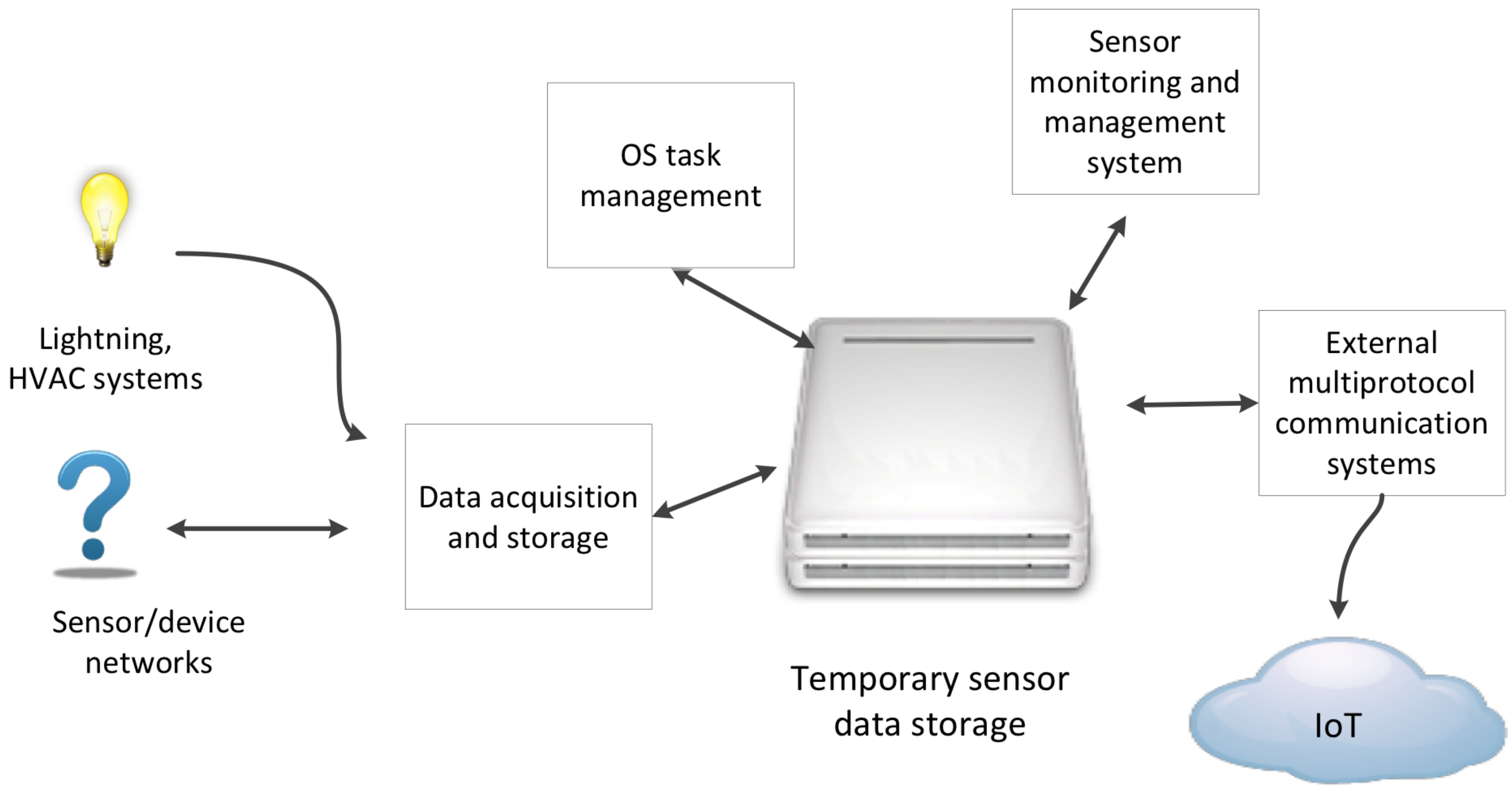
By using this architecture, it is possible to collect the monitoring data, however, it does not save energy in autonomous way, since evaluation of house devices and feedback from device control module is not provided for

Design and integration of the autonomous energy management subsystem in the smart house e-service system

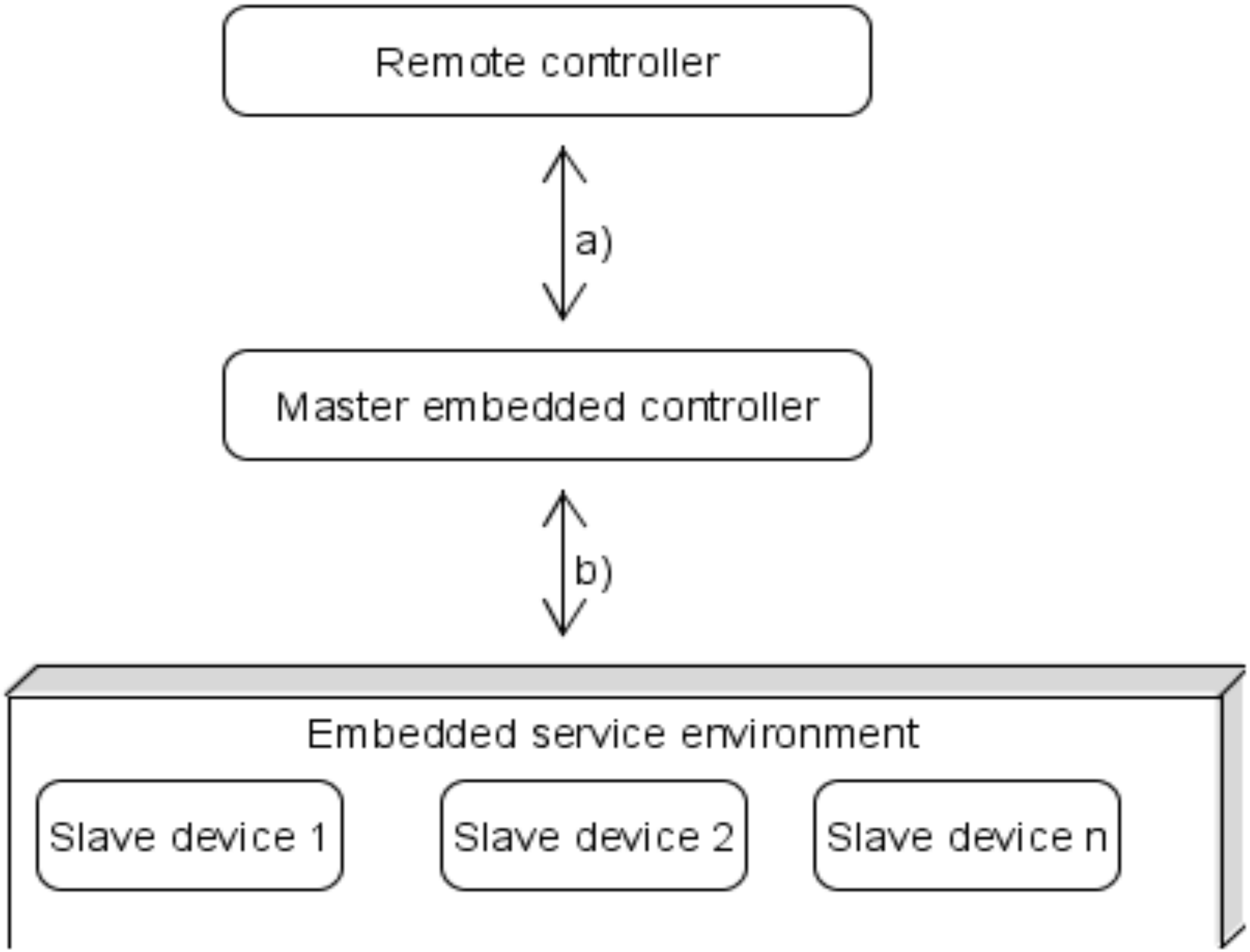
The energy consumption monitoring subsystem consists of the sensors, which collect data about the energy consuming devices. The aim of the smart object/ sensor – to collect the required data from the environment and turn them to the structured digital information (Alipp et al. 2006; Jiang et al. 2010; 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

