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DEPARTAMENTO DE LENGUAJES Y SISTEMAS INFORMÁTICOS

Energy-Saving Policies in Grid-Computing and Smart Environments

International Doctoral Dissertation presented by
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A mis padres.

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ABSTRACT

This thesis, presented as a set of research papers, studies the problem of energy consumption growth in two spheres: Grid-Computing and Smart Environments. These problems are tackled through the establishment of energy-saving policies developed for each environment in order to save the maximum energy as possible.

In the Grid-Computing environment, seven energy-policies were designed in an attemp to minimize energy consumption through shutting resources down and booting them. These energy policies were tested by applying usage data from French Grid'5000 infrastructure and a simulation software tool developed specifically for this purpose. In general, it is proven that around 30% of energy can be saved. The software tool, called Grid'5000 Toolbox, can simulate the behaviour of a Grid-Computing environment, whilst applying several energy policies, and can compute statistics such as energy consumption, usage, and the states of resources and can generate dynamic graphical representation of the state of the jobs deployed and that of the resources. In Smart Environments where sensors perceive lighting conditions, the energy-saving policy adjusts lighting in order to satisfy user preferences and prevents energy from being wasted. A set of wireless sensors were deployed on two offices at the department of Computer Languages and Systems. This set of sensors is comprised of a mesh network through which the sensors interact in order to retrieve information about lighting, and air conditioning, whereby this information is sent to a central node. The dataset created over several months was employed to extract information about user lighting preferences, from the application of which it is proven that around 70% of energy can be saved in lighting appliances.

RESUMEN

Este trabajo de tesis, presentado como un conjunto de artículos de investigación, estudia el problema del aumento del consumo de energía en dos ámbitos: computación Grid y entornos inteligentes. Estos problemas se han abordado a través del establecimiento de políticas de ahorro energético, desarrolladas para cada uno de estos entornos con el objetivo de ahorrar la mayor cantidad de energía posible.

En entornos de computación Grid, siete políticas han sido diseñadas para intentar minimizar el consumo de energía apagando y encendiendo los recursos. Estas políticas han sido probadas haciendo uso de los datos de uso de la infraestructura francesa Grid'5000 y una herramienta de simulación, desarrollada para este propósito. Grid'5000 Toolbox simula el comportamiento de un entorno de computación Grid, aplicando varias políticas y calculando estadísticas. Muestra además una representación gráfica y dinámica del estado de las tareas y los recursos. Se demuestra que alrededor del 30% de la energía puede ser ahorrada.

En entornos inteligentes dotados con sensores, las políticas de ahorro energético ajustan la luminosidad para satisfacer las preferencias de los usuarios y evitar el malgasto energético. Un conjunto de sensores inalámbricos fueron desplegados en dos despachos del departamento de Lenguajes y Sistemas Informáticos, formando una red *mesh* y recogen información sobre luminosidad y acondicionamiento que envían a un nodo central. El conjunto de datos creado durante varios meses fue usado para inferir las preferencias lumínicas de los usuarios, y se demuestra que alrededor del 70% de energía para iluminación puede ser ahorrada.

PART I

Preface

CHAPTER 1

INTRODUCTION

$E = m \cdot c^2$

Albert Einstein, 1905

1.1 Research Motivation

Energy efficiency and sustainability are two areas of great interest in recent decades. CO_2 emissions worldwide continue growing significantly as shown in Figure 1.1 and detailed in Table 1.1. From 1990 to 2009 CO_2 emissions rose by approximately 38% while population grew about 28% [60], which indicates 10 points of growth in percentage terms. There are some good news: energy generation is now more efficient as can be observed in Table 1.1. The kilograms of CO_2 per Gross Domestic Product (GDP) is currently about 15% less than in 1990, which means that the generation of products and services around the world is also more efficient.

However the efforts of both developed and developing countries, and the commitment for a more sustainable world cannot be relaxed. Developing countries, such as China and Brazil, have greatly increased their energy requirements over the last decade, and have used non-sustainable sources of energy, such as coal and oil.

