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Experimental Plant for Supervision and Monitoring of an Intermittent Heating System for Engineering Training*

MILADIN STEFANOVIC
Faculty of Engineering, University of Kragujevac, Serbia. E-mail: miladin@kg.ac.rs

MILAN MATIJEVIC
Faculty of Engineering, University of Kragujevac, Serbia. E-mail: matijevic@kg.ac.rs

DRAGAN LAZIC
Faculty of Mechanical Engineering, University of Belgrade. E-mail: dlazic@mas.bg.ac.rs

In this paper we will present the development and implementation of automation, regulation and measurement of heating energy consumption in the University auditorium, which could be used for training and education in different engineering fields (civil engineering, control engineering, process engineering and software engineering). Using a real remotely controlled system, educators are able to demonstrate the real-world principles of thermodynamics, fluid mechanics, and controls as well as to compare data from real systems and from models and software simulations. The presented system is in use at the Faculty of Mechanical Engineering in Kragujevac.

Keywords: HVA; heating systems; engineering education; energy consumption; buildings

1. Introduction

The increasing prices of energy resources and growing environmental awareness of climate change have focused a great deal of attention on energy conservation approaches and technologies that can improve energy efficiency and reduce energy consumption. In particular, energy expenditure for temperature control in buildings accounts for up to 30% of the total budget and it is set to increase with the proliferation of air conditioning systems [1].

Buildings and obtaining energy savings through different appoaches is a very important issue. Annually, buildings in the United States consume 39% of America's energy and 68% of its electricity [2]. The energy consumption of residential and commercial buildings is a very important issue and has been the focus of many researches. This issue could be addressed from different stand points, starting from civil engineering, process engineering, control engineering, and information and communication technologies. All these approaches have in common the goal of reduction of energy consumption. One approach could be based on the reduction of energy consumption in buildings through the automation of objects, especially in the fields of regulation and measurement of heating energy consumption. The control of smart structures is a particularly interesting application area. These include flow control, vibration, etc. [3].

Home and building automation are concerned with the monitoring and automatic control of building services. These are primarily heating, ventilation and air conditioning (HVAC) systems and devices for lighting and shading [4]. Good HVAC control is often the most cost-effective option to improving the energy efficiency of a building [5]. It is important to provide an ongoing process that improves the operation of buildings using measured hourly energy use and environmental data [6].

Developed countries have been dealing with issues of energy saving and savings in heat energy, taking in to consideration not only the efficient distribution of heating energy but other factors that influence the heating of objects such as: the times at which specific parts of buildings or whole buildings are out of use; solar radiation; and the latent heat of individuals who are present or electrical devices. Several standards have been developed in parallel for the integration of heating systems, cooling systems, ventilation and lighting systems in one unique control system. The European KNX/EIB and the American LON standard are dominating the designs of these systems. A number of papers and researches give reviews of the current state for specific aspects of a fully automatic operation of heating for both domestic and University buildings [7, 8].

It is clear that engineering education in the field of increased savings of energy and reduced energy consumption in different types of buildings is a multidisciplinary and interdisciplinary task. In engineering education, for energy saving in buildings, it is hard to provide real system that students can use for testing or for data analysis.

Over the last few decades, a large amount of

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software for building energy consumption and savings programmes has been developed, improved and is currently in use. The core tools in the building energy field are whole-building energy simulation programs, which provide users with key building performance indicators such as energy use and demand, temperature, humidity and costs [9]. There is no doubt that this software is useful but a number of concerns remain nevertheless: the performance of the indicated capabilities and, most importantly, the scope of the model used. Other approaches use developed models of buildings and testing either directly or over the network [10, 11]. Although educators need to be aware of the limitations of commercially available building automation systems, remotely accessed Heating, Ventilating, and Air Conditioning (HVAC) equipment is an excellent way of demonstrating the real-world principles of thermodynamics, fluid mechanics and controls [12, 13]. The widespread use of computer controls for optimizing the efficiency of mechanical and electrical systems in commercial buildings has created a real opportunity for delivering lab-based distance education, so different remotely controlled HVAC laboratories have been developed [12, 14], as well as other remotely controlled laboratories for laboratory experiments in different fields of engineering (control, process, industrial engineering) [15, 16]. It is also clear that laboratory set-ups and models have their own limitations. In some cases work with a real-life system is the best way to demonstrate some real-world principles, as well as to provide the most challenging and interesting environment for creative [17] and problem-based projects [18] for engineering training and education.