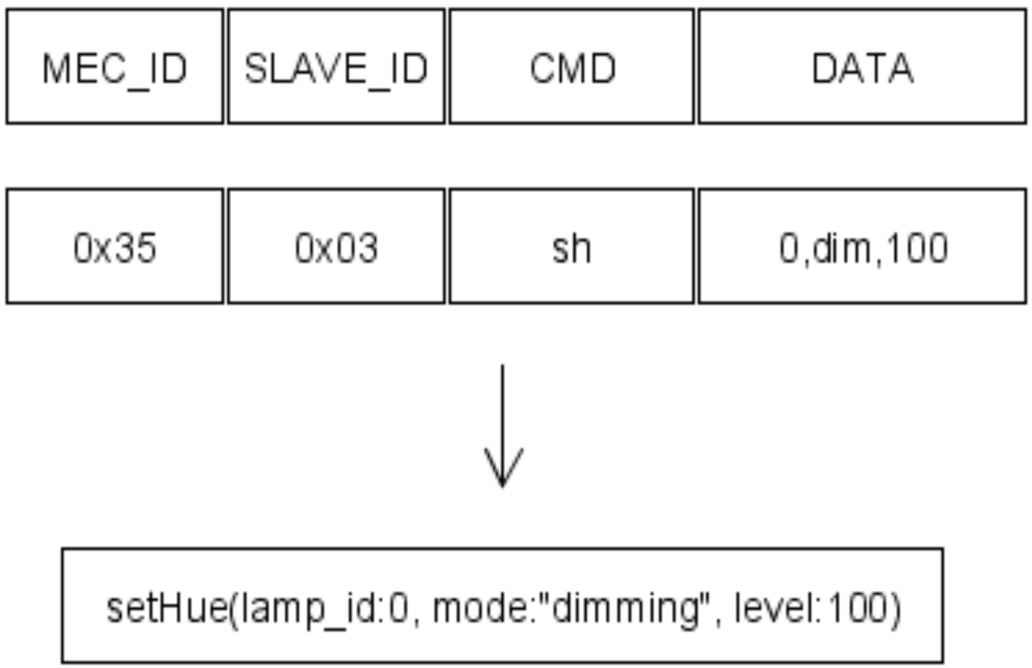
Sensor concentrator



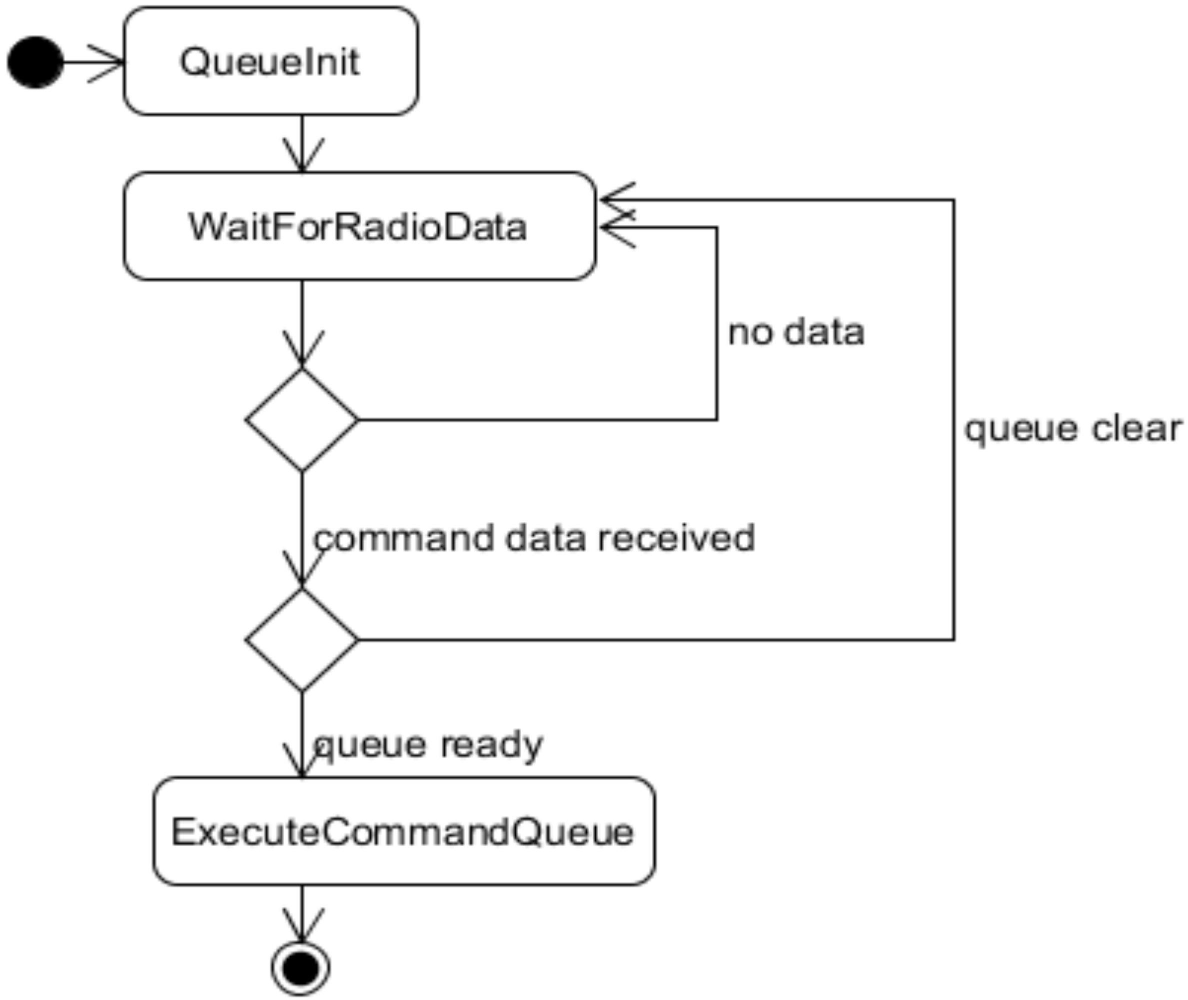
Structure of the network of embedded system



Command interpretation



Management of the command in the device

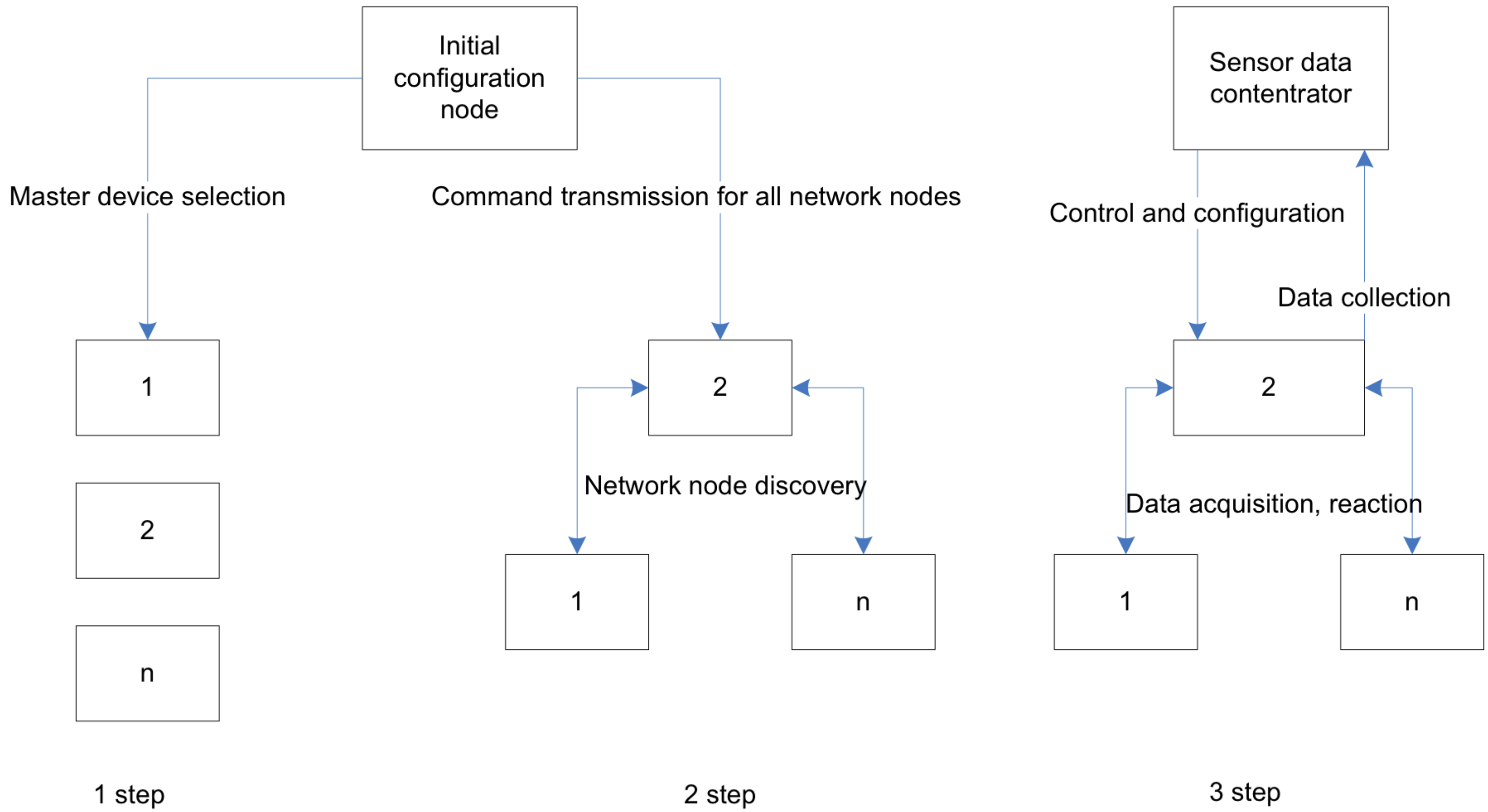


Development of wireless sensor network application layer and data communication methods in the SHMS

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

Structure of combining the embedded devices into autonomous wireless network



Energy forecast types

- Forecast of consumption demand
- Forecast of energy production
- Device management based on estimated forecast

The use of forecast results allows this functionality to be achieved: the system can respond not only to the instantaneous power consumption but also to rely on the future forecast in order to adjust the system to the maximum permissible monthly or other interval cost

