DEVELOPMENT OF ENERGY CONSUMPTION FORECASTING IN SMART HOUSE ENVIRONMENT

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PROBLEM

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

The problem to be solved is – 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

OBJECT

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

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

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

OBJECTIVES OF RESEARCH (2)

- 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

- 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

OBJECTIVES OF RESEARCH (3)

- 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

RESULTS TO BE ACHIEVED (1)

- The prototype of autonomous ECMS, enabling to connect the embedded sensor nodes under mobile and adaptive topology network conditions, was planned to be developed

The prototype dedicated for energy consumption management, and it is integrated in the smart house service system. It 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

RESULTS TO BE ACHIEVED (2)

- To interconnect the embedded devices (sensors and controllers), the mobile network application layer and communication interface also was planned to be 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

RESULTS TO BE ACHIEVED (3)

- The task schedule module was planned to be developed as well 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

NOVELTY

- 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

PRACTICAL IMPORTANCE

- The examined monitoring data of physical power parameters and reading of instantaneous values by using the small-scale embedded systems can 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 in the work, 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

The smart house service components are usually used for provision of the following services

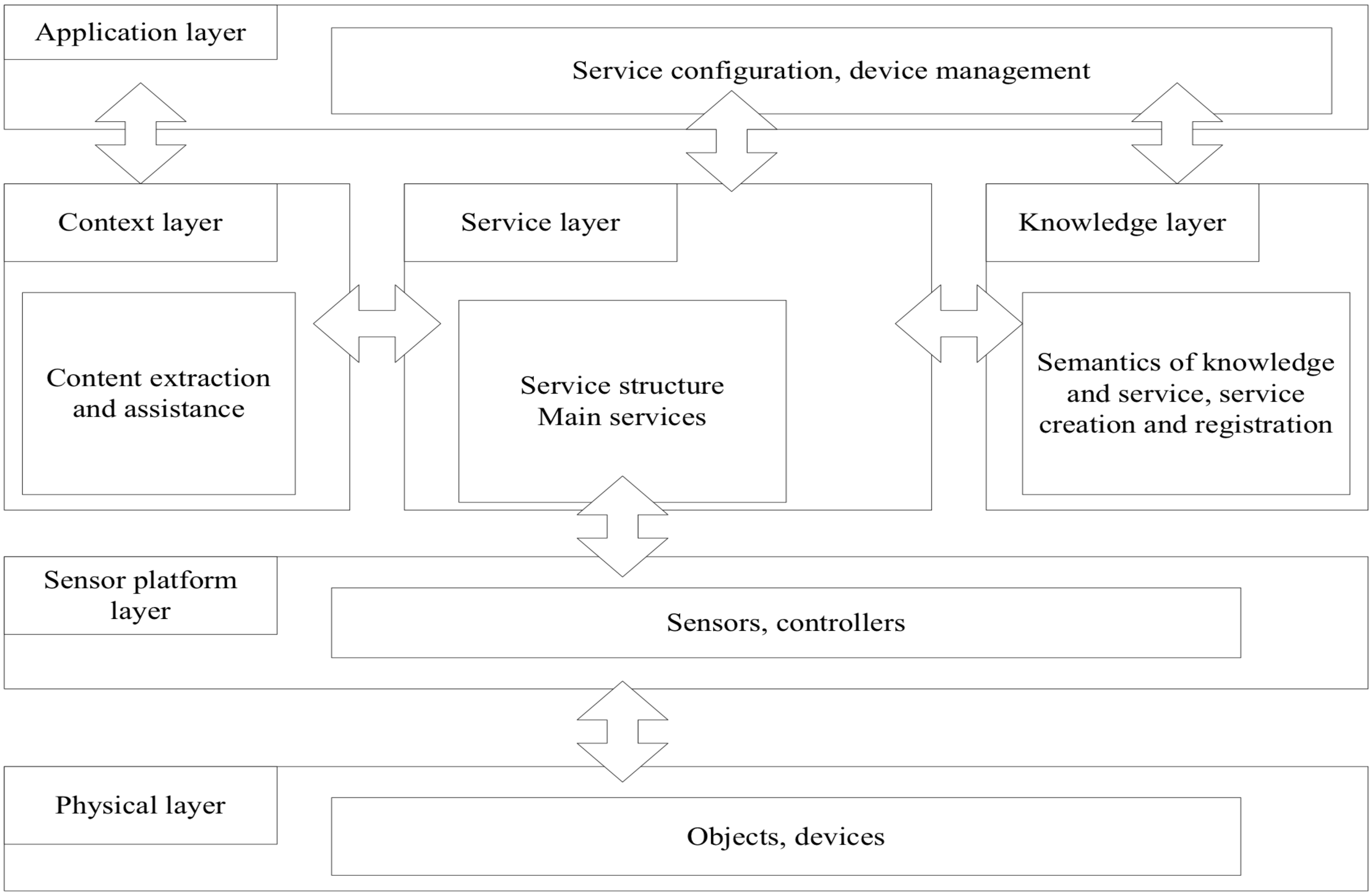
- indoor climate control (HVAC systems, temperature and humidity monitoring systems)
- lighting (automatic turn on and off according to the task list, lighting selection by considering the environmental conditions, etc.)
- protection (video surveillance cameras, human detection, smoke, fire, water, natural gas leakage sensors and control systems)

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

- physical level (embedded devices and other electronic components)
- sensors' platform level (the parameters are collected from environment)
- service level (includes the services, provided in house)
- 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)

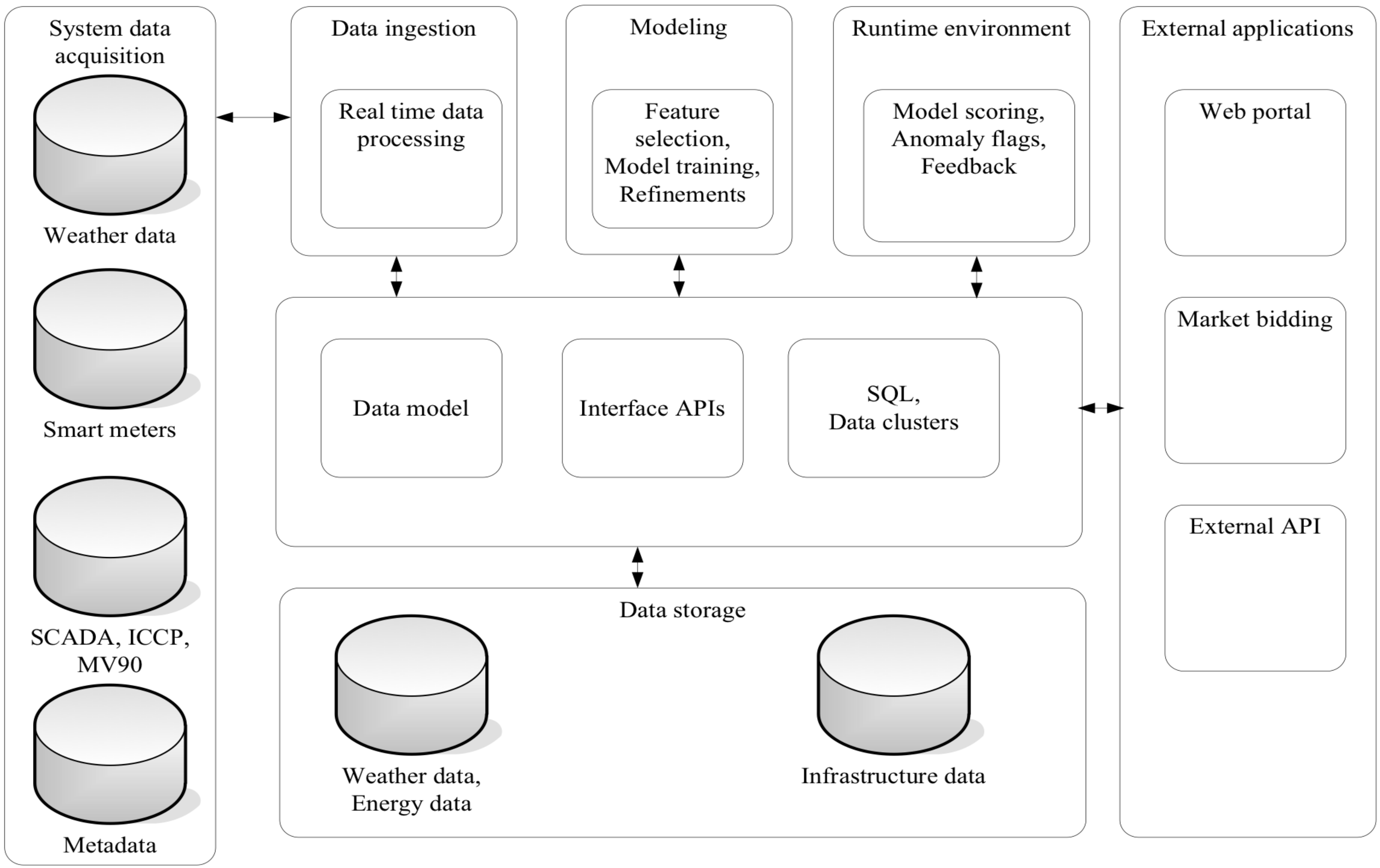
SMART HOUSE INFRASTRUCTURE IMPLEMENTATION LEVELS

(Various management and context view interfaces are created for the user would have connection with the surrounding services)



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

ARCHITECTURE OF THE ENERGY DATA COLLECTION AND ANALYSIS SYSTEM



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

The embedded systems of the home automation e-service system are characterized by these 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

Seeking to develop the network, where all devices could run in an autonomous manner, this work 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

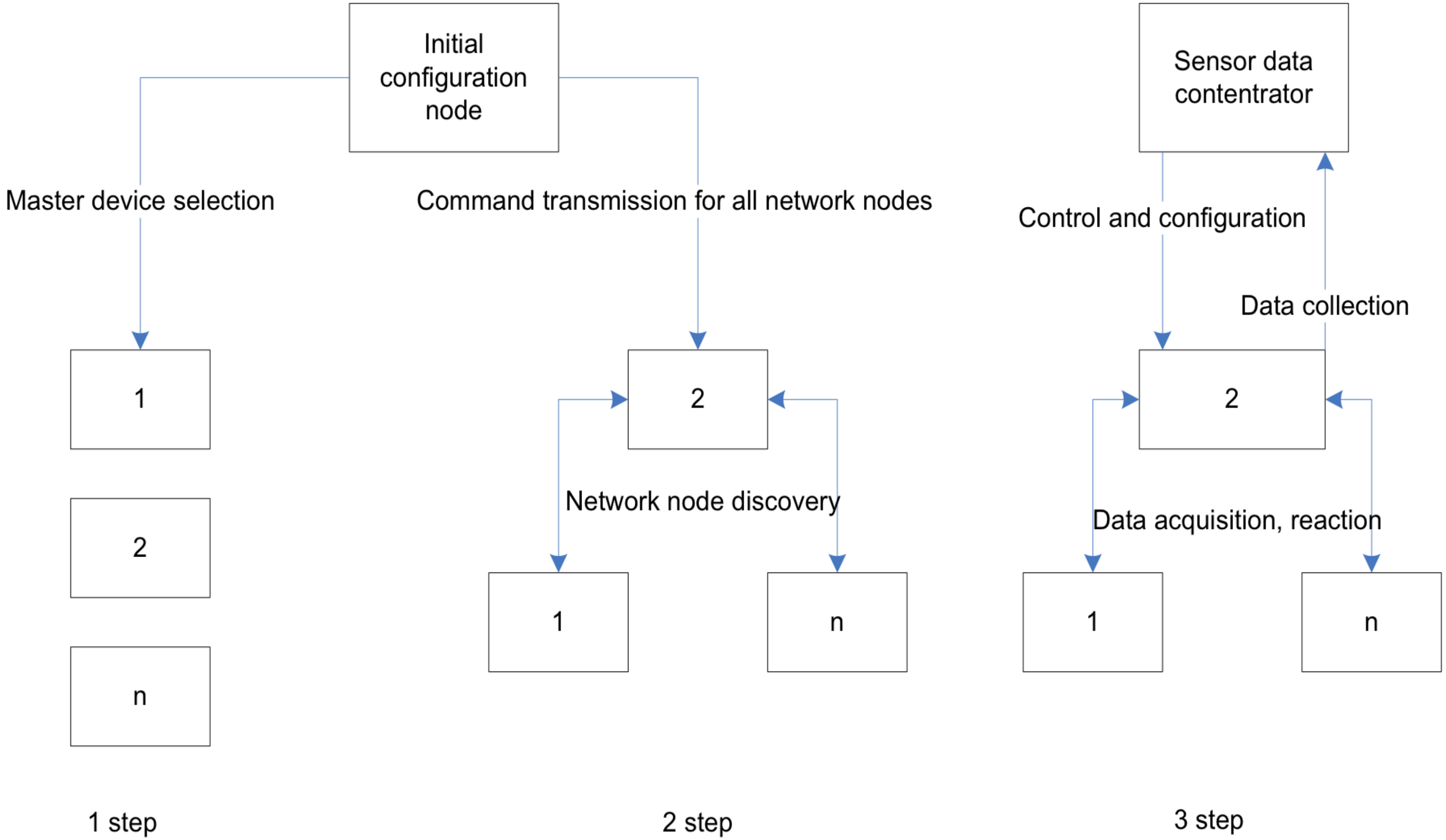
3) Management and configuration, data storage