In this paper we present the automation of a real-life system, developed and implemented in order to provide an educational system that will demonstrate energy use and demand, consumption and savings of a real system under real-life conditions.

In this paper, we present an experimental plant for the supervision and monitoring of an intermittent heating system of a University building. An auditorium for students is automated for the regulation and measurement of heating energy consumption. All the measured data are stored in an open database that is available for students and a third party. For advanced education purposes it is possible to change the control algorithms and parameters on the regulators. This system is integrated with a system for an RFID (Radio-frequency identification) -based access control system (which tracks the number of students in the auditorium) to further increase the control schemes with presence detection and time table information. In this paper we have presented the technical characteristics and the implementation of a controlled system as well as its educational possibilities.

2. Technical characteristics and implementation of a controlled system

2.1 Technical characteristics of the system

In educational buildings the movement of students and teachers and, usually, a lack of personal responsibility often results in a high consumption of heating and electrical energy. So university rooms, buildings and heating substations typically offer a large potential for improving energy efficiency [19]. The main idea is to provide automation of the object (here the auditorium at the Faculty of Mechanical Engineering) for monitoring, control of the heating system and its integration with an RFID-based access control system. (In the faculty all students possess RFID identification cards (MF1 IS S50-Philips).) Transceivers are placed in front of the auditorium and near the exit, so students can easily check in and out. The support software was developed using PHP/Java solution with MySQL Data Base.

The general aim is to evaluate heat energy savings, estimate the effects of the heating control concept, coupled with information about the occupation of the auditorium and to provide an educational platform for analysis of the measured data and for the testing of different control and engineering strategies. For control and educational purposes the control algorithm could be changed and adjusted as well as the full measured data from all the subsystems.

The technical solution is based on the KNX/EIB standard. As the first open standard for automation of objects, KNX is a standardized (EN 50090, ISO/IEC 14543), OSI-based network communications protocol for intelligent buildings. This standard is common for home and building automation [21].

Based on a predefined and measured temperature, a regulator control signal is generated and the signal is sent to regulatory valves that regulate the flow through heating circles and heating consumption. Using a calorimeter: heating consumption, temperature distribution and the return temperature, and flow of water is measured.

All devices are connected by bus cable for the interchange of information between each other and using a special device, are connected to the local computer network. This makes all measured parameters and data about the system condition available on the local computer network.

Using a special computer, FacilityServer, complex control functions, graphical representation of system parameters and access through the local computer network and Internet could be realized.

Some of the characteristics of this solution are:

- optimal energy consumption with greater comfort,
- a simple set of heating regimes and defined temperatures,
- intuitive graphical visualization,
- acquisition of data for analysis,
- the supervision, control and maintenance over the local computer network or Internet,
- implementation on the existing heating systems,
- the possibility of interaction with other heating systems, cooling systems and climatization systems, lights and blinds.

The complete system was implemented in the auditorium at the Faculty of Mechanical Engineering in Kragujevac. The functional scheme of the system is presented in the Fig. 1.

The auditorium is 1200 m^3, has 247 seats, a flat roof, and 42 m^2 of 3-mm glass on two sides, north and south. Heaters have been placed along the south and north walls of the auditorium. The fluid flow through the heater – convectors is controlled by two independently controlled three-way valves V1 and V2. In the case of control with a closed feedback loop, the feedback is closed according to the defined/desired temperature in the auditorium. Six internal temperatures are measured: three sensors are on the bottom of the auditorium, two are on the top, and one in the middle. Five of them are placed at a height of 1m, and one at 1.70 m. The two sensors are one above the other in the bottom-right/south of the auditorium. Temperature regulation is controlled according to the temperature T3 for the right flow, and T1 for the left flow. The control algorithm is PI (Proportional and Integral). Some findings state that using PI – heating control versus standard thermostats results in a 10–15% saving, others report 20–30% savings in residential and large apartment buildings [14]. It is also possible to easily (implementating different software) change the control algorithm and its parameters. A calorimeter with an integrated module for KNX/EIB is used in the system.