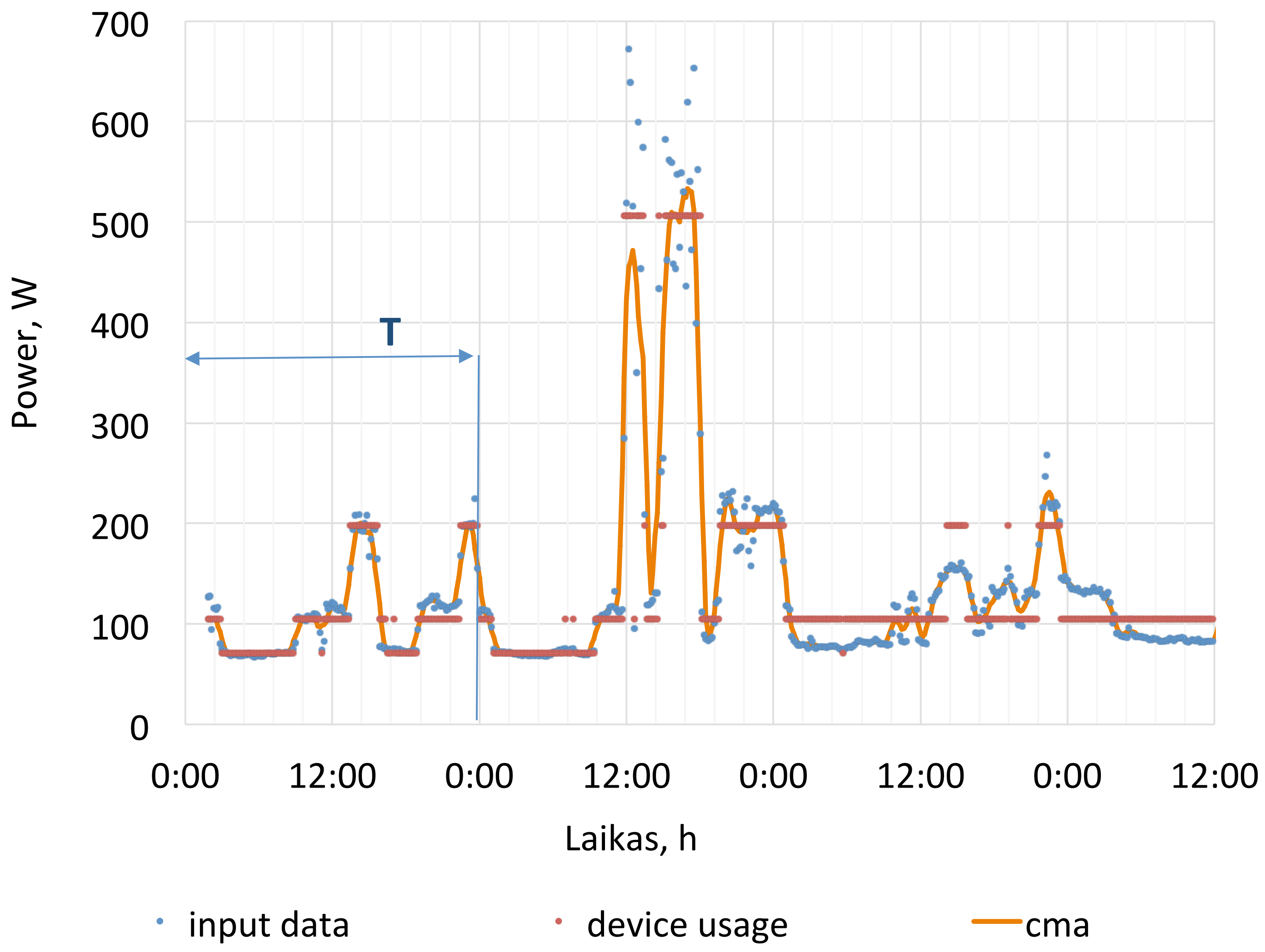
Experiment

Experiment was designed to find out application of mathematical models and nonlinear algorithms in the embedded systems in order *to obtain feedback* for the correction of management decisions. Experiment examines the result of the ARMA model and Kalman filter algorithms for calculating the power consumption forecast. The aim is to clarify the used forecast algorithm in the initial data processing based on the task execution plan

Experiment (2)

Within experiment, an implementation plan for the equipment according to the time of use of the laboratory equipment was made. Different sources of artificial lighting have been used to obtain the diversity of data consumption. To validate the feasibility of using the task plan, evaluate: statistical, nonlinear autoregressive and filtering forecast models

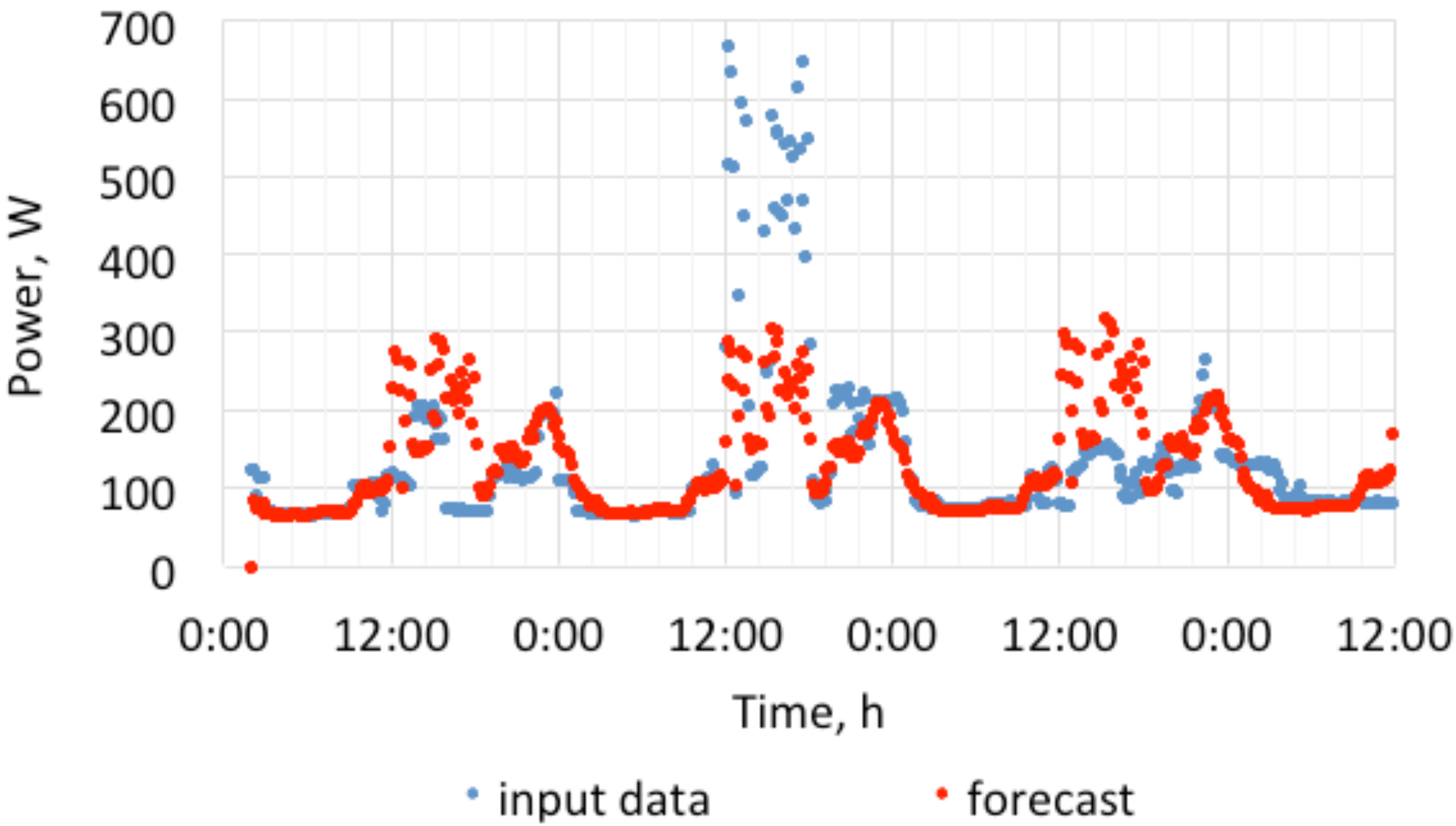
Device schedule plan and real energy consumption



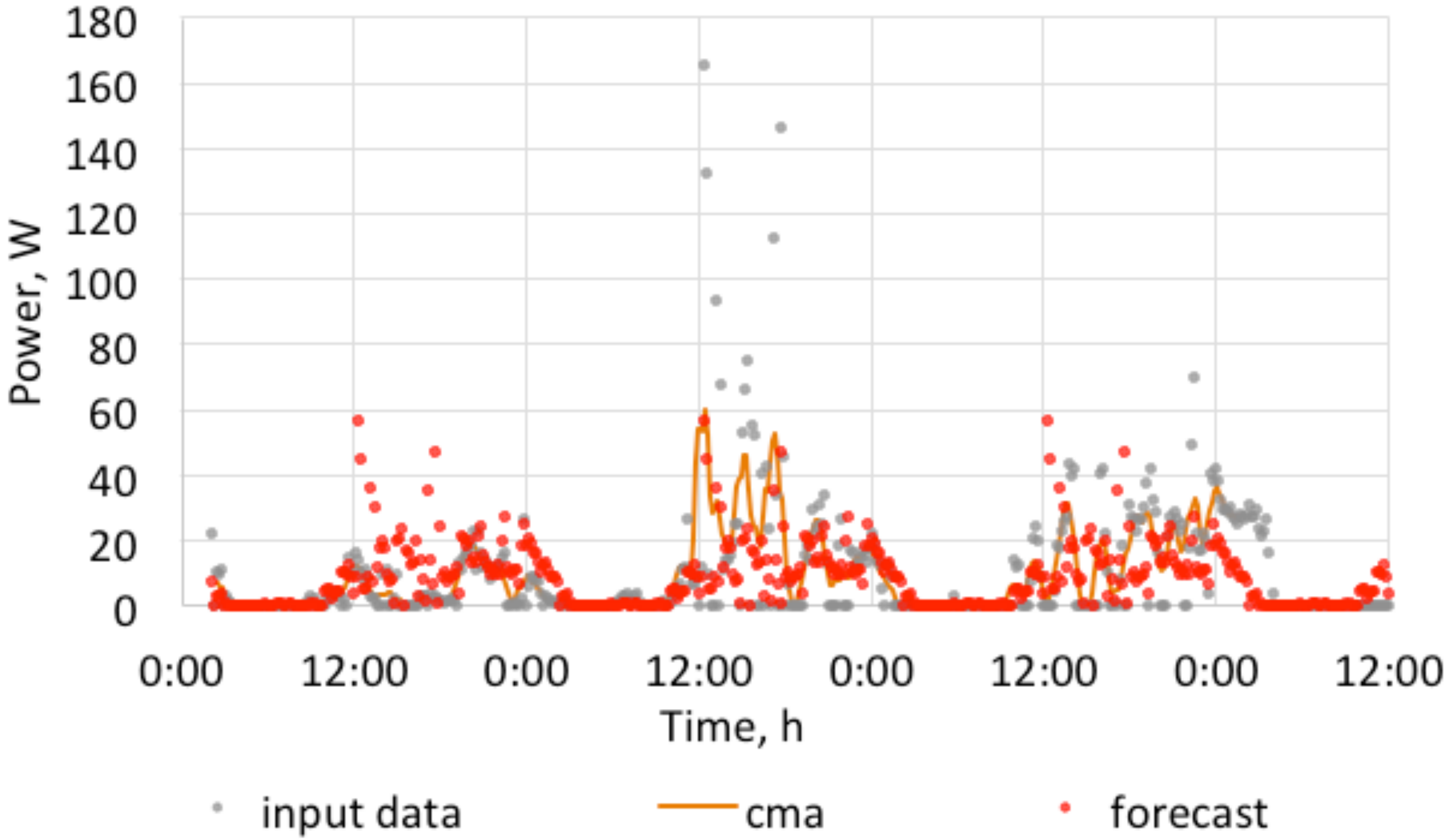
Here: input data – consumption data, device usage – device schedule plan data, cma – centered moving average