Before developing the network, the following device groups could be identified:

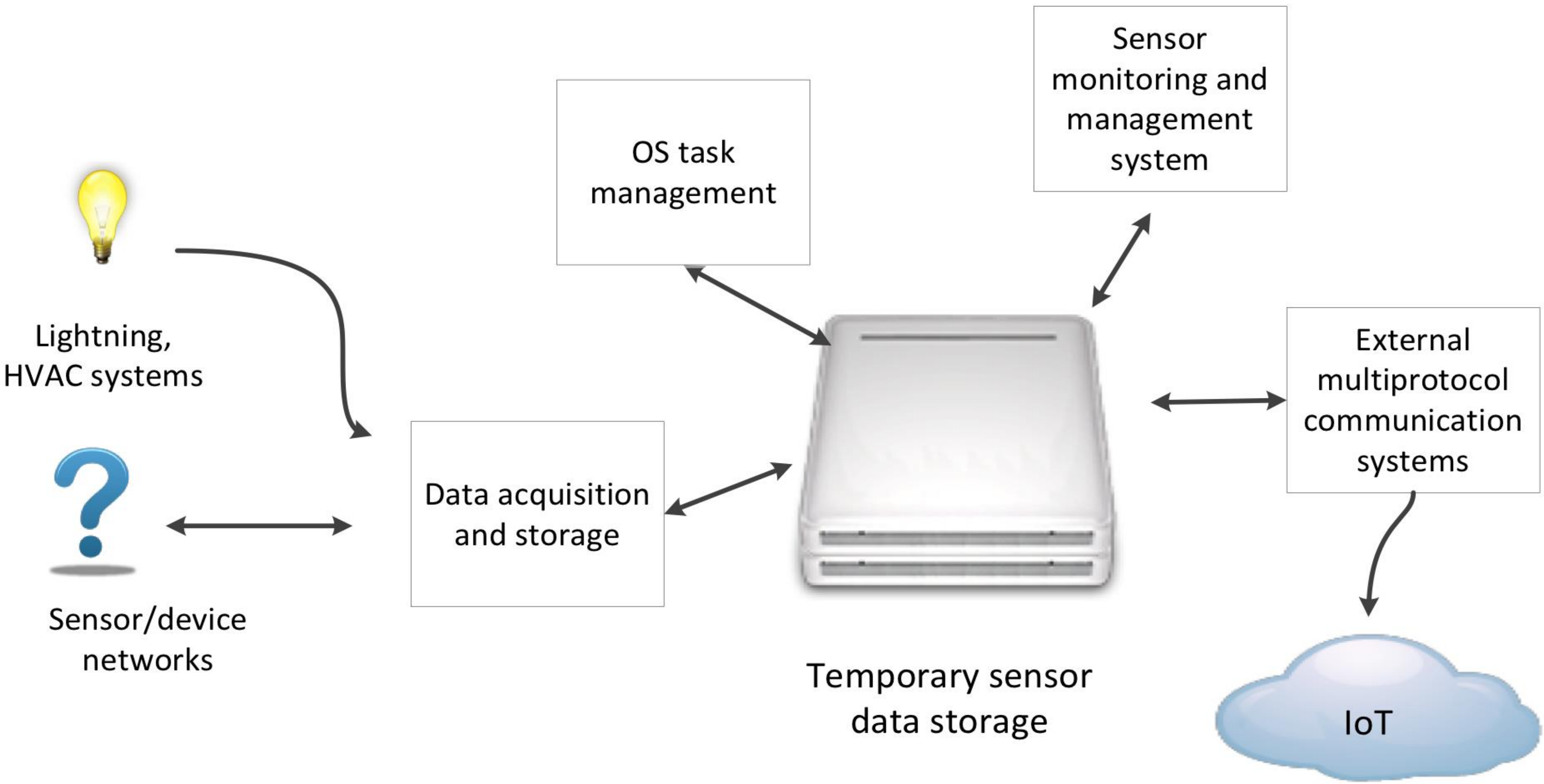
smart sensors and controllers, primary configuration node and sensor data concentrator (the primary configuration node may be any device, able to communicate with smart sensors and controllers, for example, a computer with terminal capability).

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 below:

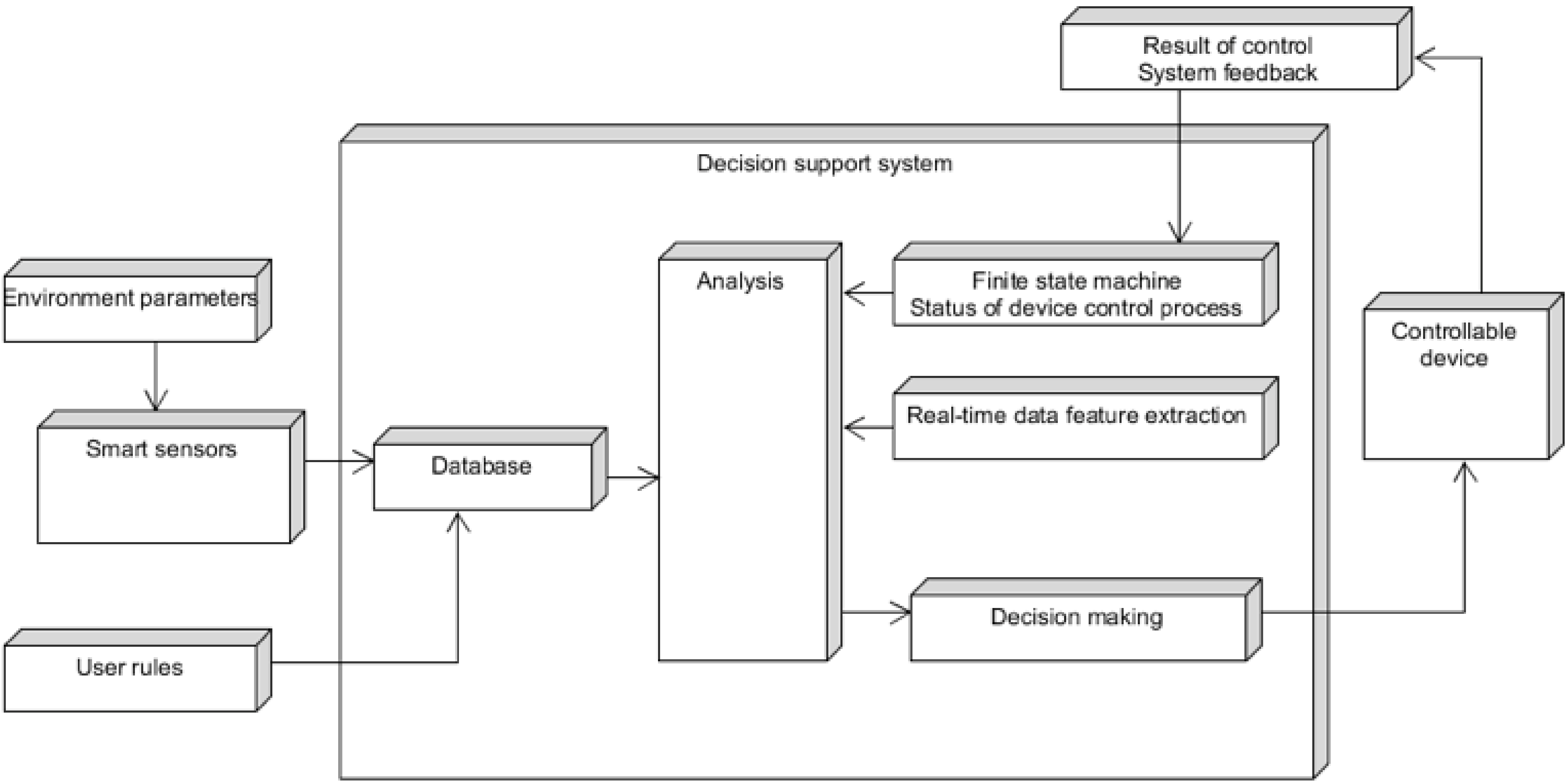


Sensor concentrator



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

STRUCTURAL SCHEME OF ENERGY MANAGEMENT DECISION SUPPORT SYSTEM



The decision support system is a part of e-service system and may be analysed 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

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

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
- what response will be received from the system to confirm the management decisions

For this purpose, the task, management, and analysis modules were proposed

ARTIFICIAL LIGHTING MANAGEMENT SUBSYSTEM

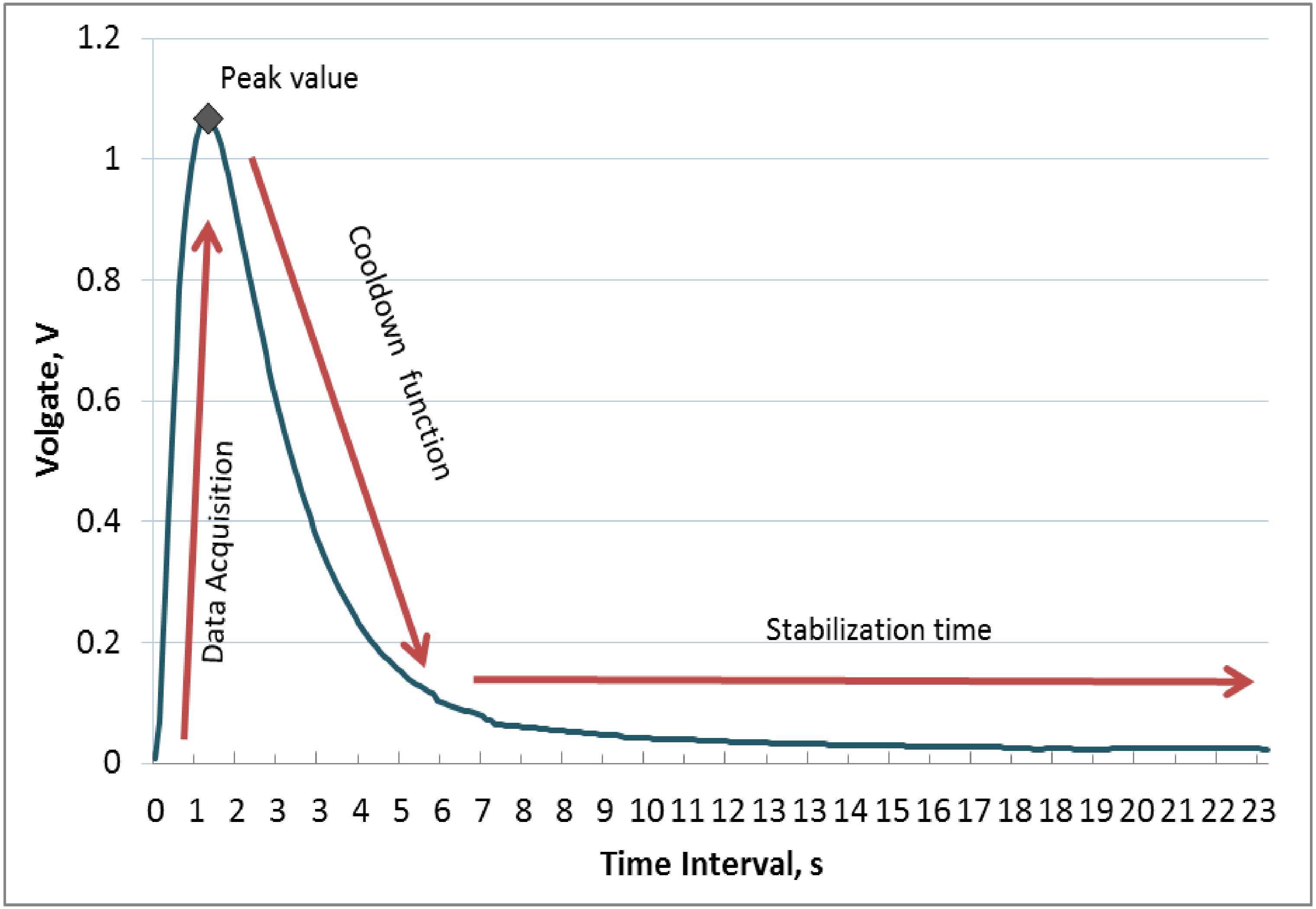
Smart e-service system must include the lighting control subsystem, which would be able to provide the lighting management services by ensuring comfort with lowest energy consumption. In human environment, lighting can be described by various modules. For example, the case when human environment is limited, 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 $E_a(P)$

