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Towards a Context-Driven Platform using IoT and Big Data Technologies for Energy Efficient Buildings

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Abstract— Context-awareness is crucial for leveraging energy-efficient buildings by developing intelligent control approaches in which sensing and actuation tasks are performed according to the contextual changes. This could be done by including the users' actions and behaviours in up-to-date context taking into account the complex interlinked elements, situations, processes, and their dynamics. In this paper, we introduce a holistic platform that integrates recent sensing/actuating and Big data technologies for monitoring and data processing. The main aim is to develop context-driven control approaches whereby energy consumption, production, and storage could be controlled according to actual situations (e.g., occupancy, occupant behaviour patterns, energy production patterns, and weather data). A platform prototype was deployed in our university test site. Experiments have been conducted and preliminary results show the usefulness of this holistic platform for monitoring and data processing in energy efficient buildings.

Keywords—Energy Efficient Buildings, Big data, IoT, Complex-event processing, Context-awareness.

I. INTRODUCTION

Buildings are responsible for more than 40% of greenhouse gas emissions and for about 40% of energy consumption [8, 9, 10]. Reducing energy consumption and subsequently CO₂ emissions is highly required since buildings frequently use more energy than anticipated or desired. Three major aspects could be considered for reducing energy consumption, *i*) integrating renewable energy, *ii*) reducing energy consumption by ICT infrastructure and by developing less-energy-consuming equipment, methods and protocols, and *iii*) reducing energy consumption in all applications by integrating ICT concepts. These aspects might contribute substantially to the improvement of winning and saving energy and CO₂ reduction towards smart and efficient buildings. For instance, many studies demonstrated the importance of optimal control strategies for reducing the energy waste of its equipment (e.g., HVAC, lighting) and then improving the overall building energy efficiency while satisfying the occupants' comfort [8,14,15,27].

Furthermore, renewable electricity produced by wind and solar equipment are considered as promising green resources for supporting the continuous growth of electricity demands. The intermittent nature and uncontrollable variability of the produced

electricity constitutes, however, the main challenge is their large-scale and efficient integration in buildings. Energy storage systems are considered among the most promising technologies that could balance energy production with electrical energy consumed. It can be performed by managing efficiently and in real-time actual loads and variable energy production [1,2]. In fact, batteries (e.g. lead acid batteries, fuel cell) are prominent storage solutions, but they have to be integrated efficiently in standalone systems because they are the most expensive and sensitive components. However, the high unpredictability of the energy production and electricity consumption make these systems very complex because of the uncertainties and the variability of the actual context (e.g., weather, building occupancy).

Most of the works to date use software simulation tools for modelling, assessment and the optimization of these systems. Despite the importance of modelling and simulations, the deployment of real test sites for conducting experiments is required in order to study and assess on the accuracy of these models. The work presented in this paper is a part of the work we are undertaking under two on-going related projects, named MIGRID [5] and CASANET [6,7], with the aim to develop techniques and tools for sizing, modelling, simulation, and experimentation of a smart micro-grid for EEBs (Energy Efficient Buildings) [3,4]. The main goals of these projects are *i*) demonstrate how ICT can contribute to reduce energy consumption and CO₂ emissions, *ii*) study the impact of occupants' behaviour on buildings' energy use, *iii*) develop intelligent control approaches for efficient match of fluctuating power generation with buildings charges (demand/response).

In this perspective, a holistic platform that integrates IoT (Internet of Things) [22, 26] and Big data technologies [17] is under development for real-time monitoring and data processing for controlling standalone RES systems (PV, Wind, storage devices, loads). IoT and Big data technologies are considered in many studies as two of the most remarkable technologies for developing real-time context-driven decisions and control approaches [16,17]. In this paper, we shed first more insight on the usefulness of integrating the power of these technologies into a holistic platform for monitoring and data processing. Scenarios

we have developed are integrated into the platform and deployed in our university sentry box. We also highlight the challenges we are tackling together with some preliminary experimental results.