- 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

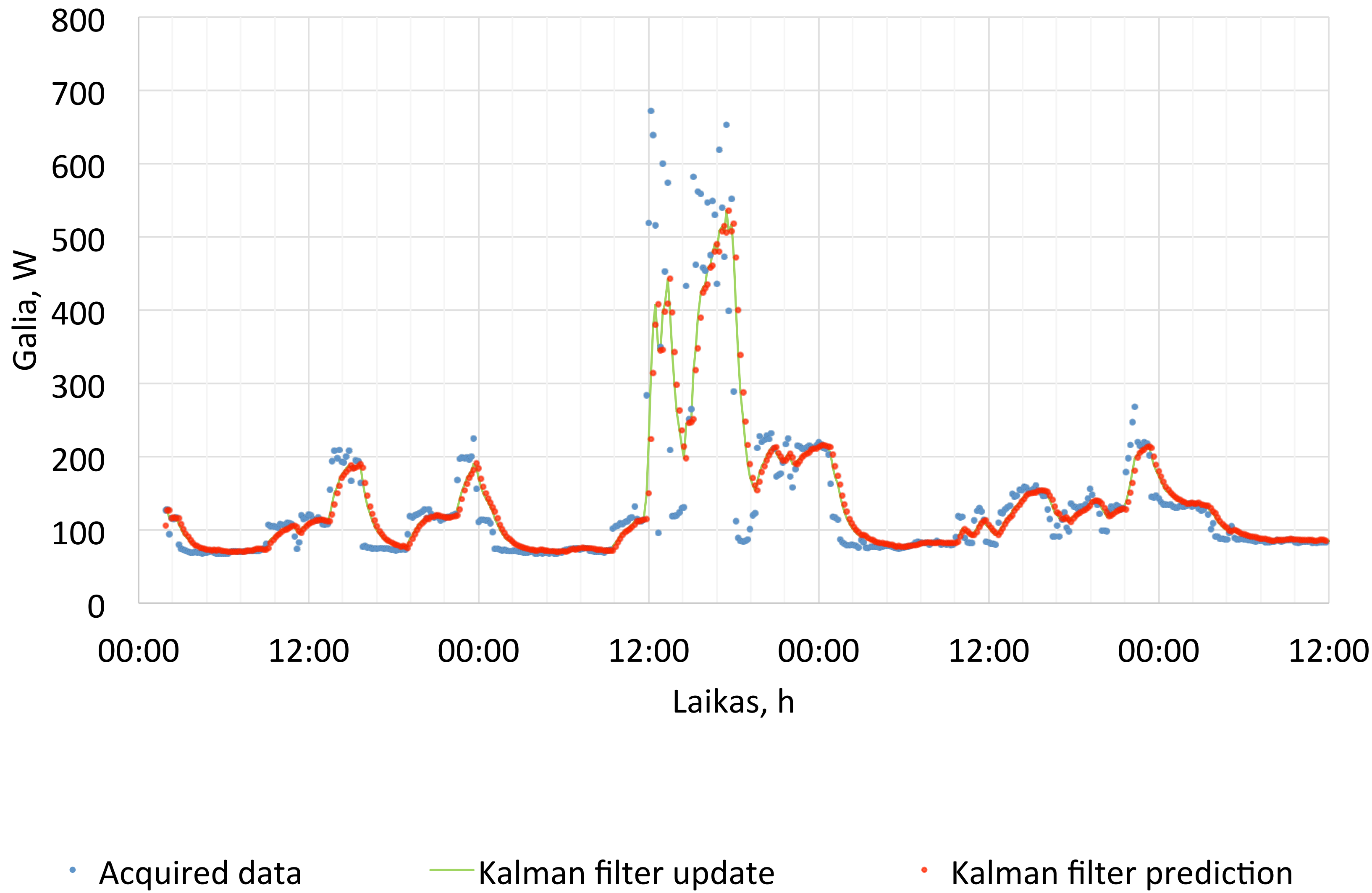
Forecasting with ARMA model



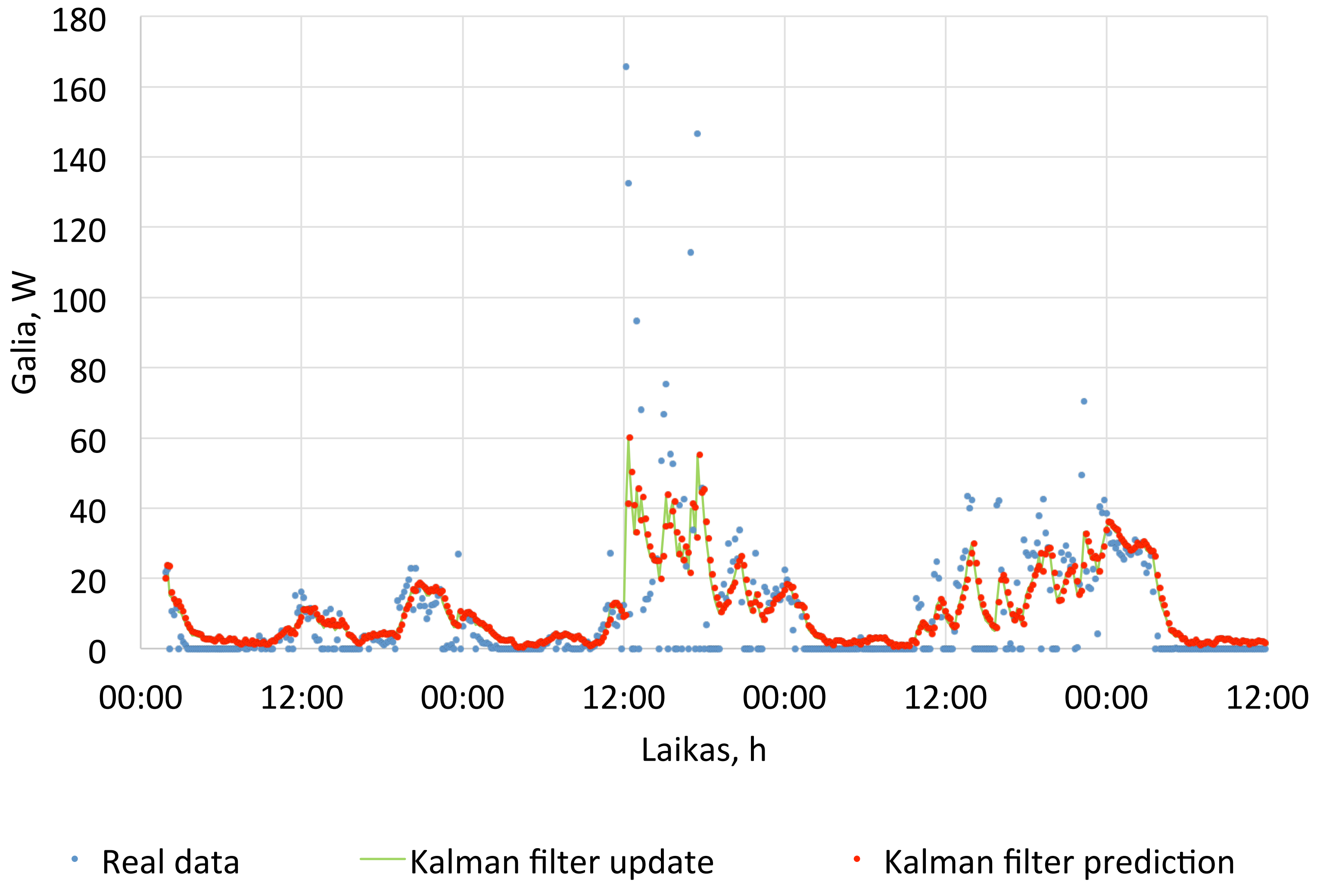
Forecasting with ARMA model by applying the device schedule plan



Forecasting with Kalman filter



Forecasting with Kalman filter by using the device schedule plan



Summary of the forecasting results

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 *x1*,*x2*, …,*xn* can be expressed as:

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

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

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

Summary of forecasting results (2)

	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

Summary of forecasting results (3)

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, fore-casting 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

Summarization of training and neural networks of the system

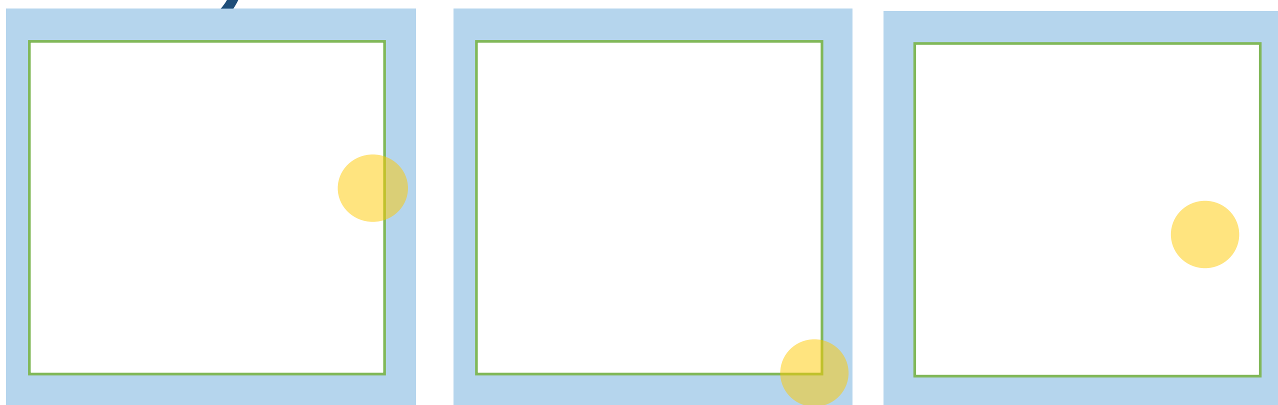
Unlike ARMA and Kalman filter, neural networks are based on nonlinear algorithms and artificial intelligence. Subject to the selected neural network and data frequency characteristics, the corresponding forecasting result may be different, therefore, it is hard to obtain a strict error estimate. Each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

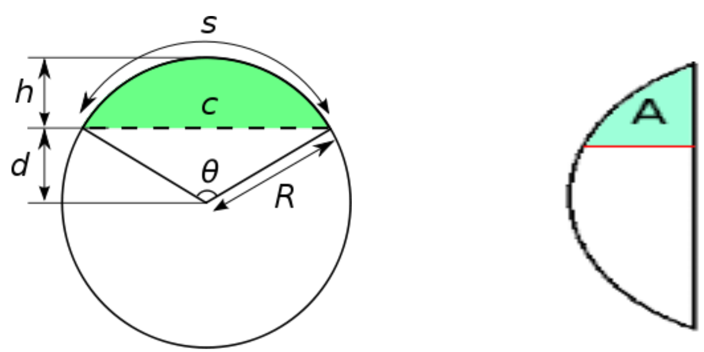
Assessment of solar illumination in the energy management system