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

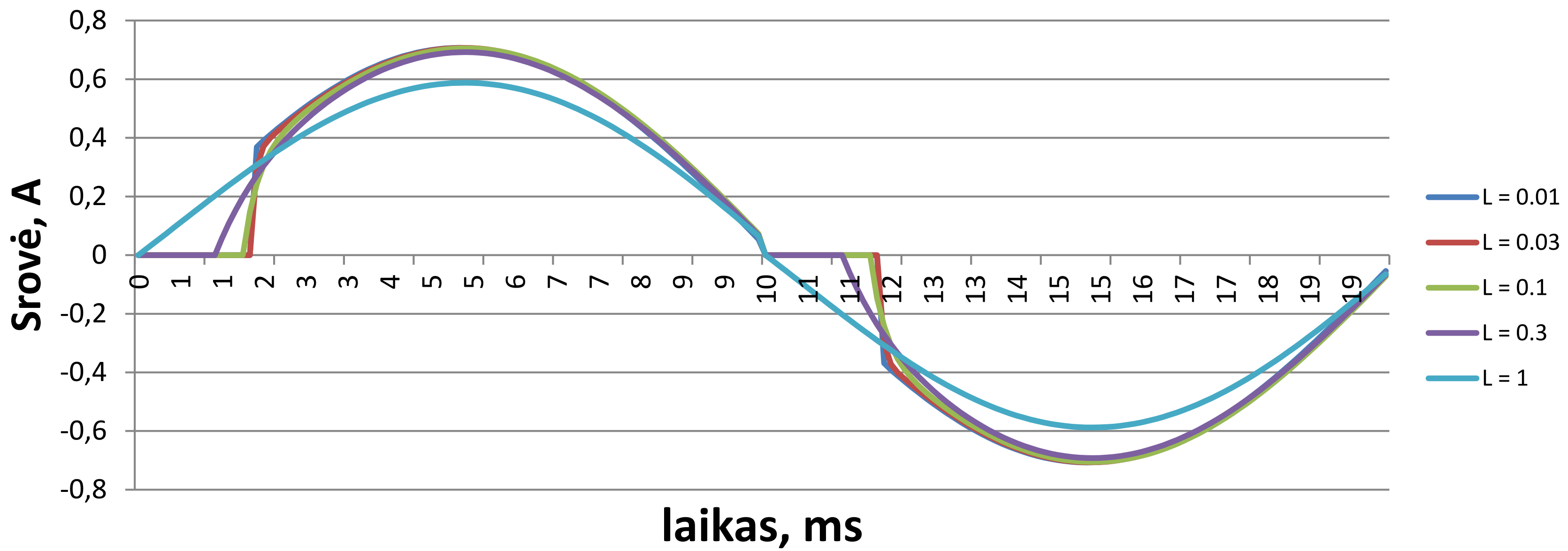
$$+\frac{I_L\frac{Lumen}{1000}\cos(\gamma)^3}{d^2} + \frac{Lumen\cdot\eta\cdot M\cdot P}{Sum_{AREA}\cdot(1-\sigma_{weighted})}$$

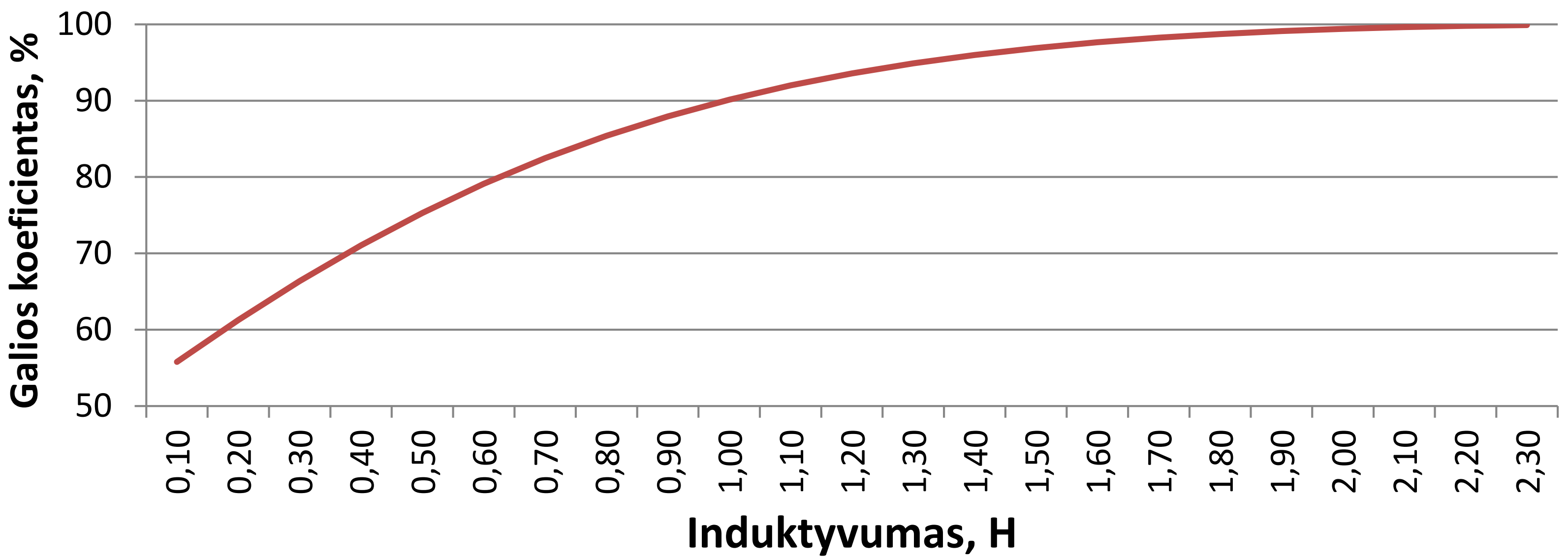
Where $E_a(P)$ – environment lighting at the considered point $P(x,y,z)$ (*lx*), $E(ND_{gl})_j$ – natural diffusion lighting through window (lx), $E(NR_{gl})_j$ – natural window-reflected lighting in window (*lx*), $E(NAT_{gl})_j$ – natural direct lighting through window (*lx*), C_{mc}/C_{mr} – diffusion 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