The remainder of this paper is structured as follows. Section 2 highlights the prominence of developing a holistic platform for EEBs. An overview of the platform architecture and its main components are presented in Section 3. The test site we have deployed together with some preliminary results is reported in Section 4. Conclusions and perspectives are given in Section 5.

II. RELATED WORK

Recent studies presented in [11,12] showed that energy consumption in buildings could be cut by up to 70 percent with the support of ICT-based innovation and solutions. However, integrated and collective adaptive platforms are required to show how buildings are operated, maintained and controlled. These platforms should integrate recent technologies from autonomic computing, IoT, Big data, context-aware computing, machine learning and service-oriented architecture, including occupants' actions and behaviours. In this direction, the building can be seen as a socio-technical system that integrates different heterogeneous entities (e.g., sensors, actuators, lighting, HVAC, occupants) that could interact dynamically and in collective manner to balance between energy efficiency and occupants' comfort. More precisely, making buildings more energy efficient while ensuring occupants' comfort require incorporating mechanisms and techniques, which allow entities interacting in order to perform suitable actions (e.g., tuning On/Off HVAC and lighting, balancing the fluctuation between power production and consumption).

As stated in [8, 14, 23], systems operating in dynamic environments with these capabilities are qualified as socio-technical Collective Adaptive Systems (CAS). These systems should learn and evolve by performing distributed decisions at different temporal and spatial scales while self-organize when entities join or leave the collective (e.g., occupants' number and presence). For instance, platforms for buildings' energy management could react to the dynamic changes (e.g., buildings occupants' preference, number, presence) for lowering energy consumption while making occupants' life more comfortable.

These systems are composed of several layers with increases in complexity. For instance, the first layer CAS is limited to small geographical area (e.g., smart house) and adaptation is within the minute in case of controlling HVAC and lighting systems. For the second layer CAS, networks of components (e.g., sensors, actuators, equipment) together with actors (e.g. occupants) integrated on the long run, concentrated among a dedicated geographical place (e.g., a building), spanning several minutes and hours. For the third layer CAS, networks of CAS (e.g. houses, offices, buildings) are connected together involving both short and long time scales. Table 1 shows the three layers with involved CAS aspects. As shown in this table, the complexity, the heterogeneity, and dynamicity increase from the lower layer to the higher layer and this requires distributed and real-time control with increases in conflicting goals and objectives, which

may create unexpected phenomenon. Self-managing and control techniques based on the notions of dynamically updated data (i.e., contextual data), monitoring, run-time models of the system, and dynamic enforcement of decisions are required.

Aspects of CASs	First layer CAS	Second layer CAS	Third layer CAS
Heterogeneous components	Artificial entities (few human input)	Human, groups of human, services	Communities, networks
Many units/nodes	Dozens	Hundreds	Thousands
Different spatial scale	House, office	Building	Campus
Nodes may join or leave	Rarely	Commonly	Continuously
Different temporal scale	Short term (minutes, hours)	Medium term (days to weeks)	Long term (weeks)
Conflicting objectives and goals	Unique goal (no conflict)	Independent homogeneous goals with possible conflict	Social heterogeneous conflicting goals involving arbitration
Decision-making	Centralized	Partially decentralized	Highly decentralized
Emergence and control	Limited emergence and full control	Limited emergence and distributed control	Emergence of unexpected phenomena, distributed control
Nodes may join or leave	Rarely	Commonly	Continuously
Social scope	limited	Bounded	Unbounded

There are mainly three techniques that could be used for handling the requirements of these systems: model-driven, data-driven, and context-driven techniques. Model-driven techniques have been extensively used for engineering and developing CAS. However, they become inefficient for large, heterogeneous and dynamic environments. Data-driven techniques have been proposed to handle the dynamicity of these systems. This development was accelerated with the emerging Big data technologies (e.g., Hadoop/Mapreduce) that allows the processing (i.e., Batch computing) of large volumes of data sets in order to develop and enhance existing models that best suit the targeted system. However, for large, heterogeneous and dynamic systems, entities produce continuous and real-time streaming events.