- 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

Estimation of natural landscaping (perspective)



Position of sun



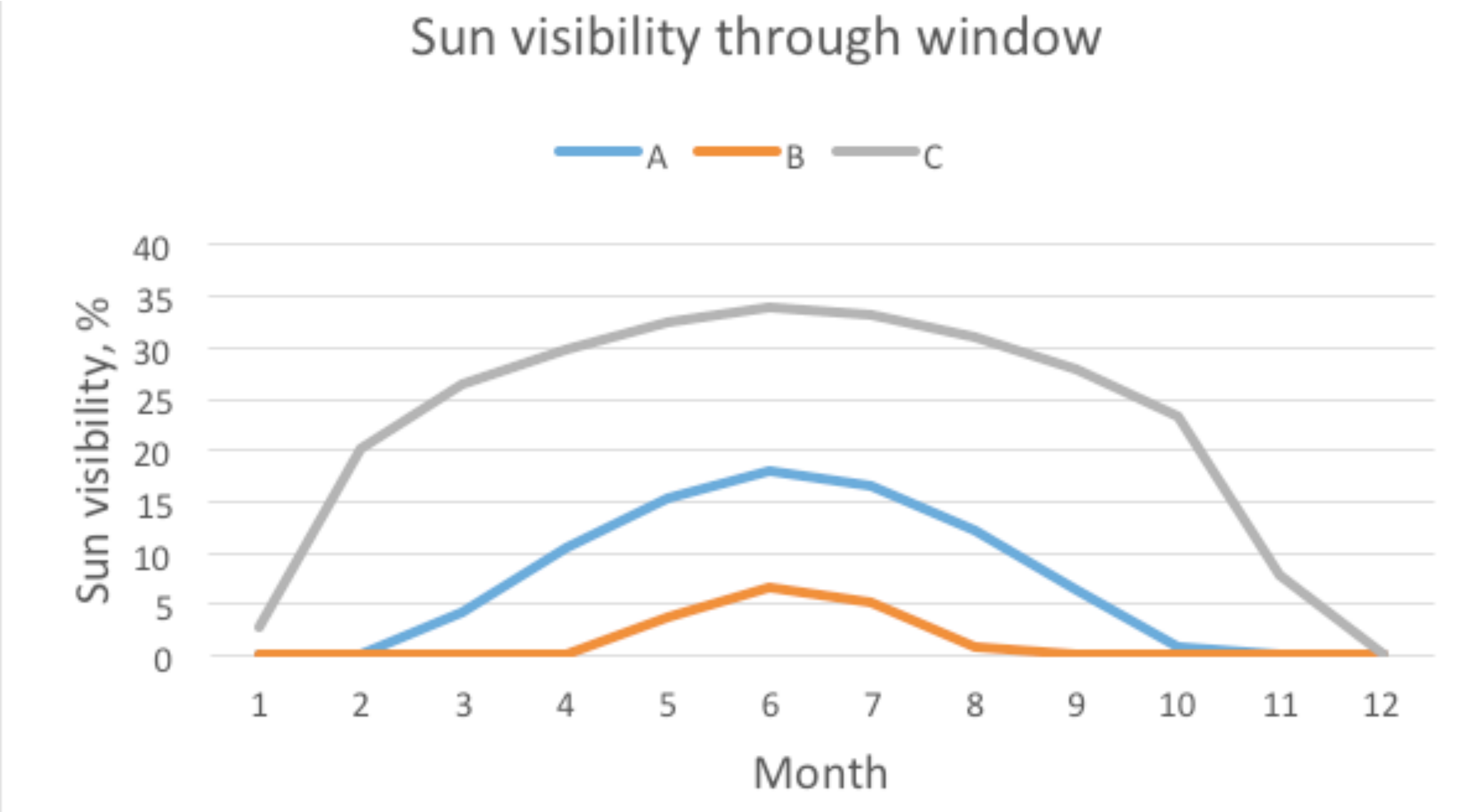
Visibility of the sun through the window

(A - area to be calculated)

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 below

Sun visibility through window over a month



Lighting in human environment must meet the defined norm. Otherwise, the comfort problems as eye fatigue or eye irritation are faced

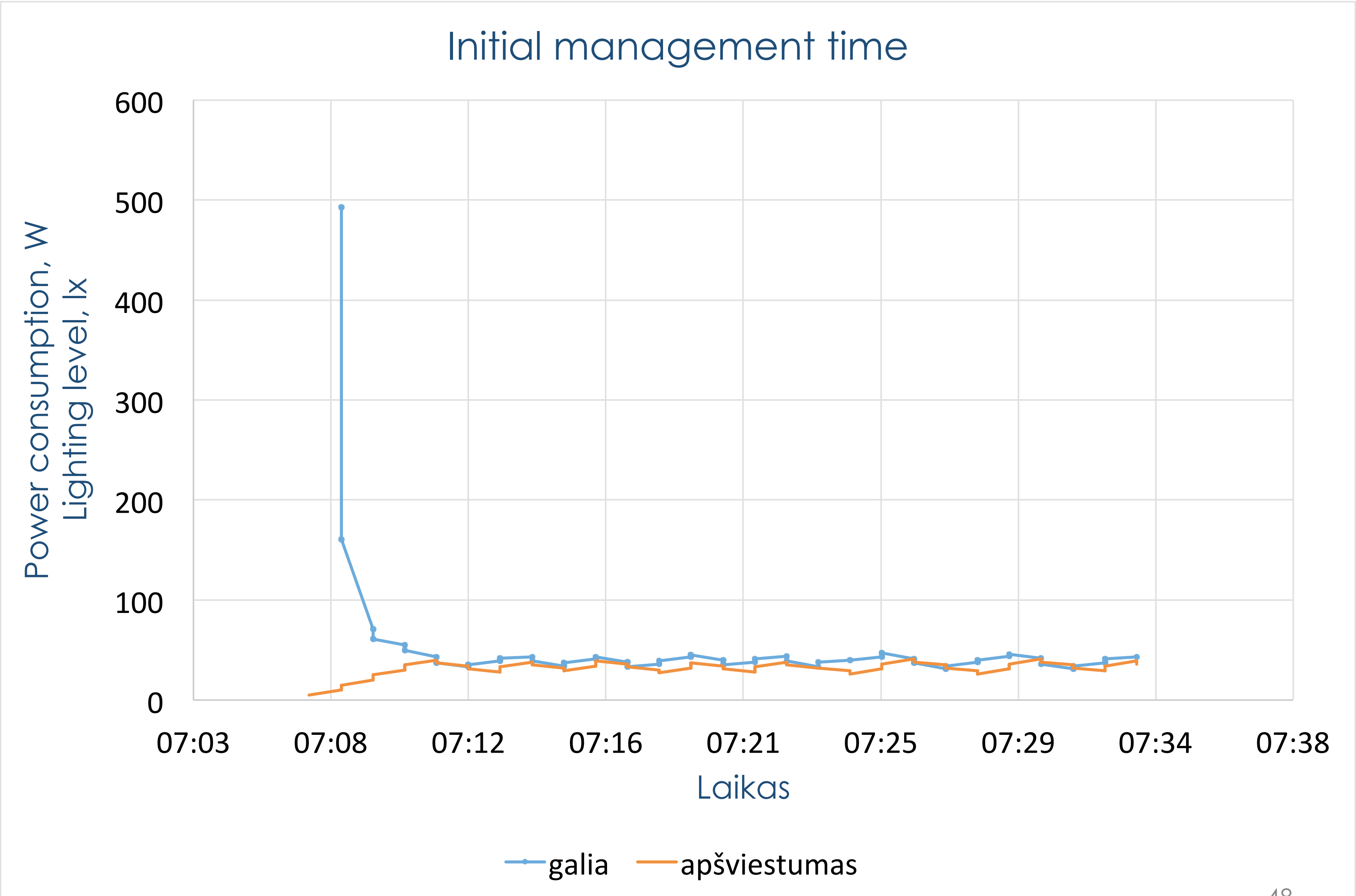
To study the model, the software, able to capture lighting in the specified points, perform lighting measurement and adjust the lighting of artificial light source was developed (Zanoli et al. 2012)

$$E_a(P) = \sum_{j=1}^{2}\left[\left|C_{c_j}\cdot E_{(ND_{gl})_j} + C_{r_j}\cdot E_{(NR_{gl})_j}\right| + \frac{\tau_j + V_j\cdot A_{gl_j}\cdot\sigma_{weighted}}{sum_{AREA}\cdot(1-\sigma_{weighted})}\cdot E_{NAT_{gl_j}}\right]$$