IMPORTANT STABILIZATION TIME INTERVAL

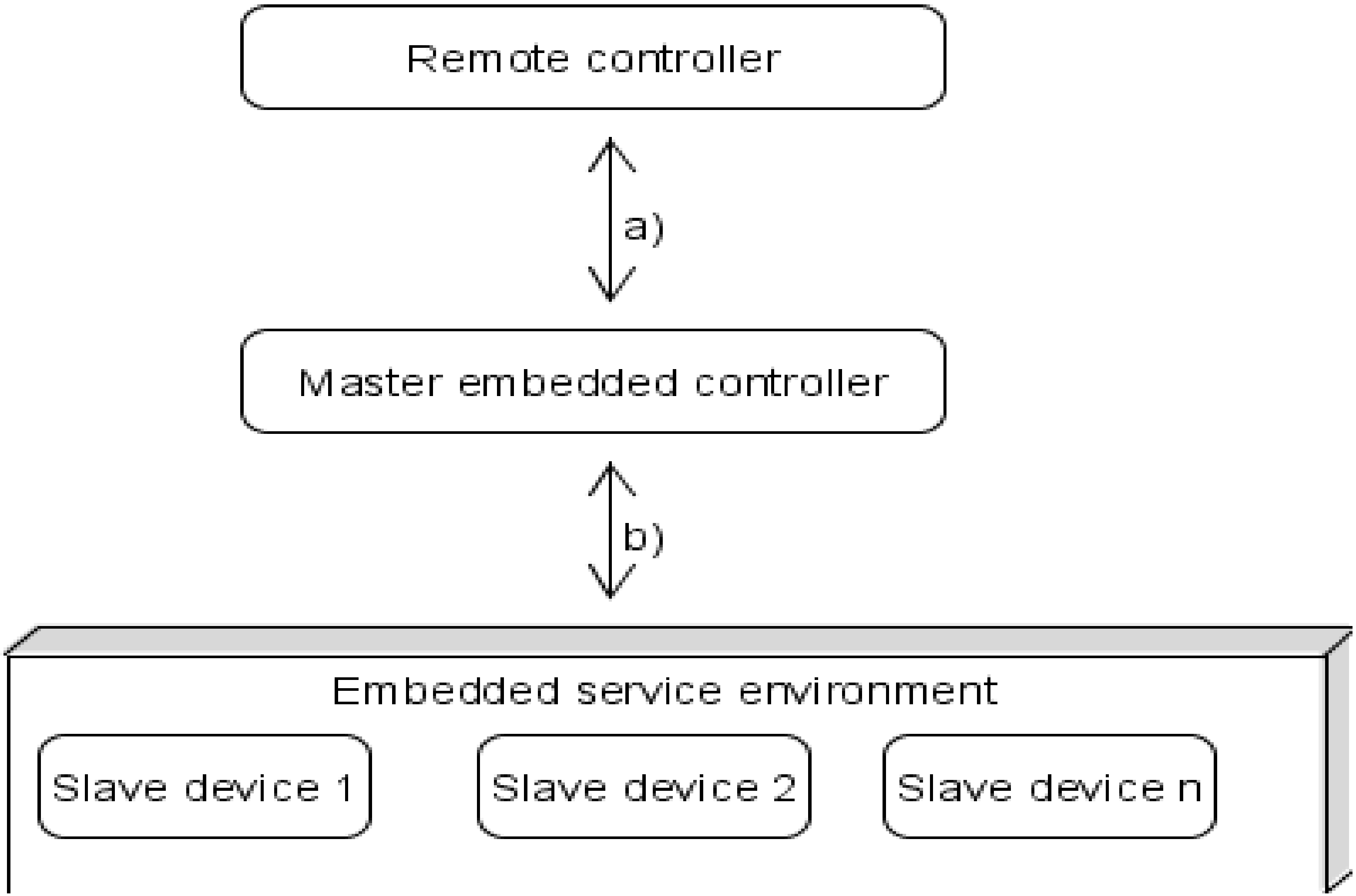


EXAMPLE OF MAXIMUM ADJUSTMENT OF THE DEVICE

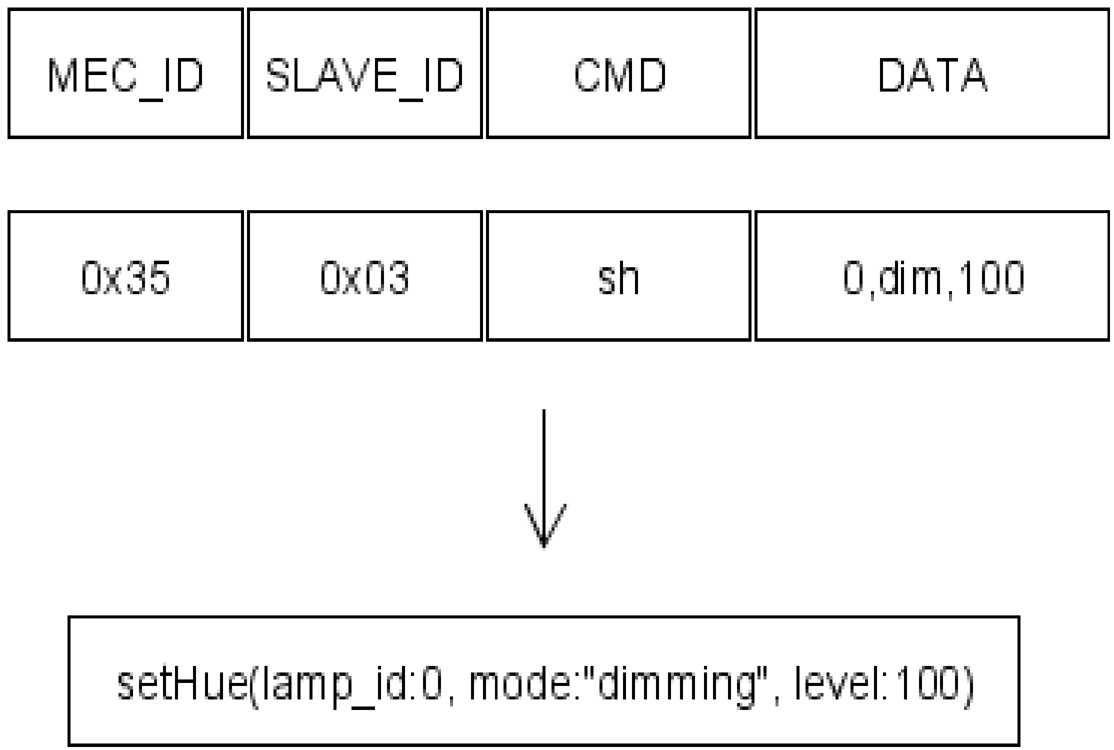




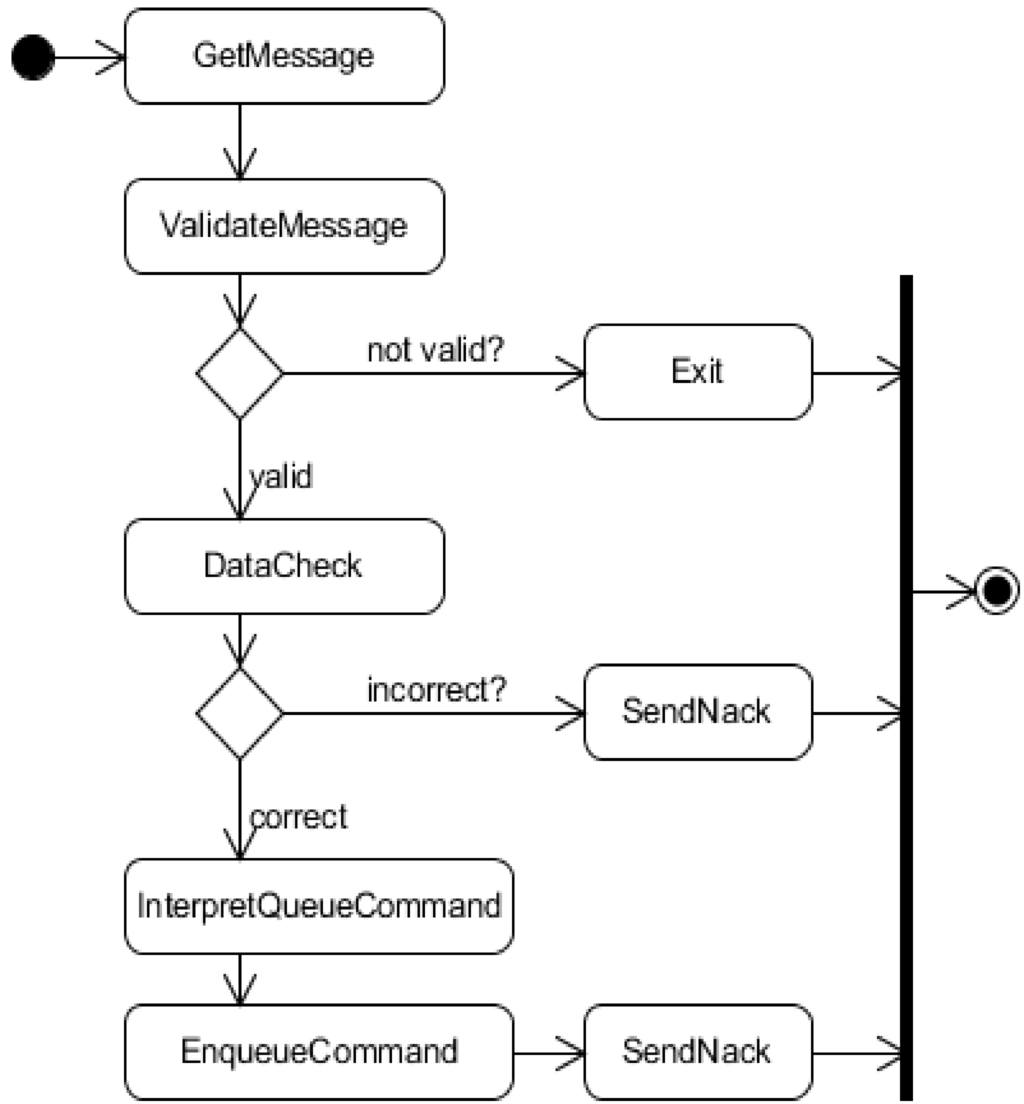
STRUCTURE OF THE EMBEDDED SYSTEM



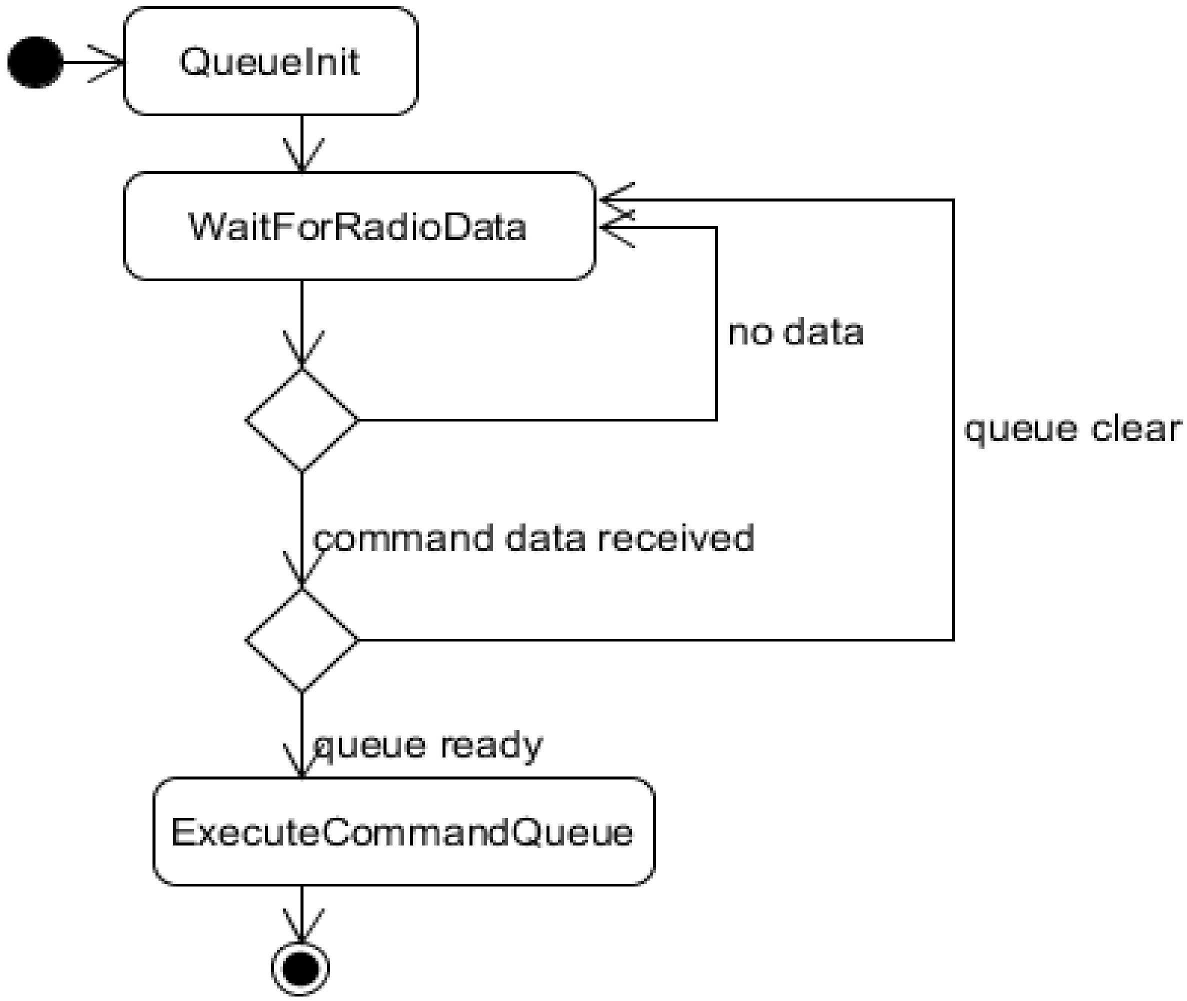
COMMAND INTERPRETATION IN THE DEVICE



INTERPRETATION OF TRANSFERRED DATA MESSAGE



MANAGEMENT OF THE COMMAND STRUCTURE IN THE DEVICE



TYPES OF ENERGY FORECASTS

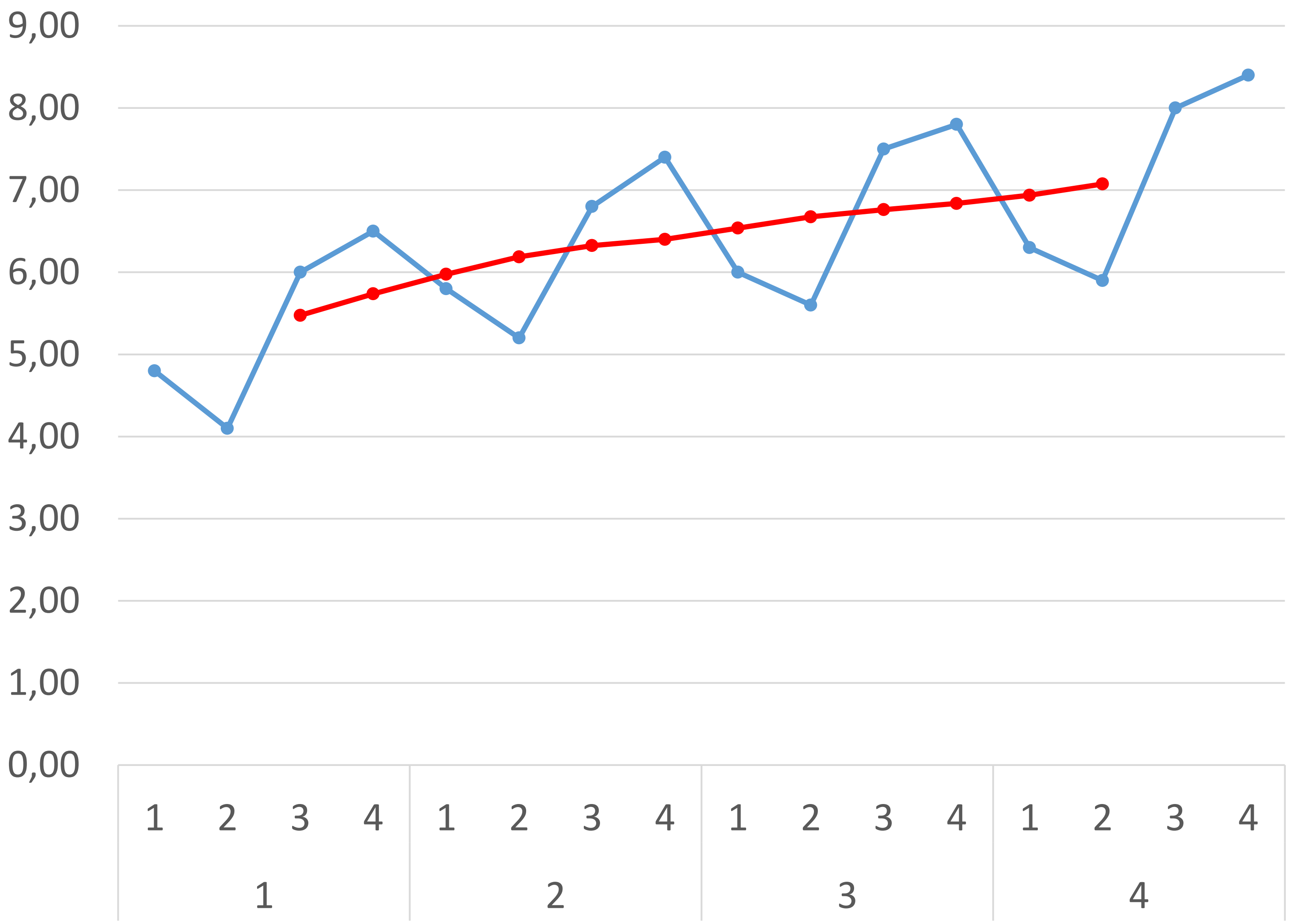
- Consumption demand forecast
- Energy production forecast
- Device management based on estimated outcomes

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

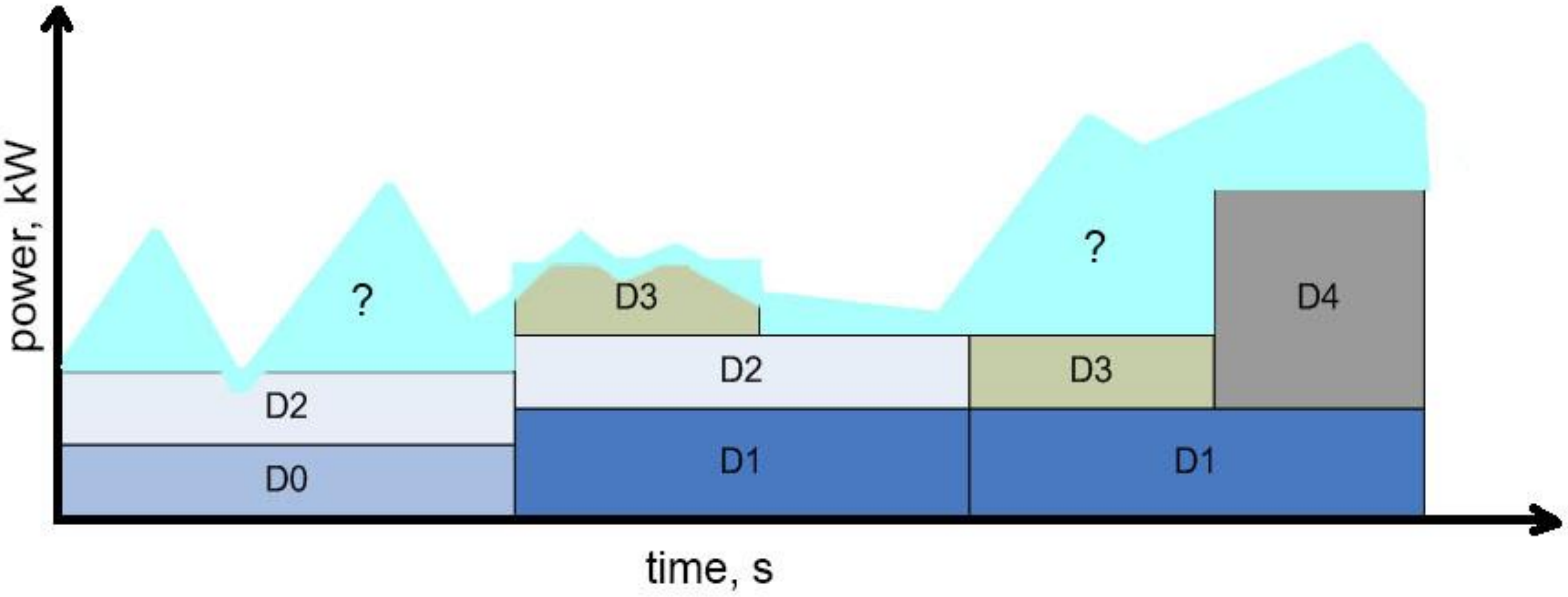
DATA OF ENVIRONMENT PARAMETER

seasonality

direction



THE DEVICE SCHEDULE PLAN AND THE USE OF RESOURCES



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)

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 “?”.