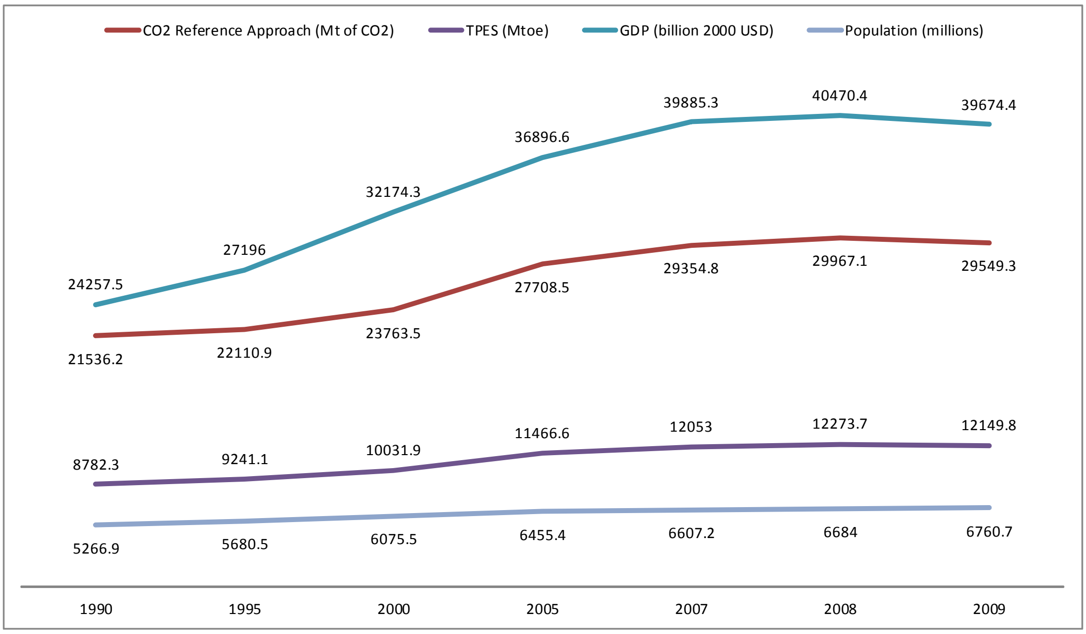

Figure 1.1: Key Indicators of World CO_2 Emissions[(1)]

The Reference Approach and the Sectoral Approach often give differing results since the Reference Approach is a top-down approach using a country's energy supply data and has no detailed information on how the individual fuels are used in each sector. The Reference Approach provides estimates of CO2 for comparison

(1) *TPES*: Total Primary Energy Supply. *PJ*: Peta-Joule (10^{15} Joules). *MTOE*: Million Tons of Oil Equivalent. *GDP*: Gross Domestic Product. *2000-USD*: The value of a United States Dollar in year 2000. The reference price taken. *PPP*: Purchasing power parities are the rates of currency conversion that equalise the purchasing power of different currencies. A given sum of money, when converted into different currencies at the PPP rates, buys the same basket of goods and services in all countries. In other words, PPPs are the rates of currency conversion which eliminate the differences in price levels between different countries.

	1990	1995	2000	2005	2007	2008	2009	Var. Rate 90-09
CO_2 Sect. Approach (Mt)	20966	21791	23492	27188	29047	29454	28999	38.30%
CO_2 Ref. Approach (Mt)	21536	22110	23763	27708	29354	29967	29549	37.20%
TPES (PJ)	367696	386906	420014	480084	504633	513874	508690	38.3%
TPES (Mtoe)	8782	9241	10031	11466	12053	12273	12149	38.3%
GDP (billion 2000 USD)	24257	27196	32174	36896	39885	40470	39674	63.6%
GDP PPP (billion 2000 USD)	33340	37834	45799	55547	62111	64095	64244	92.7%
Population (millions)	5266	5680	6075	6455	6607	6684	6760	28.4%
CO_2/TPES (tCO_2/TJ)	57	56.3	55.9	56.6	57.6	57.3	57	0.0%
CO_2/GDP (kg CO_2) /2000 USD)	0.86	0.8	0.73	0.74	0.73	0.73	0.73	-15.4%
CO_2/GDP PPP (kg CO_2/ 2000 USD)	0.63	0.58	0.51	0.49	0.47	0.46	0.45	-28.2%
CO_2/population (t CO_2/capita)	3.98	3.84	3.87	4.21	4.4	4.41	4.29	7.8%

Table 1.1: Worlwide CO_2 emissions indicators.

with estimates derived using a Sectoral Approach. Theoretically, it indicates an upper bound to the Sectoral Approach: "1A fuel combustion", because some of the carbon in the fuel is not combusted but instead emitted as fugitive emissions (as leakage or evaporation in the production and/or transformation stage).

Within this context the increasing energy consumption of Information Technology (IT) companies and infrastructures propel us towards finding solutions which enable us to save energy while maintaining or even improving current services.