Batch computing techniques could not be used to process these streaming data. In fact, these streams have to be handled and processed on-the-fly in order to get valuable information (e.g., context changes) that could be used to develop context-driven control approaches. Context-driven technologies, such as Storm and S4 as well as complex-event processing technologies [19, 20, 21, 24], have been proposed to handle data streams in real-time in order to get valuable insights and figure out hidden patterns. In the next section, we show how IoT and recent Big data technologies could be integrated into a holistic platform for real-time monitoring and data processing in EEBs.

III. PROTOTYPES AND EXPERIMENTAL RESULTS

The prototypes we have deployed in our sentry box, as depicted in Figure 1, consists of : *i*) solar panels with a maximum power of 240W, attached to a rotation mechanism in order to change its orientation, and battery devices to store the excessive power, *ii*) appliances (e.g. air conditioner, lighting bulbs, an electrical barrier). In addition to these components, we have deployed a platform that integrates both IoT and Big data technologies in order to test and evaluate the scenarios we have considered for assessing energy efficiency and occupants' comfort in buildings [16]. The platform is composed of two main layers, data acquisition and data processing/visualization. For data acquisition, we have developed a Kaa application (i.e., IoT technique [26]), which is used to receive data from deployed sensors. We have also used MQTT (Message Queue Telemetry Transport), which is a publish-subscribe-based protocol for IoT applications. For data processing and storage, Storm [21] services have been used. Mainly a topology composed of Spouts

and Bolts was designed and developed to allow receiving and processing streaming data from sensors. The spouts receive the data from the Kaa application, and then transmit it to the Bolts for processing and storage into the database (e.g., MongoDB) for further in-depth analysis. Furthermore, a Web application was developed for remote and real-time visualization.

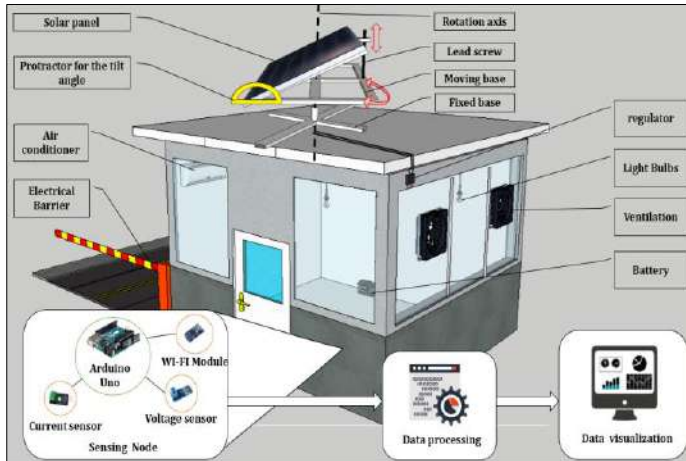


Figure 1: The test-bed prototype and the platform architecture

In the rest of this section, we present prototypes already deployed into the test site in order to study the usefulness of the platform by focusing mainly on four scenarios: *i)* power production monitoring, *ii)* power consumption monitoring, *iii)* ventilation control, and *iv)* Heating and air conditioning control.

A. Power consumption monitoring

In this scenario, we focus on processing and visualization of the raw data collected in real-time using the deployed platform as illustrated in Figure 2. These data could be analyzed in order to figure out the distribution of electricity power consumed and discuss variations of hourly and daily profile. The main objective of this scenario is to evaluate the performance of this platform for real-time tracking and analyzing electricity consumption. This experimentation allows visualizing the detailed power consumed by each appliance (i.e. Electrical barrier, Bulb, Air-conditioner, Plug).