The system also contains other components:

- Siemens Pt1000 N258 input/output module for the reading of temperatures from passive temperature sensors (T0, T2, T4 i T5),
- Siemens N670 universal module for the control of the drive of three-way valves (0–10 V DC control signals),
- IP/EIB router for the connection between EIB and TCP/IP network,
- 2 × ARCUS SK03 temperature regulators with integrated temperature and air humidity sensors,
- 2 × ARCUS NZR calorimeters, and
- ARCUS Z38 controller with a touch screen, which is installed in the auditorium for the definition of regimes and monitoring of current temperatures.

The system could be in a controlled regime with the control of the position of valves V1 and V2 (Fig. 1) and in a non-controlled regime where the valves are

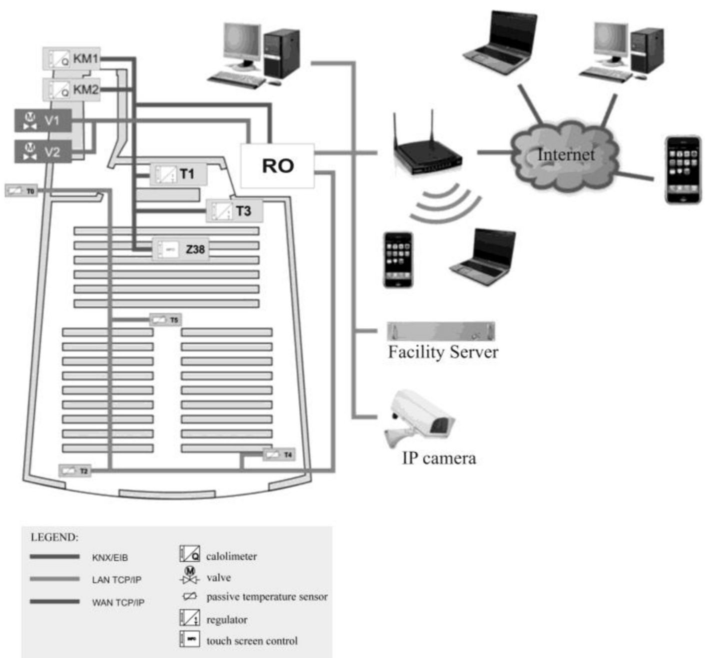

Fig. 1. Diagram of the system implemented at the Faculty of Mechanical Engineering in Kragujevac.

maximally open (100%). In both cases all indicators could be measured.

2.2 Data acquisition

A large amount of data has been collected in order to support a wide usability of the experimental plant in the domain of identification, modelling and control of complex dynamic systems.

Every 3 minutes we have sampling and data acquisition of the following data:

1. Percentage of openness of valve V1 for heaters on north (left) side of auditorium *V1* [%] – *control valve 1 (control for valve V1).*
2. Percentage of openness of valve V2 for heaters on south (right) side of auditorium *V2* [%] – *control valve 2 (control for valve V2).*
3. Flow through heaters on north (left) side of auditorium KM1 [m^3/h].
4. Flow through heaters on south (right) side of auditorium KM2 [m^3/h].
5. Total volume of fluid flow through north (left) side of auditorium KM1 [m^3].
6. Total volume of fluid flow through south (right) side of auditorium KM1 [m^3].
7. Total consumption of energy due to heat exchange on north (left) side of auditorium KM1 [KWh].
8. Total consumption of energy due to heat exchange on south(right) side of auditorium KM1 [KWh].
9. Output power (heat exchange in unit of time) on north (left) side of auditorium KM1 [KW].
10. Output power (heat exchange in unit of time) on south (right) side of auditorium KM2 [KW].
11. Fluid temperature in distributor on north (left) side of auditorium KM1 [°C].
12. Fluid temperature in return on north (left) side of auditorium KM1[°C].
13. Fluid temperature in distributor on *south (right)* side of auditorium KM2 [°C].
14. Fluid temperature in return on *south (right)* side of auditorium KM2 [°C].
15. Outside temperature To [°C].
16. Desired/defined temperature in auditorium [°C].
17. Air temperature in auditorium on the position bottom-left (north) T1 [°C] – sensor is placed at height of 1 m.
18. Air temperature in auditorium at position top-left (north) T2 [°C] – sensor is placed on the wall of the auditorium close to the north side at height of 1 m.
19. Air temperature in auditorium at position bottom-right (south) T3 [°C] – two sensors are placed at 1 and 1.70 m located at the bottom of the auditorium on south wall.
20. Air temperature in auditorium at position bottom-right (south) T3 [°C] – two sensors are placed at 1 and 1.70 m located at the bottom of the auditorium on the left south wall.
21. Air temperature in auditorium at position top-right (south) T4 [°C] – sensor is placed at the table on the top of the auditorium, closer to the south side, at a height of 1 m.
22. Air temperature in the middle of auditorium T5 [°C] – sensor is placed on the table at a height of 1 m.
23. Relative air humidity in auditorium at position 'bottom – left' RH [%].
24. Relative air humidity in auditorium at position 'bottom – right' RH [%].
25. Sampling time *m* [min] – form: date, time.