Information Technology energy consumption alone represents a monstruos 3% to 5% of CO_2 emissions worldwide which is similar to that of aviation transport, and hence it is worth investing time and resources in order to analyze and propound methods to save energy within IT. Moreover, buildings in Spain currently cover a sum total of 3,500 million square meters, and consume 17% of the total energy consumption [46] and therefore it seems that research into this topic is also worthwhile.

1.2 Research Methodology

This research follows the standard scientific research technique [110] which includes the following phases:

1. Literature Review. The research literature phase formed the initial stage of the research question through the retrieval of information, tools and methodologies, and consequently via the study and observation of these fundamentals.

2. Modelling. During the modelling phase the environments expressed in the research question were analyzed and studied. This model includes the computational artifacts that model the Grid design.

3. Algorithmic Development. An innovative technique with its algorithm have been developed in order to handle and cope with the various issues involved. Other techniques were developed in order to enable rigorous comparisons.

4. Prototyping and Evaluation. The simulation tools based on the model have been built in order to run the experiments and to test and evaluate the results.

1.3 Research Question

The research question that leads this thesis dissertation is: Which are the best policies to save energy in smart environments and in Grid-Computing environments?

Within the context of Grid-Computing, we focused on saving energy through deploying and undeploying resources in a Grid environment in order to save the most energy. To this end, energy-saving policies from the literature and new proposals have been tested and compared whilst making use of simulation software specially developed for this purpose.

Within the context of Smart Environments, we focused on saving energy through analyzing user preferences in lighting conditions, and by adapting the environments to these conditions. The question becomes how to adjust lighting conditions in order to save the most energy whilst simultaneously satisfying user preferences.

1.4 Success Criteria

Success will be achieved if the research question is resolved. This means that we have to check that both the model and the supporting algorithms indeed define energy-saving policies and demonstrate their validity by the experiments through the simulation software. The simulation software demonstrates that the output results match the results estimated by manual calculation.

Within the Smart Environment Infrastructure, lighting conditions over a period of months, and an estimation of results on saving energy in lighting equipment were computed for this period.

Within the Grid-Computing context, the experiments performed on the simulation software were carried out accross eight locations of the Grid infrastructure, whereby each location was composed of a set of clusters, and each cluster was compounded of a set of machines/resources.

1.5 Definition of Energy efficiency

The term *energy efficiency* is currently bandied about in politics, board meetings, research and in the press. Since energy efficiency constitutes the focus of this thesis, this term needs reviewing, and it can give an insight into the work already carried out in this field.

1.5.1 Energy versus power

Energy is a scalar physical quantity defined as the ability to exert pulls or pushes against the basic forces of nature along a path of a certain length, or equally, the capacity to do work (W). Thus, energy is usually reported in kilowatt hours, (kWh) while taking into account the following equation: $kWh = (Watts \times t_{use})/1000$. Energy is a combination of power and time. The fewer watts or the shorter duration, the more energy saving.

In the International System of Units (SI), energy is measured in joules (J) which is the energy expended in applying a force of one newton through a distance of one metre, or in passing an electric current of one ampere through a resistance of one ohm for one second, that is, $J = (kg \cdot m^2)/s^2 = N \cdot m = Pa \cdot m^3 = W \cdot s$

1.5.2 Ratio of inputs to outputs

Secondly, it is important to recognise that efficiency is defined as the ratio of inputs to outputs. If the outputs increase faster than the inputs, then efficiency is improving.

In terms of clusters, grids, data center, and IT infrastructures in general, energy inputs are in kWh and outputs are some degree of operation of the intended IT hardware.

In terms of lighting, energy inputs can be considered in kWh and outputs as the quantity of light perceived by humans. The goal is to adjust this power in order to satisfy human preferences about lighting conditions.

1.6 Environments analyzed and discussed

Energy saving and energy efficiency is approached from two sides: Grid-computing environments and smart environments. In relation to Grid-Computing, we tackled energy saving in collaboration with the Laboratoire de l'Informatique du Parallélisme of the Ecole Normale Supérieure de Lyon, where permanent researcher Laurent Lefèvre leads the research team on saving energy in Grid-Computing and on other areas. The Laboratoire de l'Informatique du Parallélisme has 125 members and is one of the most active in research and with regard to educational topics and tasks.

In relation to Smart Environments, this research topic has been the main focus of the research group Idinfor (to which the Ph.D candidate belongs) ever since it was formed in 2003. The work presented in this document provides a solution for the improvement of lighting conditions in smart environments, by adjusting infrastructures in order to satisfy user preferences, by and minimizing energy consumption.