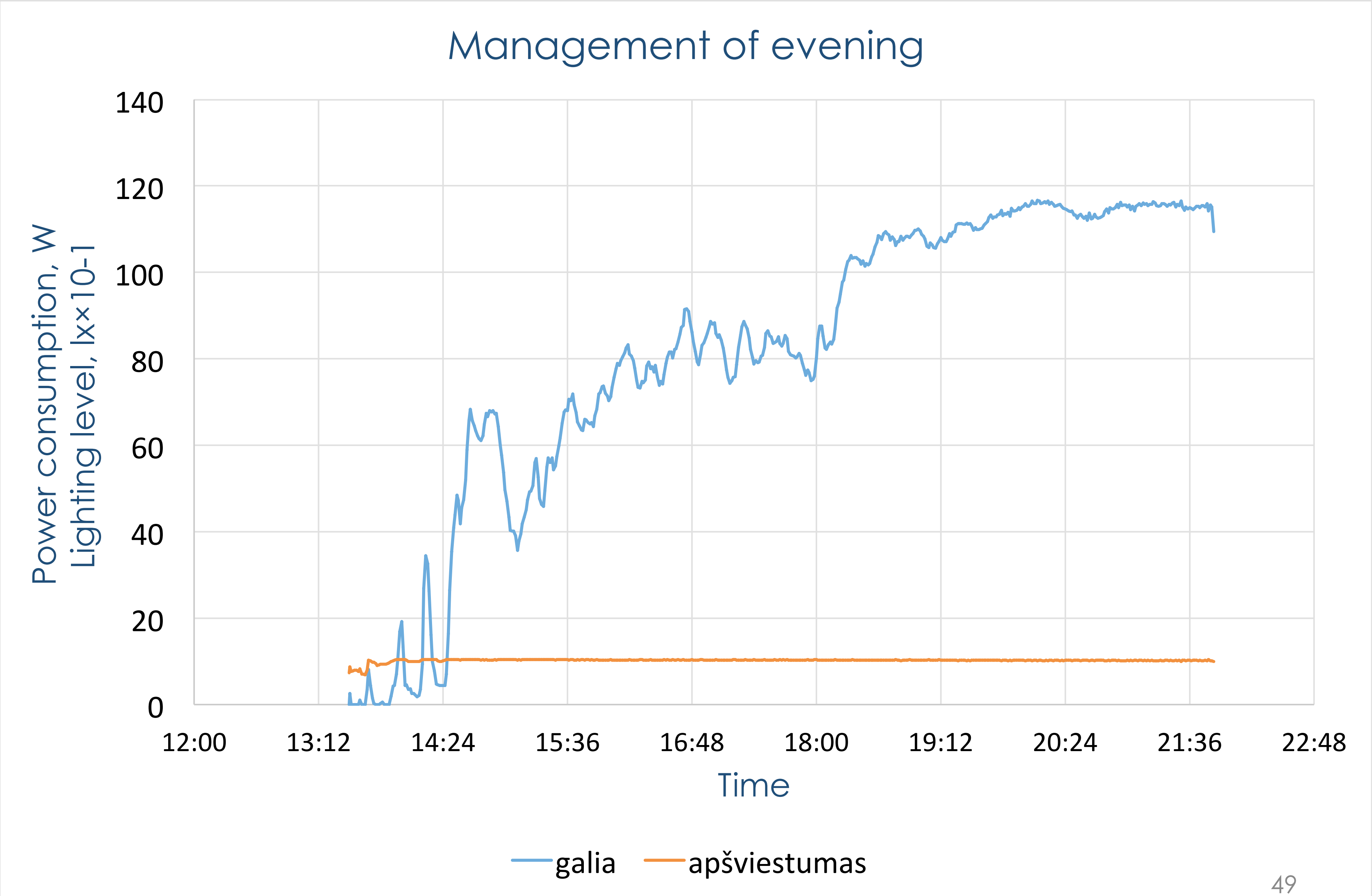
$$+\frac{I_L\frac{Lumen}{1000}\cos(\gamma)^3}{d^2} + \frac{Lumen\cdot\eta\cdot M\cdot P}{Sum_{AREA}\cdot(1-\sigma_{weighted})}$$

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

Adjustment of lighting



Adjustment of lighting



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

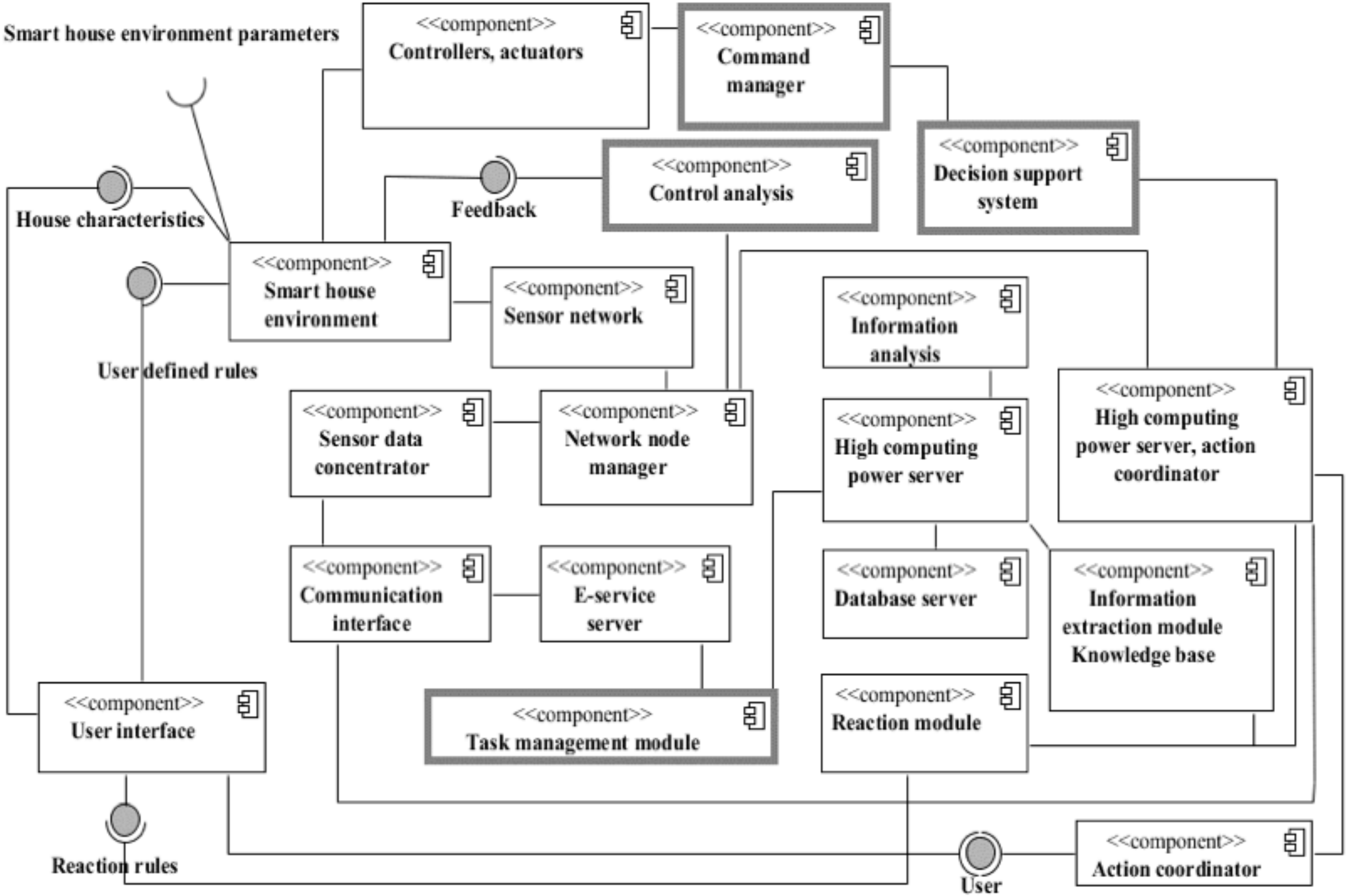
Lighting is stable over time, however, high deviations in the power system indicate that natural lighting changes dynamically behind the window

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

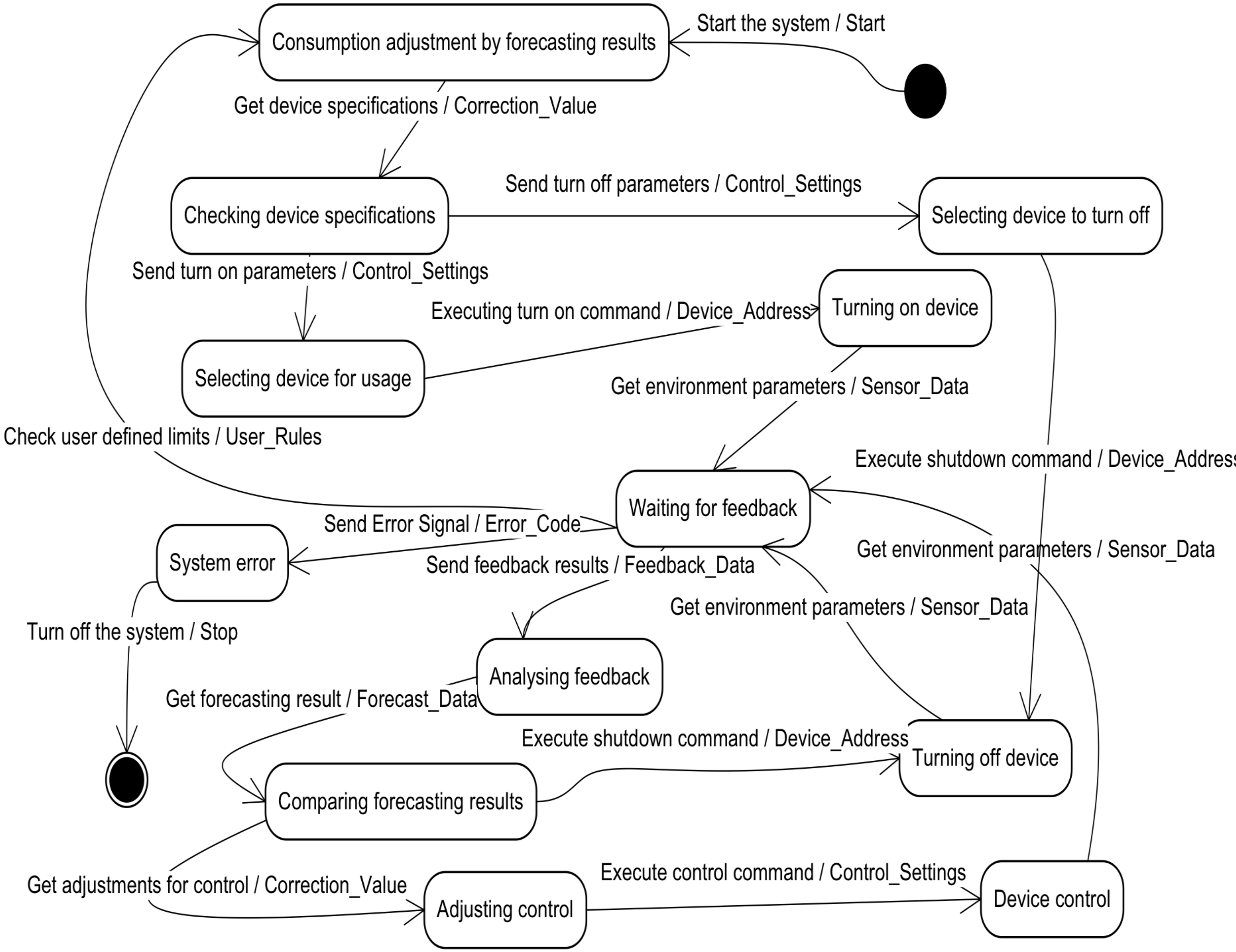
Regulation of lighting, management of evening process