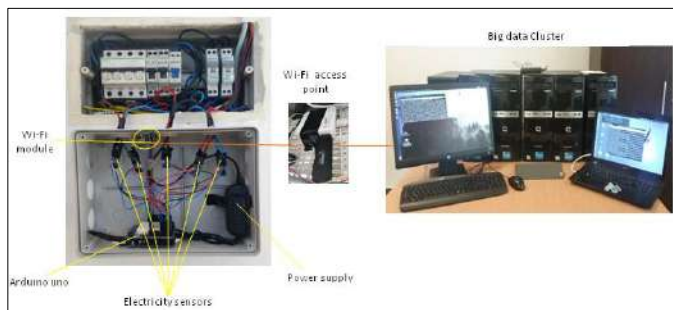


Figure 2: Scenario of power consumption monitoring.

Figure 3 shows the instantaneous consumption profile of the air conditioner and plugs; we observe, as expected that they

consume more electricity than others appliances. In fact, due to the summer season, the air-conditioner is usually turned on during the morning and afternoon periods of the day, which explains the increase in the consumption of the electric power. For the plugs, the consumption of the power can reach up higher values, which can reveal that occupants use several and additional plugged equipment (e.g. the heating plate, chargers for mobile devices). Figure 4 shows the consumption profile of the appliances with low consumption (e.g. electrical barrier and bulbs), we observe that at lunch time, the consumption of the electrical barrier rises because of the augmentation of circulation during this period; also, the consumption of the bulbs gets down during the day and rises at night and early morning.

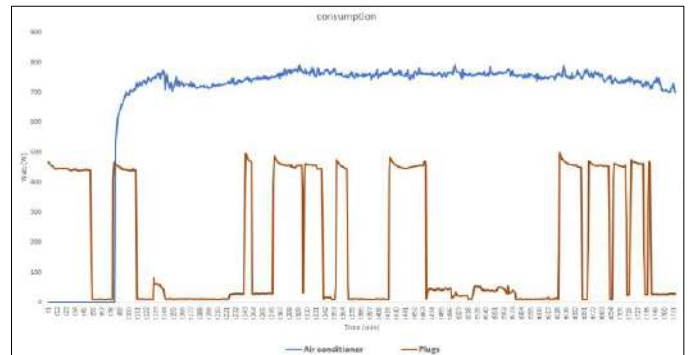


Figure 3: Equipment with high electricity consumption

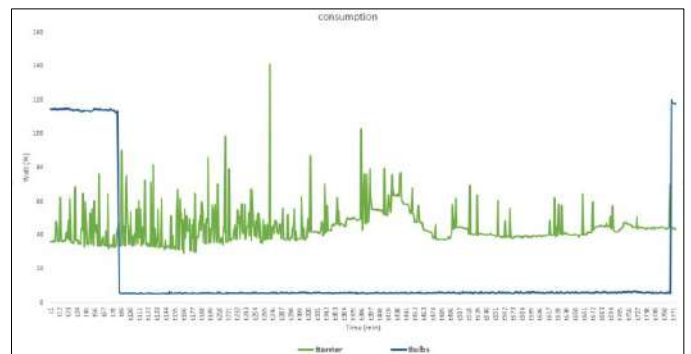


Figure 4: Equipment with low electricity consumption

B. Power production monitoring

In this scenario, we tested the usefulness of the deployed platform for tracking the power production as shown in Figure 5. The experiments first consist of measuring the power production of the PV module in different orientations (e.g. South-East, South and South-West) with a tilt angle of 31 degree. These data have been remotely processed and visualized in order to have an idea about the power production profile. The first aim is to determine the appropriate orientation to satisfy the consumption demand, while maintaining a good charge-discharge of batteries. The power production/consumption profile is also used to develop a preliminary control strategy for balancing PV production and ventilation system consumption integrating the power grid and battery. Along the day the battery is charged since the production is high. Overnight we used the battery to power the ventilators using this control strategy.