In addition to the above-mentioned values, with the same sampling period, using an integrated supervisory system the information: Number of the persons in the auditorium RFID-N [-] is collected.

The sampling time is initially set to 3 minutes but this value could easily be changed using a supervisor account. The main idea is to provide frequent measurements and to store all data in a database for analysis and educational purposes. Data stored in the database could be used for various problems in identification, modelling and control of a complex dynamic system, but it could also be used in the development of new control algorithms. In addition, all the stored data could be very useful in testing, verification and validation for defining optimal heating strategies in order to decrease energy consumption, increase savings and improve comfort in the auditorium.

2.3 Heating regimes

The standard setting of the system considers four different heating regimes: COMFORT, STANDBY, NIGHT, ANTIFROST. By changing the defined temperatures on the temperature regulators, the heating regimes can be changed. Regimes could be set using the control interface on a desk top computer, using a touch-screen panel placed near the blackboard in the auditorium or automatically by a programmed timer placed in the Facility Server.

The defined temperatures for specific regimes are:

- COMFORT 21°C – for use of auditorium (classes etc.)
- STANDBY 19°C – for pre-heating of auditorium and preparation for classes
- NIGHT 17°C – for adjusting overnight temperature and
- ANTIFROST 7°C – for periods of time when the auditorium is not in use.

Fig. 2. Graphical user interface.

While the system is under the control heating regimes the temperatures changes during the day according to the set timer in the Facility Server: at 06:00 the system is set in COMFORT regime; at 15:00 the system is set to STANDBY regime; at 20:00 the system is set to NIGHT regime, and at 00:00 the system is set to ANTIFROST regime.

All times could be changed and set using the user interface. The Facility Server is a computer connected by a local network to the IP→EIB interface for the exchange of information with devices KNX/EIB. The computer enables the visualization and performance of more complex functions. Owing to the nature of the system and its architecture software implementation, changes in the control algorithm are easy to make.

2.4 Visualization and control interfaces

There are three modules for the supervision, visualization and control of the system: supervisor (for control and setting of parameters), guest module for monitoring and module with visual supervision, (Fig. 2).

The supervisor could set the defined temperatures for a specific regime, change the control algorithm, control the flow through the valves and set all important parameters (schedule time tables for different regimes, temperatures). All users have access to the visual interface [20] in order to read all important parameters (temperatures at the control points, flow, humidity, flow and energy consumption – total consumption and current consumption in the left and right block). Users could also have a presentation of diagrams that show the desired (set) temperature and measure the temperature in a specific location or all locations, the temperature diagrams on the left and right side, as well as consumption in the left (north) and right (south) side of auditorium. Finally the user interface with monitoring gives visual feedback and data retrieved from the RFID-based access controlled system about the number of students in the auditorium.

2.5 Testing and verification

Verification of energy efficiency of the implemented solution will be performed by comparing appropriate periods and effects of the system, functioning in the new and in the old regime (non-controlled system vs. controlled system). Using the described system it is possible to monitor and control the system over a complete season.

In the first phase, internal and external air temperatures, temperatures of the water in the distribution and return flow, as well as energy consumption with and without the control are measured,

In the second phase, control signals and values for the left (north) and right (south) side of the auditorium, as well as all other values from the first phase, are measured but with temperature regulation. The parameters of the regulators are set according to recommended values for this type of heating.