1.7 Thesis outline

The document is structured as follows: Chapter 2 introduces the problem of saving energy in IT infrastructures such as Grids and Data Centers. Chapter 3 presents the domain in which saving energy in Smart Environments is developed. In Part. II, three selected journal papers are provided. These journals are included in the

Thomson Reuters JCR ranking integrated with the Institute for Scientific Information (ISI) web of knowledge. Two of these papers are related to energy-saving policies in Grid-Computing, and the third paper is with regard to energy-saving policies in Smart Environments:

- *Smart scheduling for saving energy in Grid computing* A. Fernández-Montes, et al. Published in Journal of Expert Systems with Applications, Elsevier, ISSN: 0957-4174, Date of Publication: August 2012, Volume: 39, Issue: 10, On Pages: 9443-9450, DOI: 10.1016/j.eswa.2012.02.115, [JCR-2011 2.203, JCR-5 2.455] [Q1 in three categories: Engineering, Electrical & Electronic (41/244); Operations Research & Management Science (5/77); Computer Science, Artificial Intelligence (22/111)].
- *Evaluating decision-making performance in a Grid-computing environment using DEA* A. Fernández-Montes, et al. Published in Journal of Expert Systems with Applications, Elsevier, ISSN: 0957-4174, Date of Publication: 1 Nov 2012, Volume: 39, Issue: 15, On Pages: 12061-12070, DOI: 10.1016/j.eswa.2012.04.028, [JCR-2011 2.203, JCR-5 2.455] [Q1 in three categories: Engineering, Electrical & Electronic (41/244); Operations Research & Management Science (5/77); Computer Science, Artificial Intelligence (22/111)].
- *A Study on Saving Energy in Artificial Lighting by Making Smart Use of Wireless Sensor Networks and Actuators* A. Fernández-Montes, et al. Published in IEEE Network, ISSN: 0890-8044, Date of Publication: November-December 2009, Volume: 23, Issue: 6, On Pages: 16 - 20, DOI: 10.1109/M-NET.2009.5350348, [JCR-2009 2.148, JCR-5 3.529] [Q1 in four categories: Computer Science, Hardware & Architecture (9/49); Computer Science, Information Systems (25/116); Engineering, Electrical & Electronic (37/246), Telecommunications (8/77)].

In Part. III, other related relevant research work, published in JCR Journals as *Work in Progress* and in conference proceedings, are included in this thesis. These include:

- *Pervasive Computing Approaches to Environmental Sustainability - Automating Smart Environment Systems* A. Fernández-Montes. Published in IEEE Pervasive Computing, ISSN: 1536-1268, Date of Publication: January-March 2009, Volume: 8, Issue: 1, On Pages: 54-57, DOI: 10.1109/MPRV.2009.14, [JCR-2009 3.079 JCR-5 4.395] [Q1 in three categories: Computer Science, Information Systems (8/116); Engineering, Electrical & Electronic (13/246); Telecommunications (3/77)].

- *Smart environment vectorization - An approach to learning of user lighting preferences* published in the 12th International Conference on Knowledge-Based Intelligent Information and Engineering Systems. Lecture Notes in Computer Science. ISBN:978-3-540-85562-0, Date of Publication: 2008, Volume: 5177, On Pages: 765-772, DOI: 10.1007/978-3-540-85563-7_96. This conference is indexed at the Computing Research and Education Association of Australasia (CORE) with ranking B.

- *Modeling Smart Homes for Prediction Algorithms* published in the 11th International Conference on Knowledge-Based Intelligent Information and Engineering Systems. Lecture Notes in Computer Science. ISBN: 978-3-540-74826-7, Date of Publication: 2007, Volume: 4693, On Pages: 26-33, DOI: 10.1007/978-3-540-74827-4_4. CORE ranking B.

- *Smart Environment Software Reference Architecture* A. Fernández-Montes, et al. Published in the 5th International Conference on INC, IMS and IDC. ISBN:978-1-4244-5209-5, Date of Publication: August 2009, On Pages: 397-403, DOI: 10.1109/NCM.2009.115, CORE ranking C.

- *LECOMP: Low Energy COnsumption Mesh Protocol in WSN* published in the 2nd International Symposium on Ambient Intelligence: Software and Applications. ISBN: 978-3-642-19936-3, Date of Publication: 2011, Volume: 92, On Pages: 205-212, DOI: 10.1007/978-3-642-19937-0_26. CORE ranking C.