	Average consumption, Wh	Duration, h	Consumption per 24h, Wh	Month, kWh	Price, eur	Savings, eur /%	
Adjustable 120W luminaires	38,74	08:20	322,82	9,82	0,11 €	1,12 €	32,28%
Nonadjustable 120W luminaires	120,00	08:20	1000,00	30,42	0,11 €	3,47 €	
Adjustable 150W luminaires	68,74	08:20	572,82	17,42	0,11 €	1,99 €	45,83%
Nonadjustable 150W luminaires	150,00	08:20	1250,00	38,02	0,11 €	4,33 €	

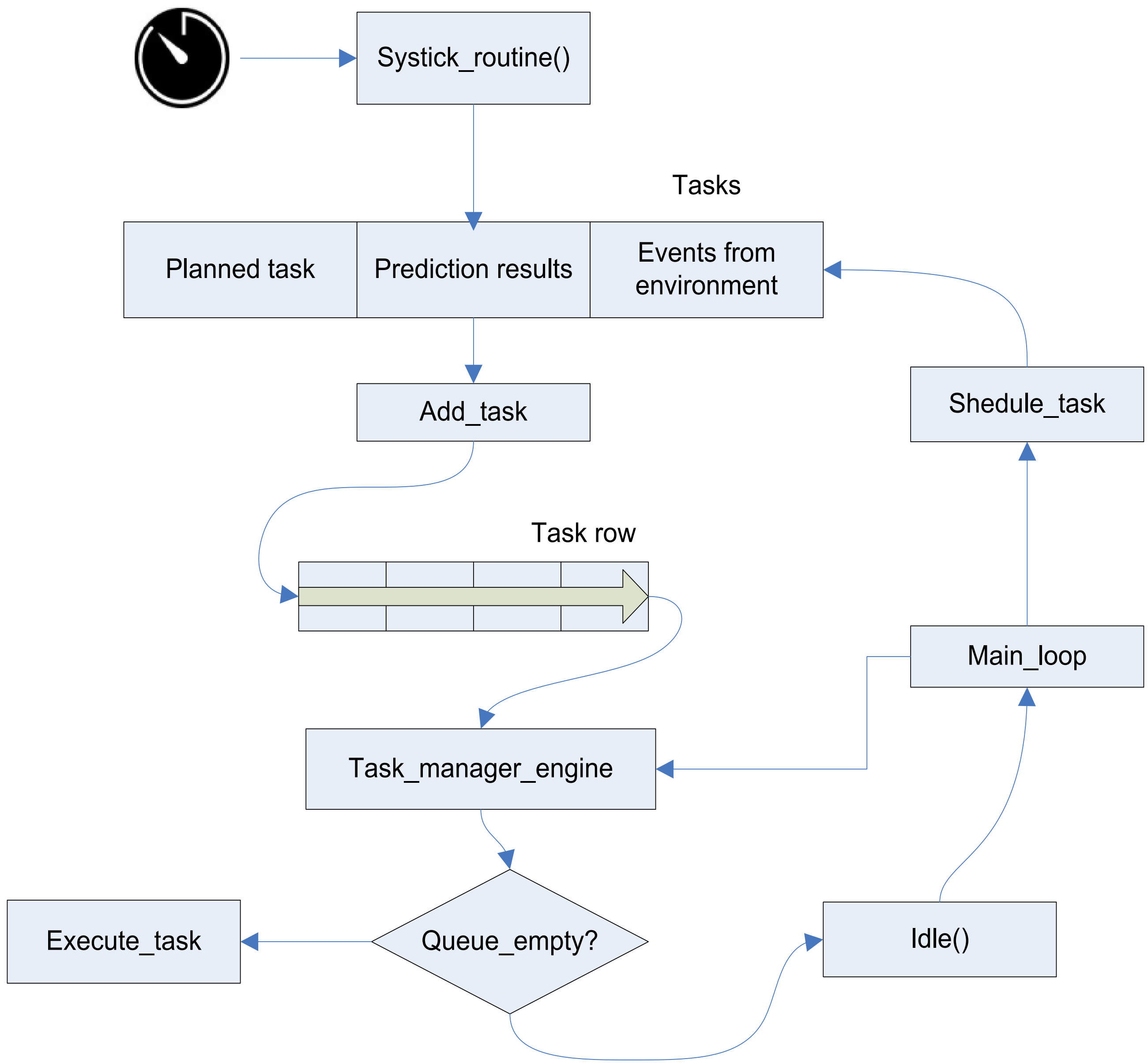
Architecture of energy management system



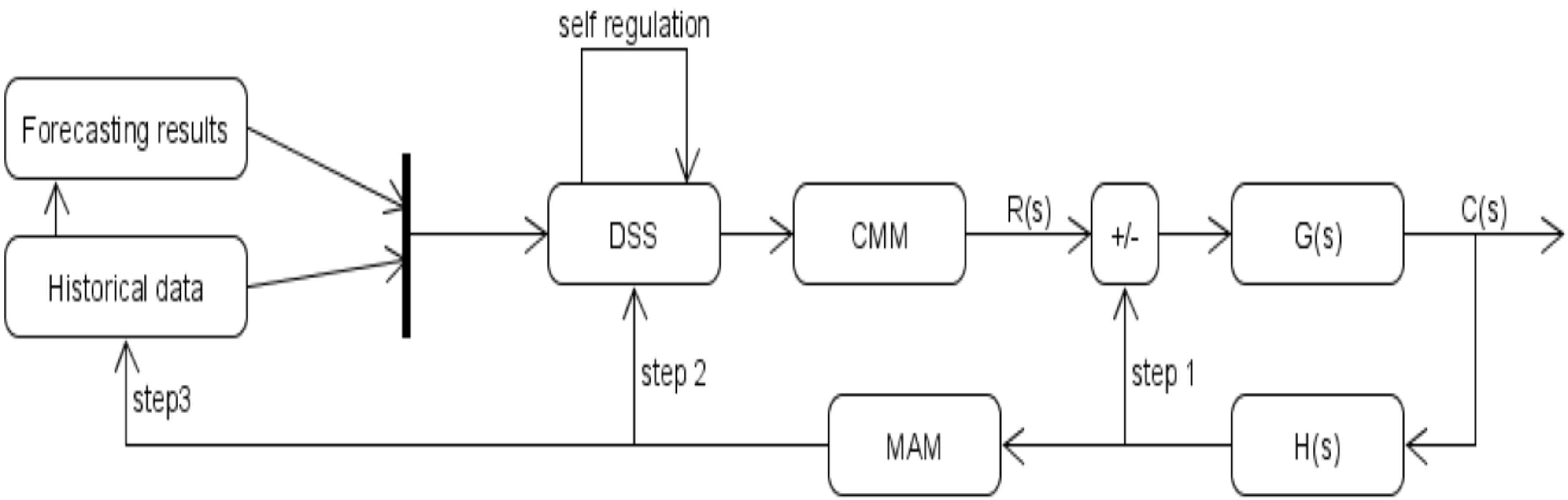
Finite-state machine of the energy management decision support system