Both phases are continually changing. Since the system is digital it is possible to set different testing regimes by implementating different control algorithms. A comparison of the results for controlled and non-controlled heating systems for working days could be presented. The same procedure was also performed for weekends.

On the same energy consumer (auditorium with 247 places) diagrams of the process values are presented when the system is controlled and non-controlled. The saving on the daily level when we read selected parameters is about 30% and about a 70% saving during the weekend. According to testing and analysis of the measured values, the parameters of the regulators could be adjusted in order to give optimal work according to comfort and energy saving. The improvement in energy efficiency is achieved without compromising student comfort. This system has performances that enable an ongoing process to improve the operation of the buildings using measured hourly energy use and environmental data.

3. Educational role

This experimental plant offers much wider possibilities because it enables an overview of a large amount of experimental data, which are available over the Internet to all interested individuals, as well as remote control of a heating system (the system could be accessed using a link [21]; during the heated season (winter time) the system provides all measured data accessible to all at [22–25]**)**. The presented system could serve in the education and training of students in the fields of:

- Civil engineering, in order to determine the technical and economical potential of energy savings in existing buildings, as well as the development and implementation of new solutions for improved energy efficiency.
- Process engineering, in order to design and implement heating systems with increased thermal performance and energy savings. It is also possible to demonstrate real-world principles of thermodynamics and fluid mechanics.
- Control engineering, to develop different control strategies employing fuzzy-based logic and other machine learning techniques, as well as different protocols, sensors and network architectures. The presented system offers the possibility for setting different control engineering problems: testing concepts of modelling and system analysis (system modelling, identification of the system, linearization of the model, study of stability and performance of the system), algorithm management in a broader sense (control of open and closed feedback; PID control procedures and adjustments of PID regulators; P control with associated compensators; synthesis of controllers in the frequency domain; feedback; controller synthesis based on the model in space conditions and concept of optimal control; implementation of observer or estimators of condition; synthesis of controller by method of setting pole; predictive control – MPC algorithms; fuzzy control) and restriction factors in the real functioning of the system (the presence of measurement noise; influence of disorders on functioning of the system; effects of no-modelled dynamics or ambiguity of the system; and effects of saturation of actuators, wind-up).
- Using this feature of the system they can control a real system, compare control strategies, test smart control algorithms on a real-life example and have a large amount of data that can support their research and learning.
- Software engineering and computer science, to develop different software architectures, as well as software solutions, for supervisory control, data acquisition, visualization and simulation, using existing systems and data (demonstration of different aspects of network architecture, KNX and other protocols, development of web based applications, JAVA programming, programming of mobile devices).

The system offers the following sets of options for engineering education: a wide range of different measured data, remote control of real-life equipment and sensors, and the development and implementation of different control algorithms. Generally, users of the system can get all the information for any specific period of time: percentage of openness of valves (V1 and V2), flow, volume of fluid, energy consumption, temperature and power (in both sides of the auditorium), temperature at five control points, outside temperature, desired temperature, humidity at two control points and number of people in the auditorium (from RFID-based access control system). It is also possible to set sampling time in minutes. A user interface for the selection of parameters as well as the selection of a period of time (for example April 13 2010, to April 17 2010) is presented in Fig. 3.

In addition to the control of a real system, students have different simulation software and laboratory models so they could compare and contrast the results of simulation or results from laboratory exercises with data gathered from a real system.

The use of the data from the described system as well as the use of the system as a learning environment have some important advantages:

1. Use of systems that include ‘noise’. Real systems have noise and disturbance effects. In

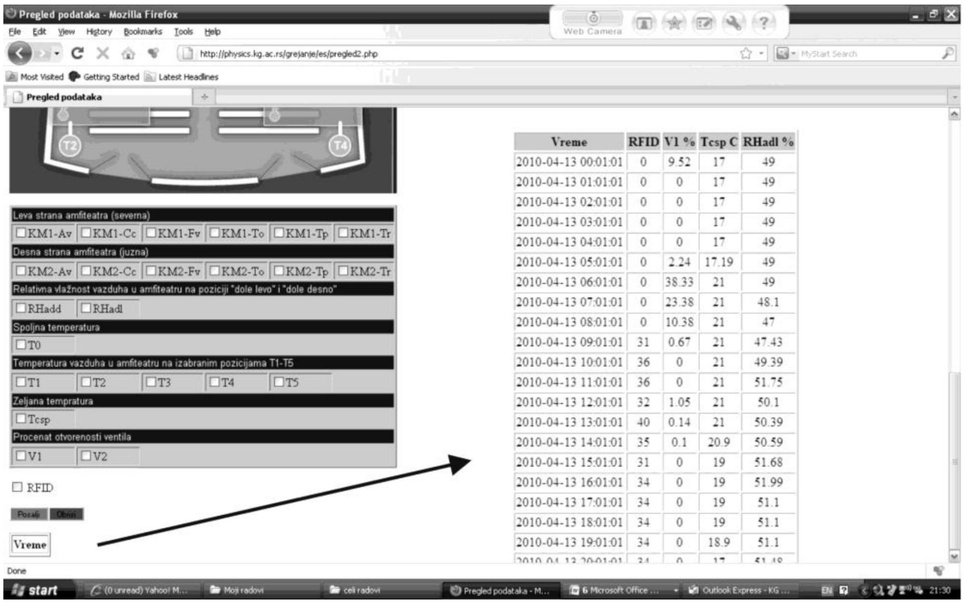

Fig. 3. Selection of parameters and part of the results from the database.

laboratories these effects could be simulated using software/hardware add-ins, on the other hand software could simulate random or systematic errors or even issues with the calibration of instruments. However, work with a real-world system has the most valuable educational effects. In this case students could control heating, flow, energy consumption, temperature and power, while having real 'noise' in the system (the number of students in the room, humidity, solar radiation, etc.). Since there is some software (or even laboratory models) for the energy efficiency of buildings, students have the task of modelling the system using the software and then comparing the model and results of the simulations with real results. Furthermore, they have to explain comparison of results and to point out how experimental results differ from simulations and why. Using this approach, students get important feedback using a real-life problem.

2. Novel approaches to meeting laboratory objectives**.** Many traditional experiments are not practical to perform via distance learning or could not fully contribute to new multidisciplinary objectives. The way of approaching the problem would not be to try to find a way to perform this or that particular experiment, but rather to develop new experiments (or complex, integrated environments) that meet the different multidisciplinary objectives and can be performed remotely.
3. Introduction of creative and problem-based projects. It is known that creative and problem-based projects improve students' motivation and the quality of learning outcomes. An example of a task for advanced control courses is to measure humidity and temperature variation to confirm the presence of a person and to validate those results with the real number of students recorded using the RFID system. Based on the presence of students, it is possible to determine the different times of events (without previous knowledge of a time table). For instance, the continual change (increase) in the number of students in a short period of time indicates the beginning of a class (event). In that case, the temperature regime could be switched or changed without previous predefinition. On the other hand, a decrease in the number of students present could indicate the end of a class; in that case the temperature could be adjusted to a lower level. These data could be used for the definition of different advanced control algorithms or a different software application using event-based programming, or the implementation of intelligent and ubiquitous functions.

The system was introduced in the educational process at the Faculty of Mechanical Engineering at the University of Kragujevac. The system and data were used in control engineering education classes both at a basic and at an advanced level, as well as in fluid dynamics (in basic courses for demonstration and basic computation, in advanced courses for the development of advanced control algorithms and for creative and problem-based projects). The total number of students who used the system for laboratory exercises was 112. According to the initial survey after the semester (the system has been in use for one semester) the students stated the following characteristics of the system:

1. Use physically realistic problems. Students show a much higher level of interest and respond much better when they deal with realistic real-life problems. In this case the realistic problem increased the interest for experimentation. The students' feedback was that knowledge should be fully tested and implemented in practice using real-world problems.
2. Connected to specific learning objectives. Students stated that the system was connected with specific learning objectives (using control techniques, development of control algorithms, identification, modelling).
3. A self-paced learning environment. The presented system motivates students for additional and further work, and experiments. Students were motivated to have autonomous work, on the one hand, and, on the other, to have a collaborative environment in order to share results and cooperate with their colleagues.
4. Increasing general engineering knowledge. Having a real system with different characteristics that requires multidisciplinary engineering knowledge put the engineering discipline and course in perspective. Using the system, control engineers, for instance, understand better that the control of heating in the building requires knowledge (or existing interfaces) of many other engineering disciplines.