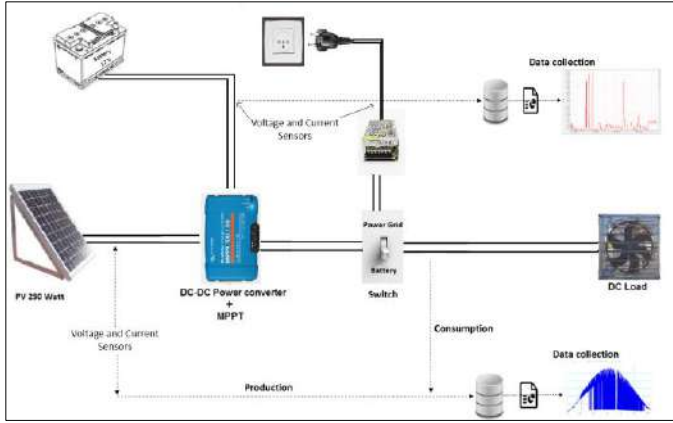


Figure 5: Scenario of power production monitoring.

Figure 6 depicts the power production of the solar panel in the three different orientations. The grey curve represents the production of the panel oriented South-East, the blue curve for the South orientation whereas the orange one is for the South-West orientation. Comparing the three curves, we conclude that the power production of the PV module is higher when it is oriented South-East. However, the South-East orientation is well suited if the building's demands is higher in the morning time. These data was also compared with the model we have developed [4]. We have also the consumption profile to develop PV sizing model for the sentry box [3].

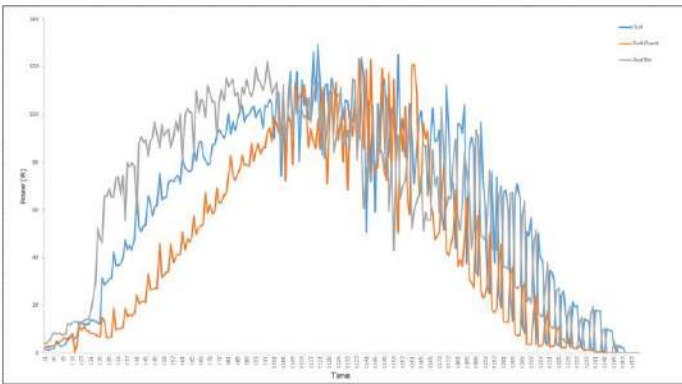


Figure 6: Real-time power production for the three PV orientations

C. Ventilation control

Ventilation systems operate at buildings level for enhancing air quality by injecting fresher air from outside into inside buildings [7,8,15]. These systems automatically act on behalf of occupants by insuring good indoor air quality, especially in cold or hot periods, or when there are no windows. In fact, the ventilation controller performs this task by adjusting fresh air as much as needed based on actual indoor CO₂ concentration. Several approaches have been implemented and deployed in real-setting scenarios, but most of them are either time-triggered or are based on fixed threshold values [8]. In this work, we propose to use contextual data, mainly indoor/outdoor CO₂ concentration, for context-driven monitoring and control of buildings ventilation systems. The aim is to improve optimal balance between energy efficiency and indoor air quality. In fact, the control strategy

maintains the indoor CO₂ concentration at the comfort set point with an efficient ventilation rate while reducing energy consumption [18,19].