Task management in the embeded system

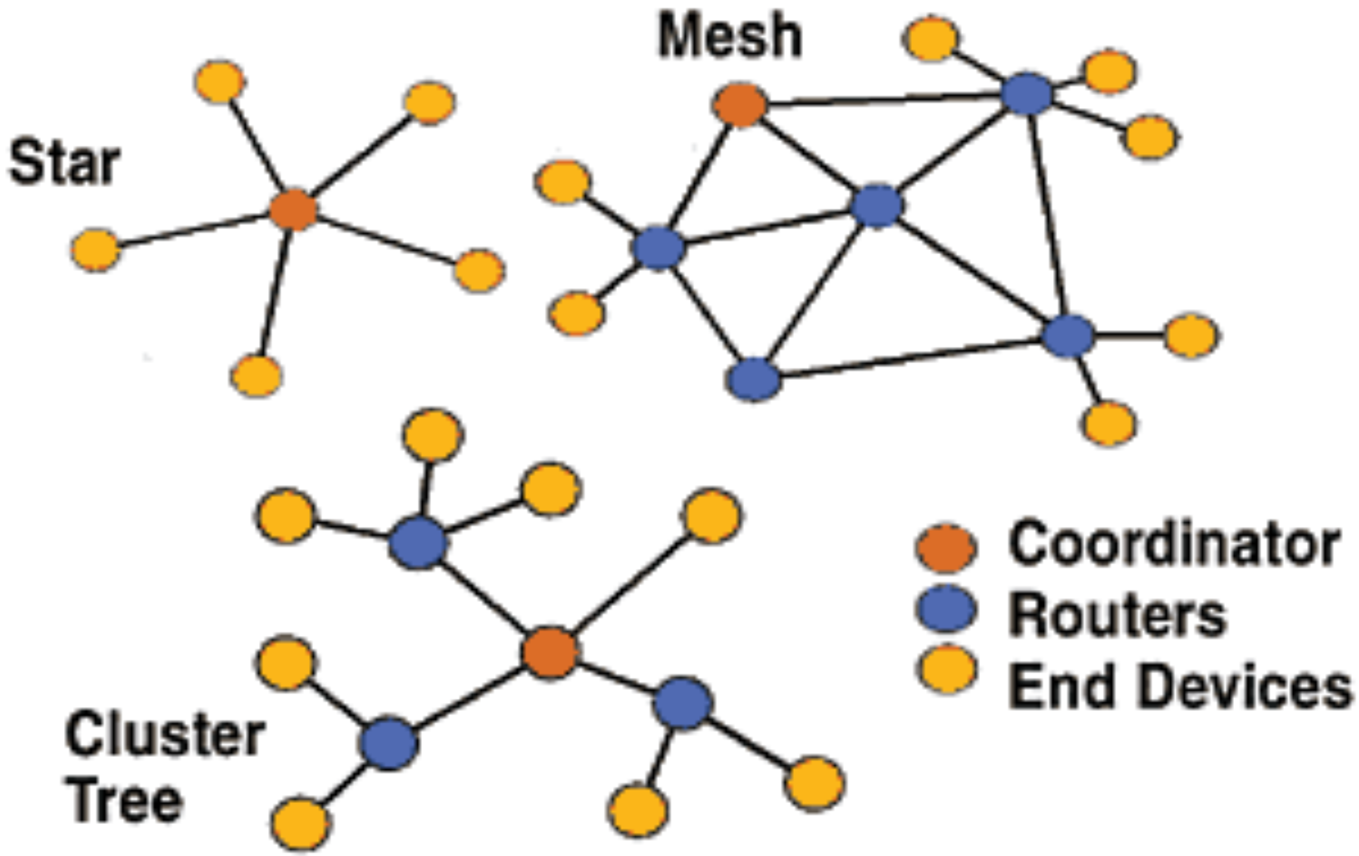


Structure of feedback in the energy management system



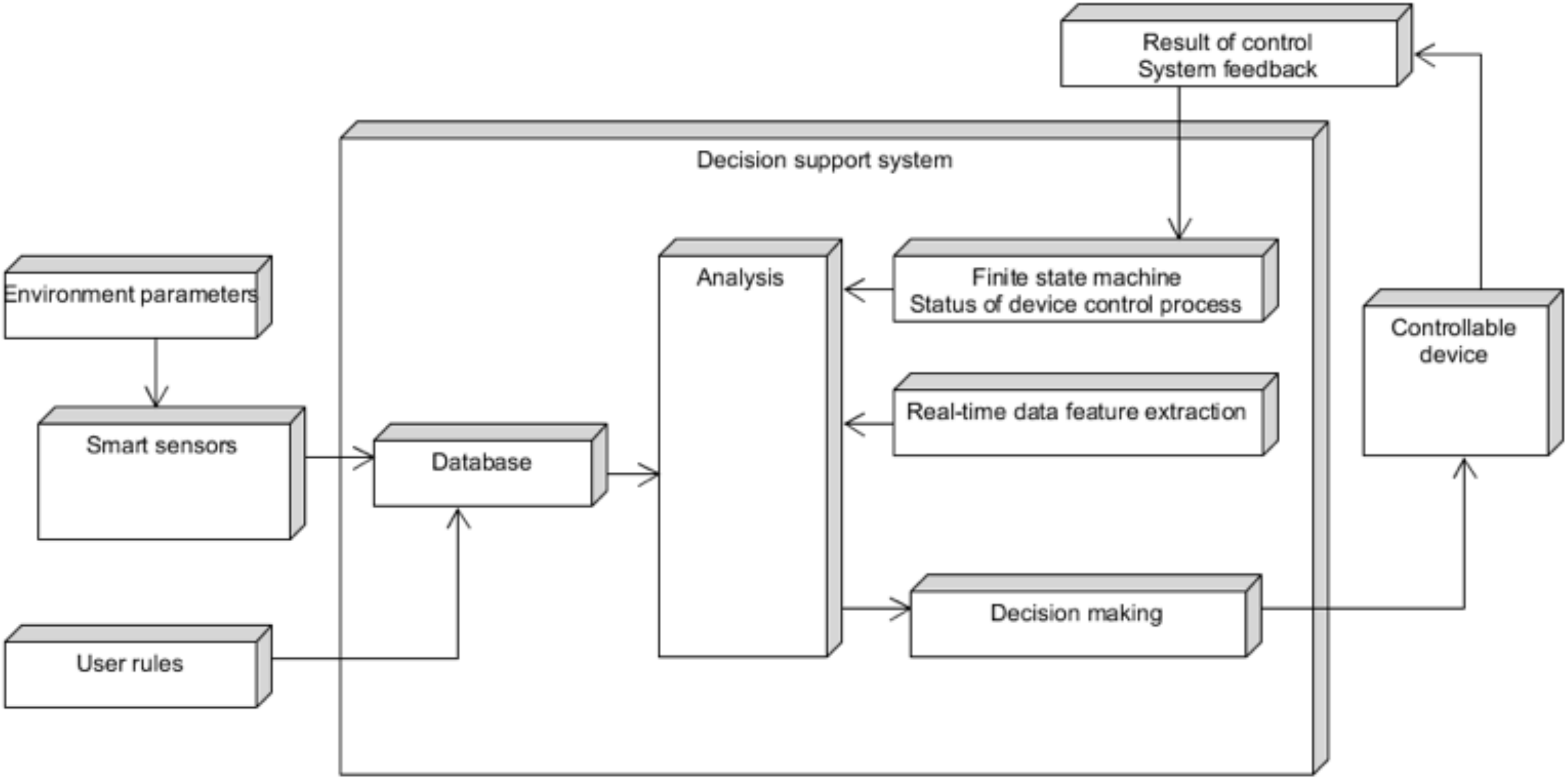
DSS – sprendimų priėmimo sistema (decision support system)
CMM – komandų valdymas (Command management module)
G(S) – tiesioginis kelias (Forward path)
R(S) – korekcijos kintamasis (Reference Variable)
H(S) – grįžtamojo ryšio kelias (Feedback path)
MAM – (įrenginio valdymo analizė) Management analysis module

Typical network topology examples

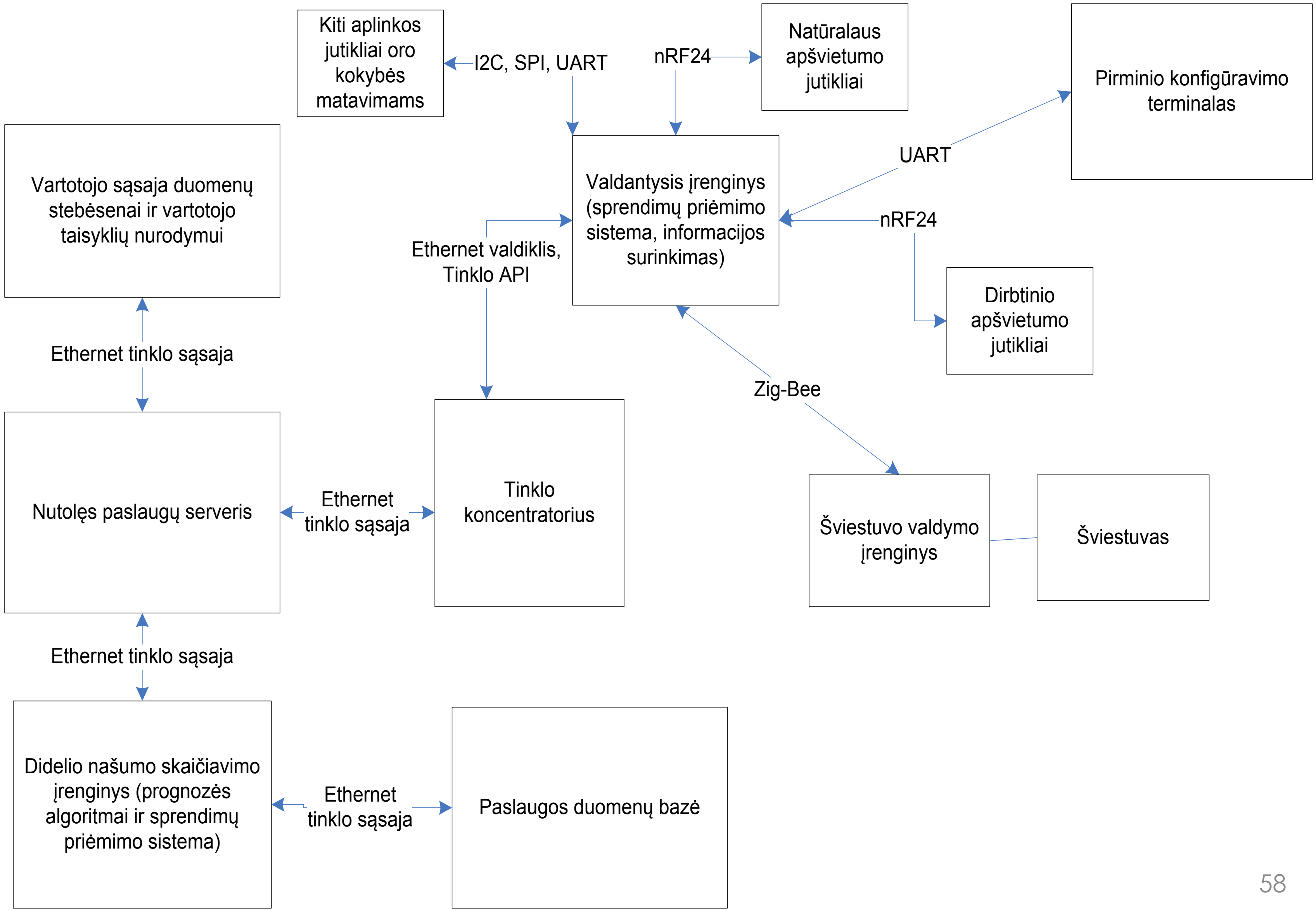


(Kanda, 2016)

Decision-making system



Energy resource management and monitoring prototype system



Features of energy consumption management system

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.

Results and conclusions

- Having analyzed the architectures of energy management systems created by other authors, the possibilities of using these architectures were summarized: systems for predicting energy production, user power consumption accounting systems.

- In home automation, in the mobile network of devices, a widely used mesh topology. Based on the grid topology, a method has been developed for connecting devices on the network without predefining the device code in the destination code. The created application layer allowed the devices to be connected in the way suggested by this work, creating a mobile topology network of varying degrees

Results and conclusions (2)

- The proposed network application layer allows you to define the purpose of the device, create a hardware solution and install the device with sensors and controls in a smart environment. The author's proposed sensor network devices are configurable during runtime. This ensures not only a mobile but also a real-time network topology

- If the seasonality and trend components are not clear in the cost data of the Energy Resources Management System, it is proposed to use autoregressive neural network algorithms. Possible to use the Kalman filter prediction when you need a prediction of one deviation to the future. In any prediction, a task plan can be adapted that adds accuracy to any of the algorithms in question

Results and conclusions (3)

- Testing the prototype of the system has monitored the real-time management of artificial illumination. The system ensured a constant illumination, but a change in power curve was observed when the illumination was steady and the environment was natural (in the evening). The system data accumulation was ensured by a 3-step feedback structure that allows the accumulation of power parameter values

- An intelligent housing power management architecture consists of modules that are defined by overviewing the solutions offered by other authors for building service systems. The modules for forecasting with the implementation of the task plan are distinguished, as well as for ensuring the functioning of the decision-making system, since their use is used to find out how to manage the e-mail solution.

Thank you for your attention! ☺