EXPERIMENT (1)

The experiment was designed to find out the application of mathematical models and nonlinear algorithms in the embedded systems in order to obtain feedback for the correction of management decisions

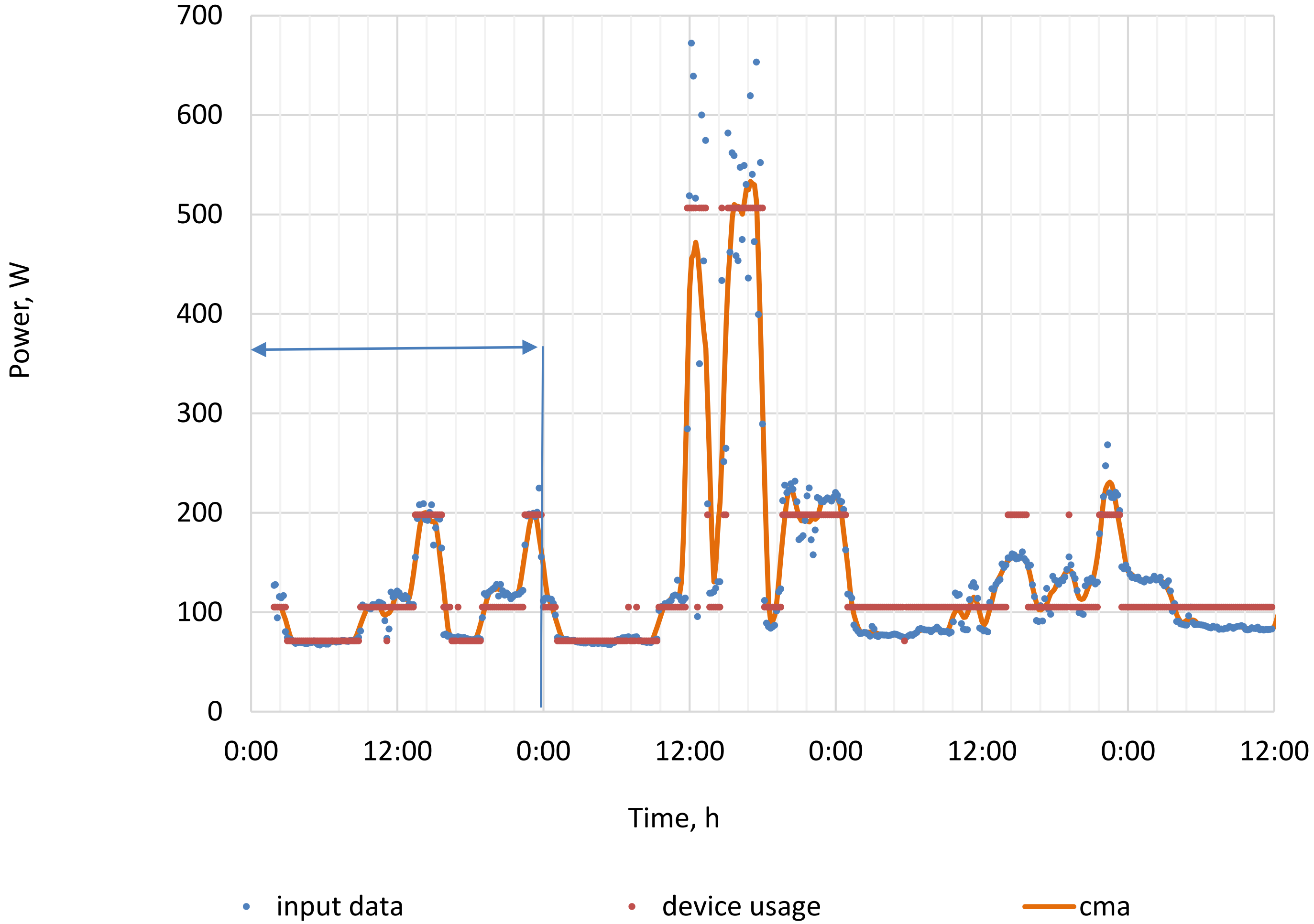
Within the experiment, the result of ARMA model and Kalman filter algorithms for the estimation of electric energy costs were considered. The aim was to clarify the used forecast algorithm in the initial data processing based on the task execution plan

EXPERIMENT (2)

During the experiment, an implementation plan for the equipment according to the time of use of the laboratory equipment was made

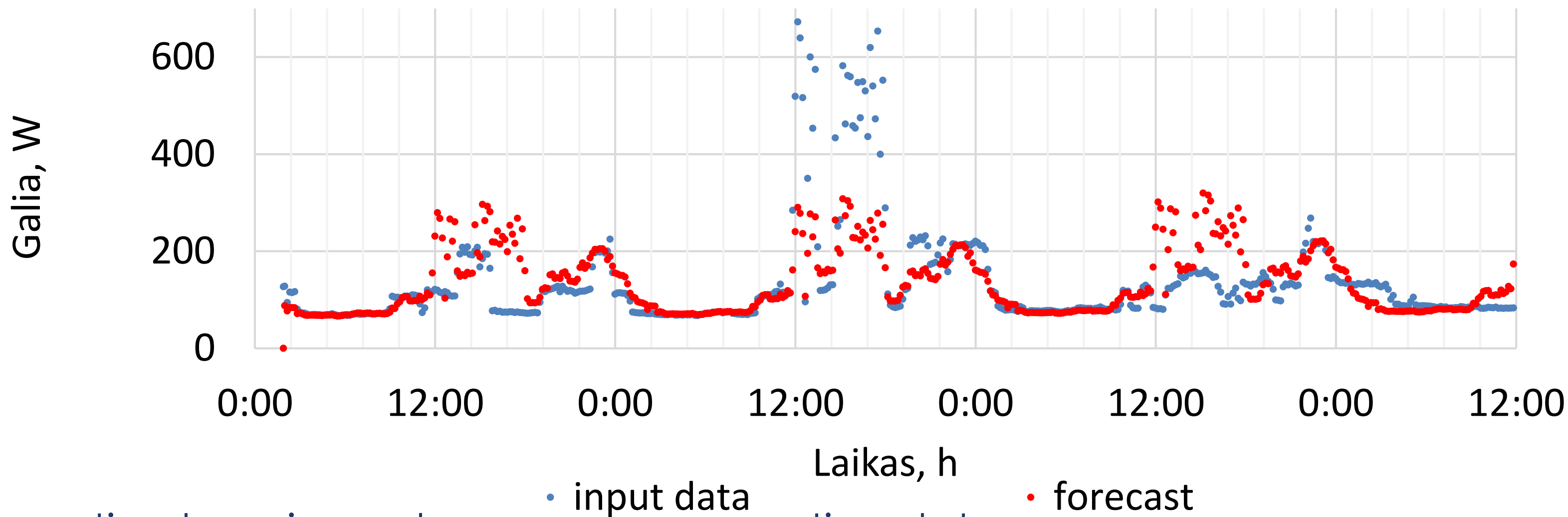
Different sources of artificial lighting have been used to obtain the diversity of data consumption. To validate the feasibility of using the task plan statistical, nonlinear autoregressive and filtering forecast models were evaluated

DEVICE SCHEDULE PLAN AND REAL ENERGY CONSUMPTION

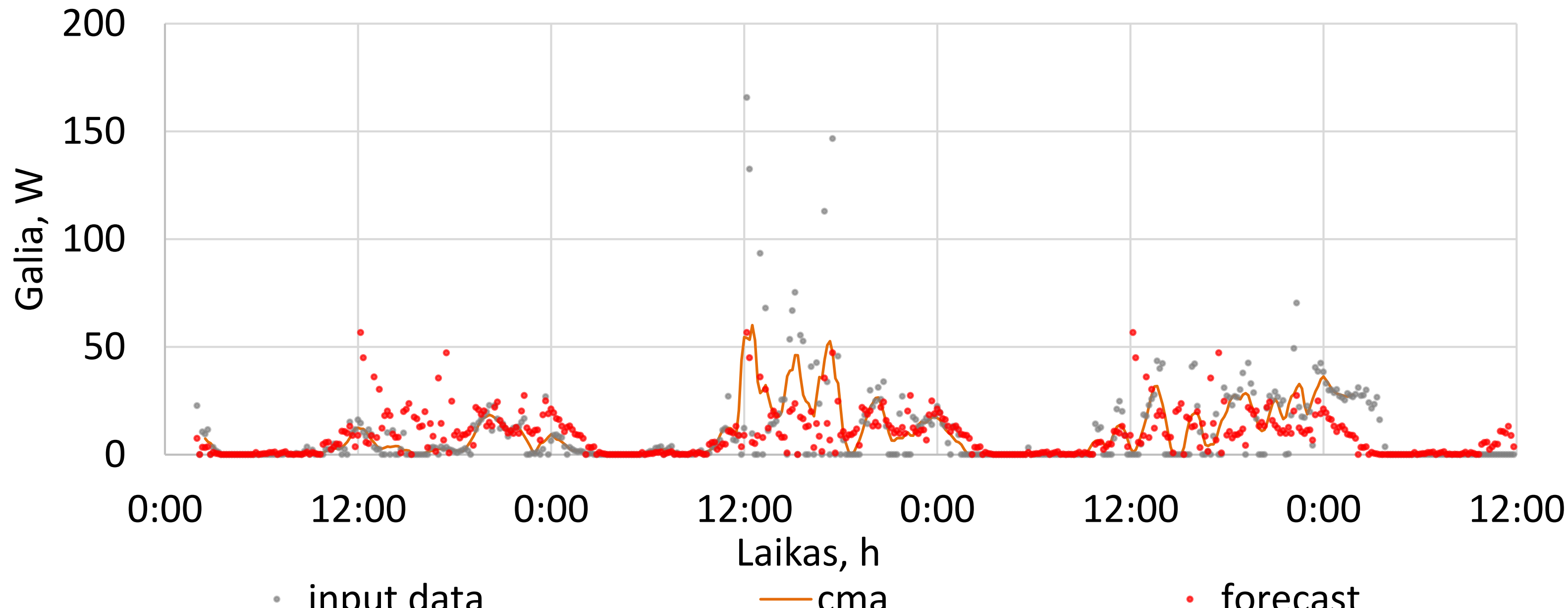


Input data – consumption data,
cma – centered moving average,
forecast – forecast data