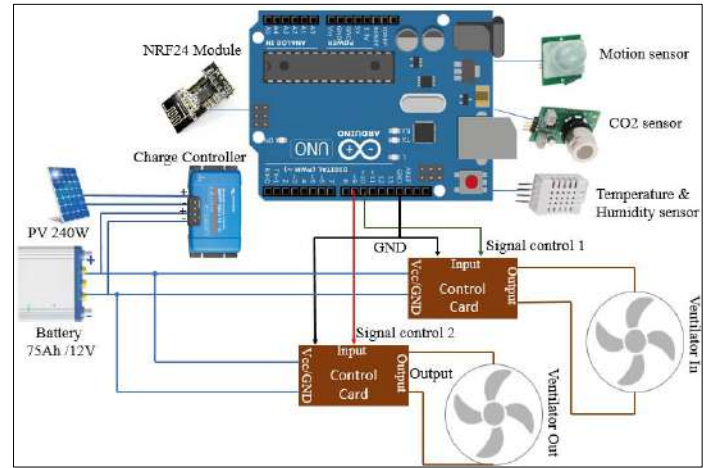


Figure 7: Ventilation system scenario

A ventilation control system was deployed as illustrated in Figure 7. Two control cards (i.e. one for each fan controller) that convert the command signals sent from the Arduino controller (5V) to the ventilators or fan (12V). Two control strategies, On/Off and PI controls have been developed, and compared them with the proposed state-feedback control strategy in terms of the indoor CO₂ concentration, the ventilation rates, and the power consumption. These strategies have been already compared using simulations and results showed the effectiveness of the state feedback strategy [15]. Experiments have been also conducted to show the operational use of the platform and the efficiency of the proposed state feedback control compared to traditional controls, such as On/Off and PID. The results depicted in Figure 8 show a good performance in reducing energy consumption.

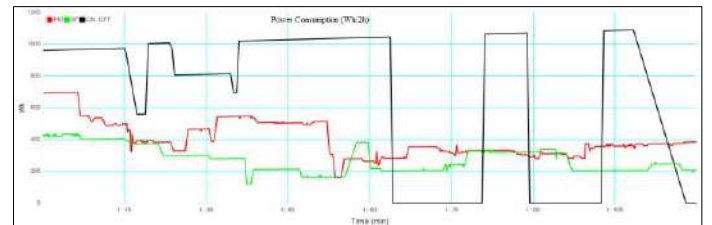


Figure 8: Power consumption of the three control strategies

D. Heating and air conditioning control

As mentioned above, heating and air conditioning systems (H-AC) is the main energy consumer in buildings. Many studies put more emphasize on developing efficient control approaches in order to deliver acceptable occupants' comfort while maintaining optimal energy consumption. In our recent work, we have investigated three approaches for controlling heating and air conditioning systems. Simulation results showed the potential of the state feedback control approach for saving energy while keeping suitable occupant's comfort [18]. In this work, we aim

to implement these approaches for controlling the H-AC system we have deployed in our university test site. We first developed a control card as illustrated in Figure 9. This card is an interface between all components in the H-AC and our control device. It allows the regulation of temperature and on/off control of the H-AC system. We mainly tested the ON/OFF control for each H-AC component (i.e. the inside ventilator, the compressor) and the regulation of the temperature based on the desired schedules (heating or conditioning and only ventilation).

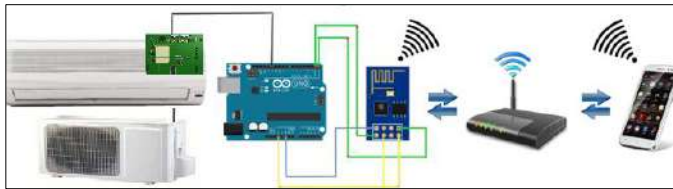


Figure 10: H_AC control prototype

IV. CONCLUSIONS AND PERSPECTIVES

The main aim of the work presented in this paper is to show the usefulness of developing an integrated platform that connects building's components using sensing/actuating, IoT, and Big Data technologies in order to leverage the real-time gathering and data processing. The platform was deployed and several scenarios have been tested and evaluated and preliminary results showed the usefulness of the platform. The platform will be further enhanced by developing other ongoing scenarios. It will be used for validating the proposed models and results mainly by investigating, *i)* the efficient connection, integration, and the management of different components [4], *ii)* the suitable dimensions for energy production and storage devices and the influence of PV orientations on batteries charge-discharge [3], *iii)* different possible demands/responses algorithms, *iv)* charged and discharged operations on the state-of-health of deployed batteries as well as PV corrosions fault diagnosis [2, 6], *v)* context-aware driven control of deployed equipment, e.g., lighting and HVAC systems [7].

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