The system provides another important feature (for illustration of energy savings for educational purposes) and it is the cost of energy consumption (on a daily basis or on per hour for any specific period). The users' input is date and/or hours and the output information is consumption in kWh, outside temperature and indoor temperature (in controlled auditorium), as well as costs (in Serbian currency – dinar), so it could be used for some economic and techno-economical analysis.

4. Conclusions

The presented system, a remotely accessed building automated heating system, with its integration with an RFID system and interfaces for educational purposes, offers an innovative and quality opportunity to enhance the educational experience of engineering and technology students. The technical characteristics of a controlled system, data acquisition, heating regimes, components of the system, visualization and testing have been presented. It has been shown that a controlled system reduces energy consumption compared with a non-controlled system. The described system has been used as a function of everyday needs and energy efficiency at the Faculty of Mechanical Engineering in Kragujevac. In addition to the process variables, the experimental plant enables the measurement and collection of data that refer to the number of people in the auditorium at a specific time (using an RFID access control-identification subsystem for a record of students' presence).

The system is developed with the intention of providing a demonstration of real-world principles of thermodynamics, fluid mechanics, and control and to support different engineering fields: control engineering, energy consumption, software engineering, process engineering, civil engineering. Using the system it is possible to gather a wide range of data (such as the percentage of openness of valves (V1 and V2), flow, volume of fluid, energy consumption, temperature and power, temperature at five control points, outside temperature, desired temperature, humidity at two control points and the number of people in the auditorium (from an RFID-based access control system)). Based on the gathered data, as well as using the opportunity to provide remote control and exchange of control algorithms, it is possible to set different engineering and laboratory tasks and projects (starting from a basic one, up to creative, advanced projects) using the students' (educational) portal. The role of the portal is to make available experimental data, their presentation, knowledge dissemination as well as a presentation of the integration of different subsystems (RFID identification subsystem, heating control. . .).

From an educational perspective it is important for students to use real-life systems, systems that have disturbances (noise). Using a real system, instead of laboratory models or simulation software, it is possible to set a new, fresh approach to meet different laboratory objectives and provide an environment for creative and problem-based projects. The system was introduced in engineering education at the Faculty of Mechanical Engineering (University of Kragujevac) in different engineering courses (at both a basic and advanced level). The students recognized the following advantages of the system: use of a realistic problem, connection with specific learning objectives, a self-paced learning environment and the potential for increasing general and multidisciplinary engineering knowledge.

From an educators' points of view it is very useful to have a complex (real) system (in this case energy control) to provide the possibility for students to work with real-life problems and to compare results from the real system with results obtained by mathematical models, software simulations and laboratory set-ups. The complex approach that would cover all of these steps would probably produce the achievement of learning objectives and a quality balance of knowledge and skills.

Another advantage is that students will gain a greater appreciation of energy savings once they have work with the sophisticated energy conservation and control strategies that are implemented in real buildings.

One of the limitations of this specific system is its size and the time that was required for its development and installation, so a recommendation could be that smaller rooms and units could be used.

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Miladin Stefanovic received his Ph.D. from the Department of Industrial Engineering, Faculty of Mechanical Engineering University of Kragujevac, Serbia. He is currently Assistant Professor in the Department of Industrial Engineering. His current research interests include web services, information systems and e-learning. He is member of IFIP Council TC3 - Education.

Milan Matijevic received his PhD on Department of Automatic control, Faculty of Mechanical Engineering University of Kragujevac, Serbia. He is currently Associate professor on Department of Automatic Control and Applied Mechanics. His current research interest includes digital control, computer added measurement and control.

Dragan Lazic received his PhD on Department of Automatic control, Faculty of Mechanical Engineering University of Belgrade, Serbia. He is currently full professor on Department of Automatic Control. His current research interest includes real time microprocessor control, design and implementation of electric, electro – hydraulic and pneumatic automatic control systems as well as control algorithms.