FORECASTING WITH ARMA MODEL



forecasting by using only energy consumption data



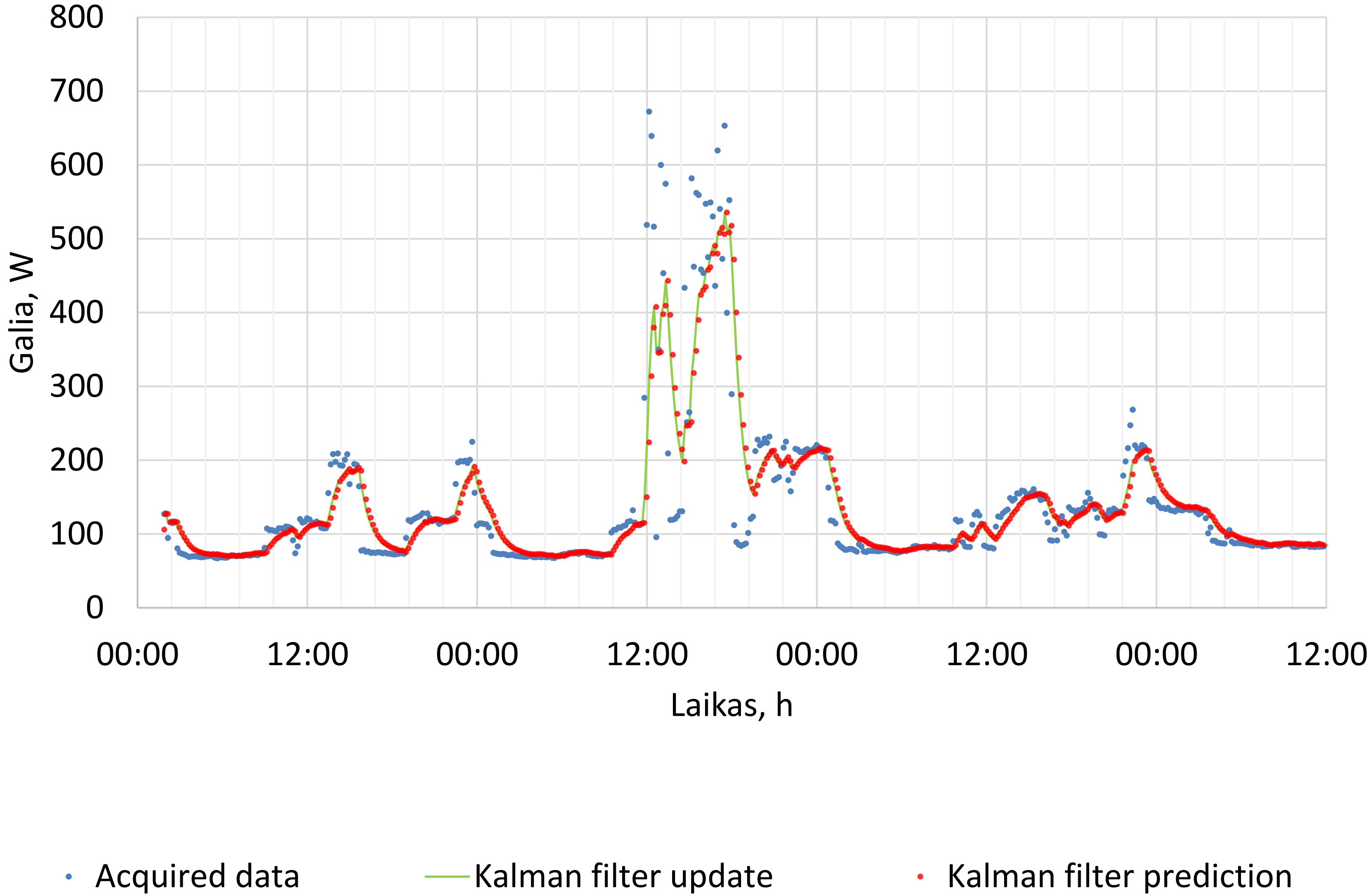
forecasting, which depends on the device schedule plan

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

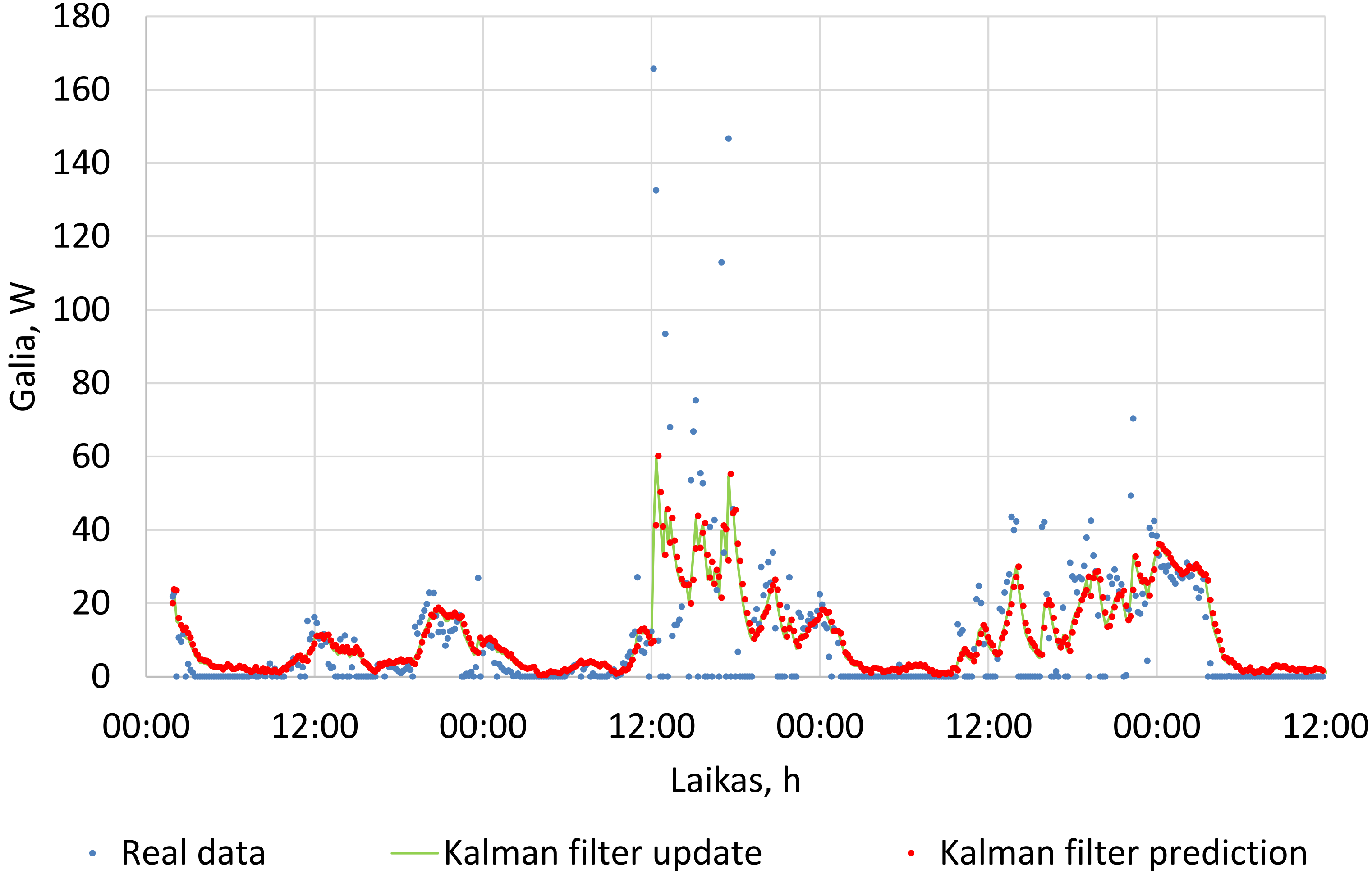
Input data – consumption data, cma – centered moving average, forecast – forecast data

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 over time. Newly obtained values are equal to the difference between the actual monitoring values and average consumption of the device

FORECASTING WITH KALMAN FILTER



FORECASTING WITH KALMAN FILTER BY USING THE DEVICE SCHEDULE PLAN



SUMMARY OF FORECAST RESULTS

The average square deviation is used to summarize the forecast results (RMS)

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

An additional estimate has been calculated in order to obtain the average percentage distance between the real points x and the values of the plan of use of the equipment point p at the same time:

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

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

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

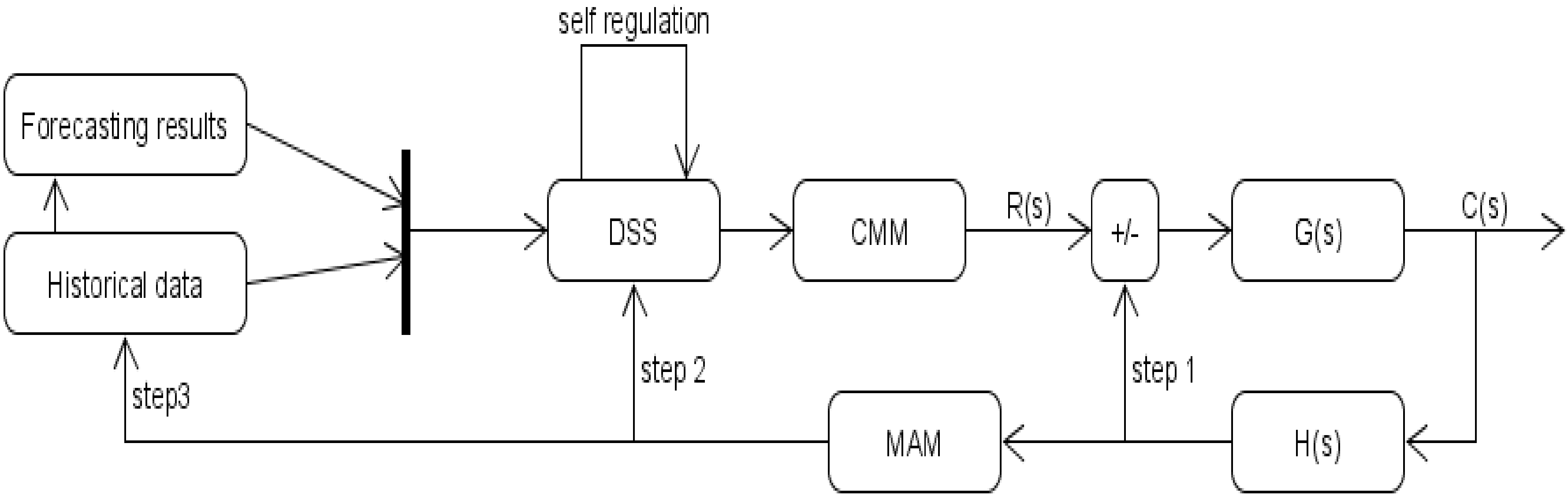
FORECAST SCORE SUMMARY

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

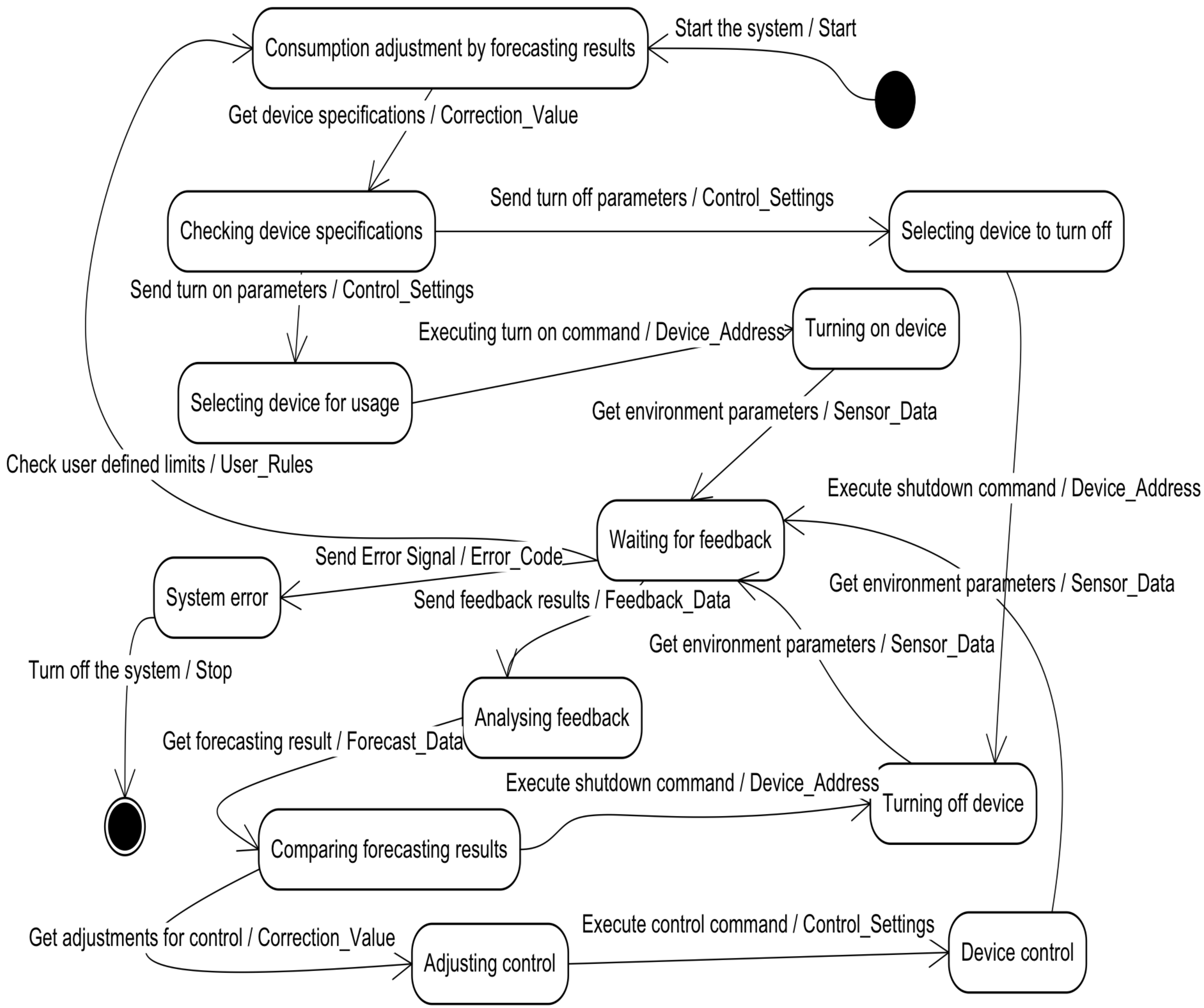
STRUCTURE OF THREE-STEP FEEDBACK IN THE ENERGY DATA MANAGEMENT SYSTEM



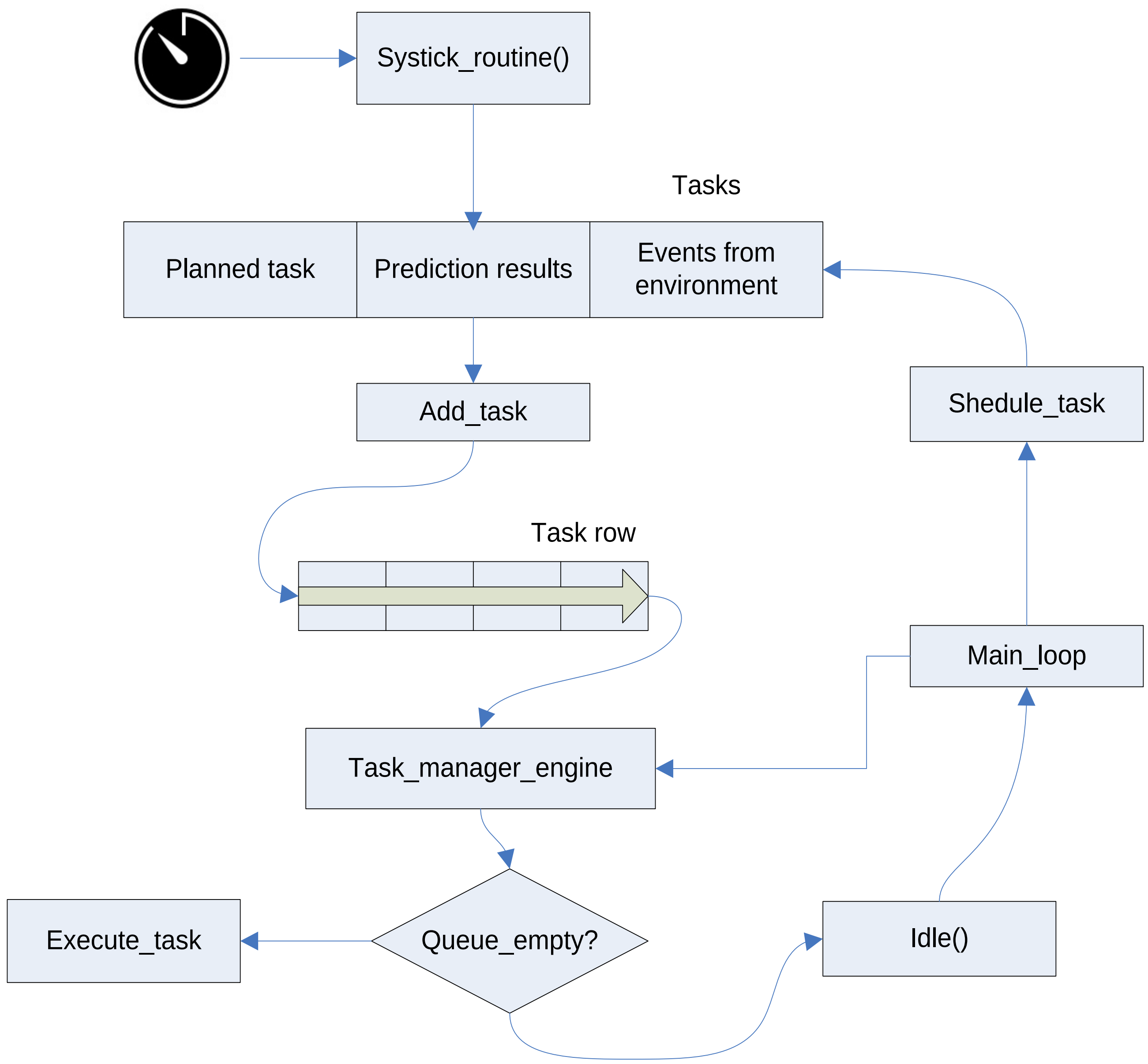
DSS – sprendimų priėmimo sistema (decission support system)
CMM – komandų valdymas (Command management module)
G(S) – tiesioginis kelias (Forward path)
R(S) – korekcijos kintamasis (Reference Variable)
H(S) – grįžtamojo ryšio kelias (Feedback path)
MAM – (įrenginio valdymo analizė) Management analysis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

Ed

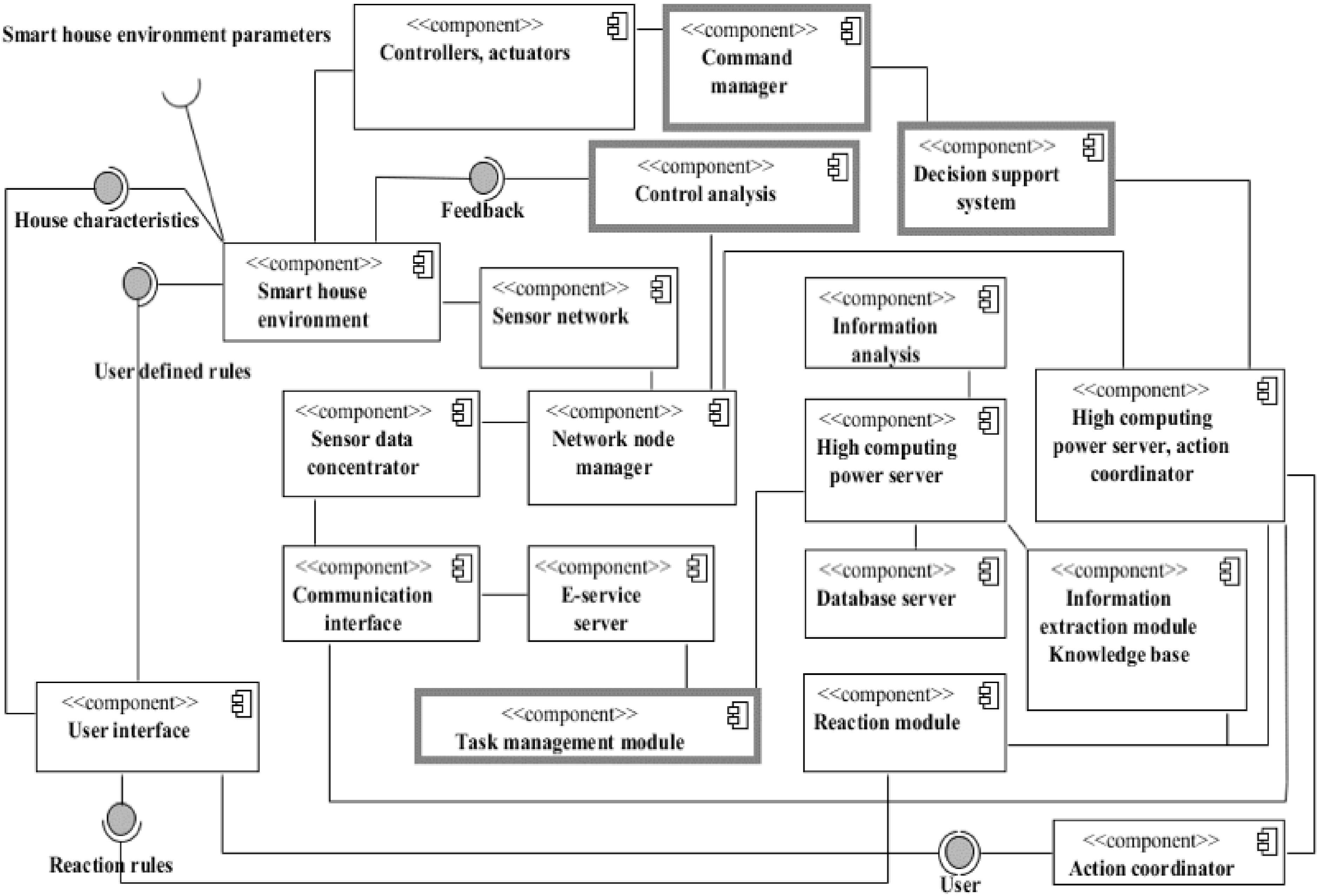
FINITE-STATE MACHINE OF THE ENERGY MANAGEMENT DECISION SUPPORT SYSTEM



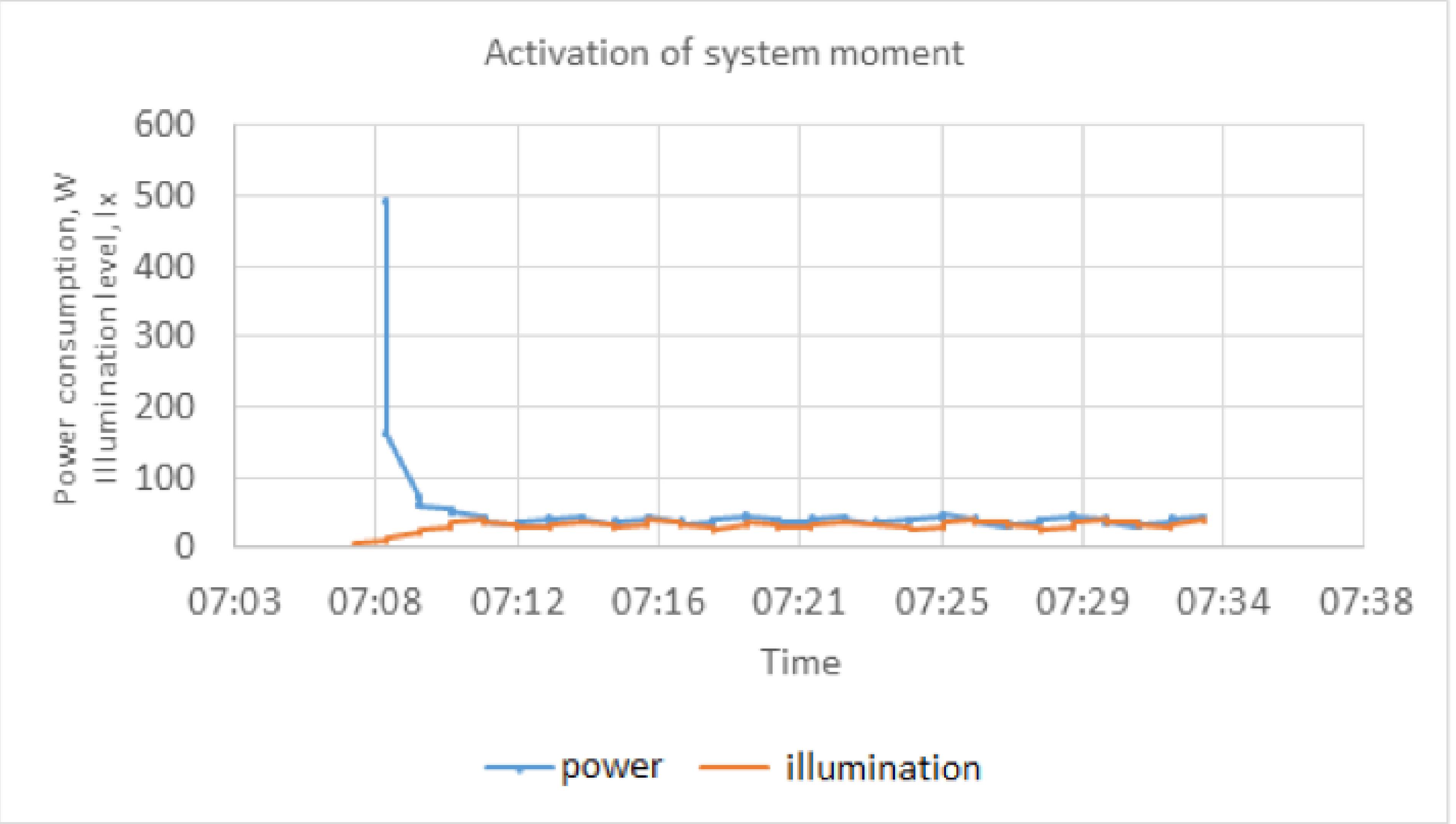
TASK MANAGEMENT IN THE INTEGRATED SYSTEM



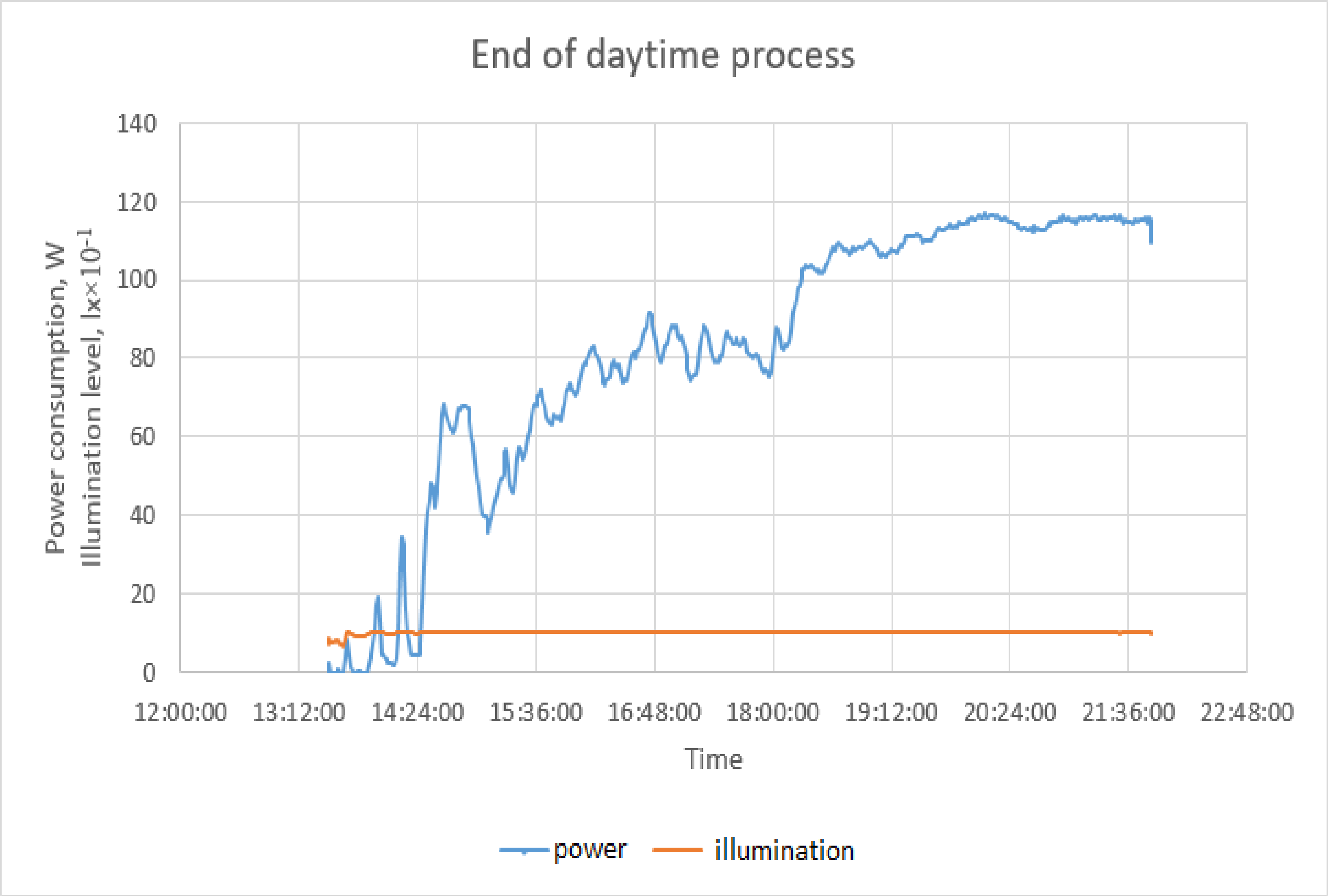
ARCHITECTURE OF ENERGY MANAGEMENT SYSTEM



ACTIVATION OF THE ENERGY SYSTEM PROTOTYPE



MONITORING THE PROCESS OF THE END OF THE DAYTIME AND AUTONOMOUS MANAGEMENT OF ILLUMINATOR



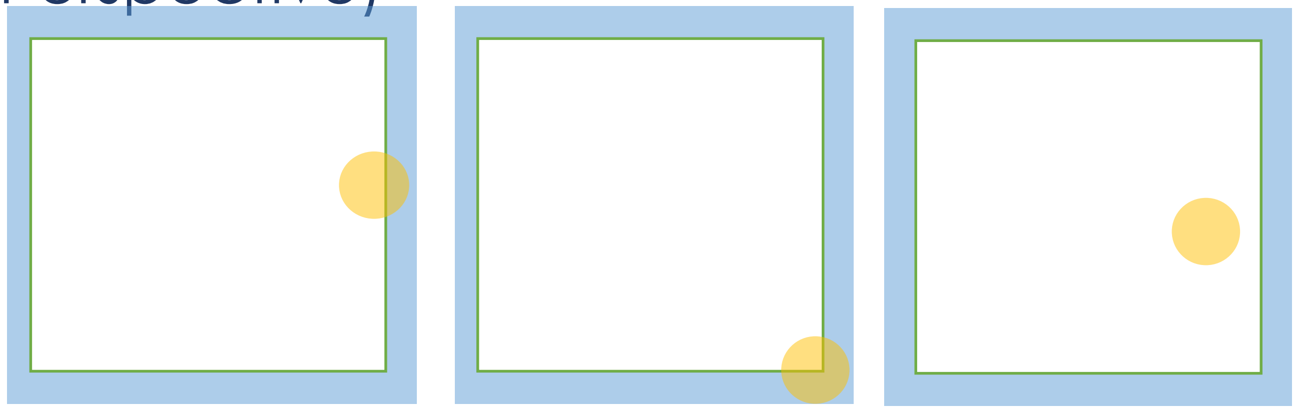
CONTROL OF LIGHTING

	vidutinės sąnaudos, Wh	stebėjimo trukmė, h	suvartojimas per parą, Wh	suvartojimas per mėnesį, kWh	el. energijos kaina	sutaupoma suma	
Reguliuojami 120W šviestuvi	38,74	08:20	322,82	9,82	0,11 €	1,12 €	32,28%
Nereguliuojami 120W šviestuvai	120,00	08:20	1000,00	30,42	0,11 €	3,47 €	
Reguliuojami 150W šviestuvai	68,74	08:20	572,82	17,42	0,11 €	1,99 €	45,83%
Nereguliuojami 120W šviestuvai	150,00	08:20	1250,00	38,02	0,11 €	4,33 €	

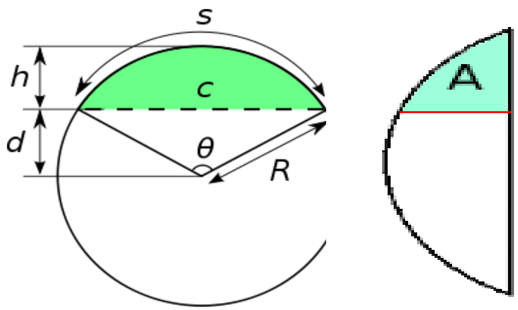
THE FEATURES AND POSSIBLE IMPROVEMENT OF THE ENERGY MANAGEMENT SYSTEM ARCHITECTURE

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.

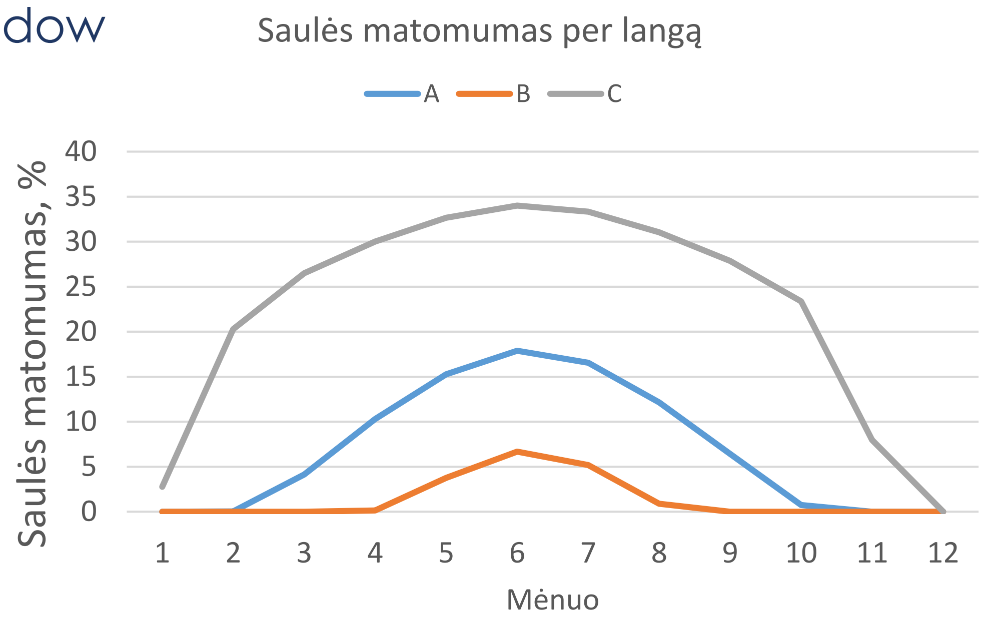
EVALUATION OF NATURAL LANDSCAPING (Perspective)



Sun's position through window

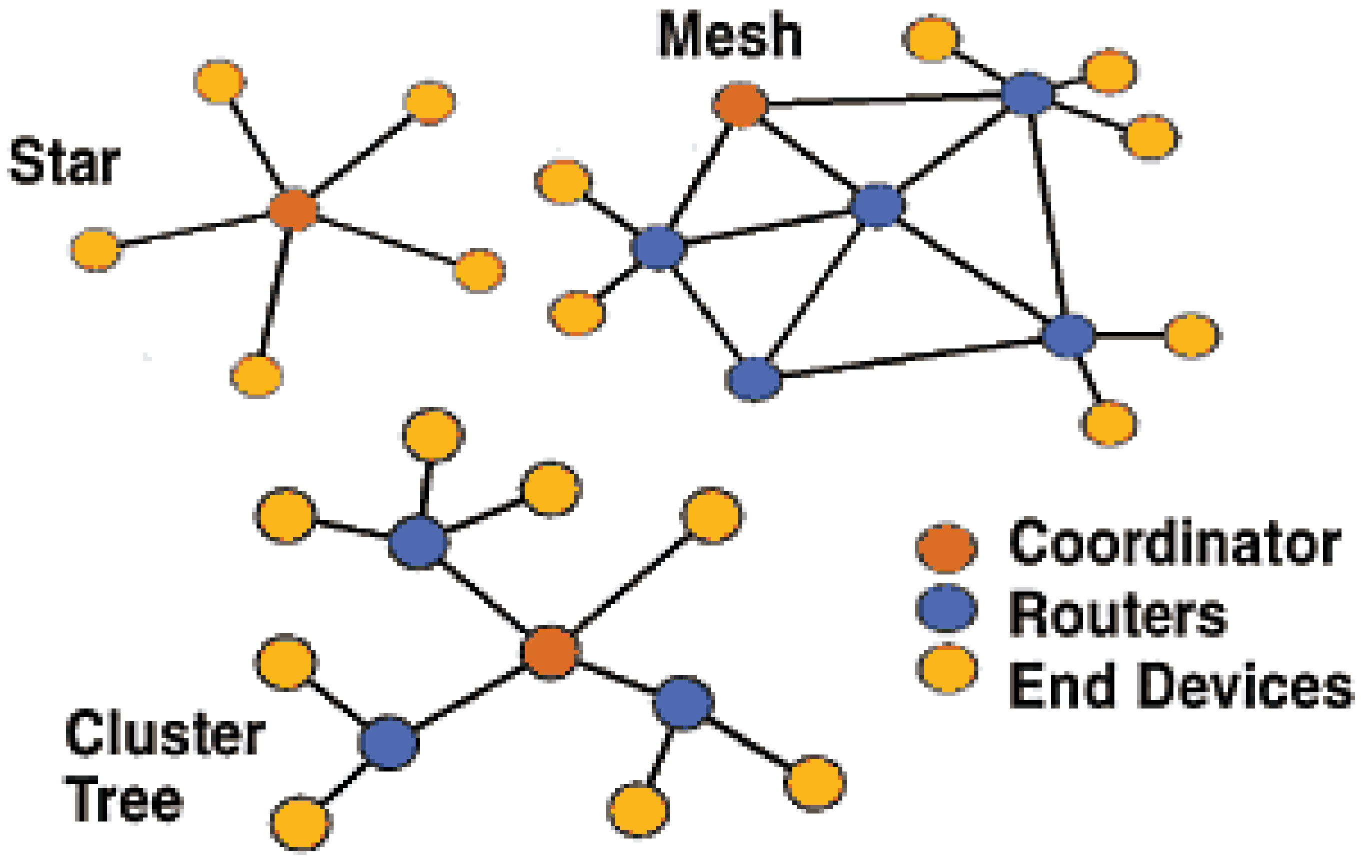


Calculation of Sun through a window



Saulės pozicijos duomenys leidzia įvertinti konkrečios aplinkos galimybes (pasinaudoti naturaliu apšvietimu)

EXAMPLES OF TOPOLOGIES



(Kanda, 2016)

CONCLUSIONS (1)

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

CONCLUSIONS (2)

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 proposed sensor network devices are configurable during runtime. This ensures not only a mobile but also a real-time adaptive network topology

CONCLUSIONS (3)

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, it is possible to 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%

CONCLUSIONS (4)

It was proposed 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 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

Thank you for your attention!