A summary of these journal papers and rankings can be found in Table 1.2.

Title	Journal	I.F.	Ranking
Smart scheduling for saving energy in Grid computing	Expert Systems with Applications	2.203	Q1 (three cat.)
Evaluating decision-making performance in a Grid-computing environment using DEA	Expert Systems with Applications	2.203	Q1 (three cat.)
A Study on Saving Energy in Artificial Lighting by Making Smart Use of Wireless Sensor Networks and Actuators	IEEE Network	2.148	Q1 (four cat.)
Pervasive Computing Approaches to Environmental Sustainability - - Automating Smart Environment Systems	IEEE Pervasive Computing	3.079	Q1 (three cat.)

Table 1.2: Summary of papers published in JCR indexed journals

Finally, in Part IV, final remarks are made, conclusions are drawn future work is discussed.

CHAPTER 2

ENERGY-SAVING IN GRID-COMPUTING ENVIRONMENTS

$$Q = I^2 \cdot R \cdot t$$

James Prescott Joule, 1843

Energy saving involves two direct benefits: sustainability and cost reduction. Within the field of IT, clusters, grids and data centers represent the greediest consumers of energy and therefore energy (saving) policies for these infrastructures should be applied in order to maximize their resources. It is proved in the published research papers included in Part II that approximately 40% of energy can be saved in a data centre if an adequate policy is applied. Furthermore, a software tool is presented where simulations can be run and results for real scenarios can be obtained.

2.1 Introduction

In today's increasingly pessimistic times not only are we faced with major economic issues worldwide, but also with those of sustainability. As a part of sustainability, researchers are encouraged to save energy in all domains, from IT to transport. Saving energy is directly related with cutting costs and environmental sustainability. Energy efficiency is therefore sought in a wide range of systems from small devices to large-scale computing.

IT energy consumption represents a momentous 3% to 5% of CO_2 emissions worldwide which is similar to that of aviation transport. While apparently trivial in quantity, this usage is symbolic since IT can greatly influence other industrial and research domains [94]. As computing requirements are ever greater, microprocessor manufacturers are doubling the electrical efficiency of computation every year and a half [96]. Nevertheless, energy consumption is still rising despite these good results, with energy consumption of data centres increasing an average of 16.7% over the last decade [65].

Some companies, such as Google [91], are committed to increasing energy efficiency in data centres and in cloud computing. The research community has also been searching for improvements in energy efficiency, whereas the majority of companies have focused their efforts on improving facilities.

The huge amount of energy consumed by Grid-Computing provides justification for a study into energy-saving methodologies, either from an economic or ecological point of view. To this end, Grid operational policies must be analyzed in order to be optimized.

An experimental Grid organization, located in France and called Grid'5000, is analyzed in this dissertation. Grid'5000 is a scientific instrument designed to support experiment-driven research in all areas of computer science related to parallel, large-scale, distributed, computing and networking. The purpose of this instrument is to supply an experimental platform to its users which can easily be reconfigured, controlled and monitored.

2.2 Grid-Computing Motivation

Since Alessandro Volta invented the electrical battery in 1800, electricity distribution has undergone huge changes. Thomas Edison and Nikola Tesla established two important milestones: the invention of the electric bulb and the development of alternating current (AC) respectively. Although Volta died before he could fully appreciate the potential of his invention, his discovery evolved into a worldwide electrical power Grid that allows access to utility power and has become a vital part of society's evolution and development.

Inspired by the features of the Grid's electrical power, an analogous infrastructure called a computational power Grid [52] was designed and developed to provide computing resources. The reason for the establishment of Computational Grids was to enable intensive scientific applications to be tackled that require a high number of resources, more than those available from a single computer or supercomputer. A Grid provides the sharing and aggregation of distributed (in different locations) of supercomputers, data storage systems etc. for the solution of vast computational problems in many different disciplines.

In order to build a Grid, services are required to be developed and deployed in several levels, as low-level services (security, information, directory) and high-level services and tools for application development and deployment, selection of resources, job scheduling etc. [52, 20, 22]. Among these services, this document is focused on the selection of resources and the scheduling of jobs.

Resource management and scheduling in these environments is a complex task, in our case driven by the needs of energy saving, energy efficiency and sustainability. The producers of these computational resources and the consumers may have opposing interests, particularly in terms of energy consumption. This thesis focuses on the interest of these producers in these terms, whilst bearing in mind the minimization of the impact on the availability and Quality of Service (QoS) of the Grid environment. To this end, several energy-saving policies are proposed and compared in the highest layer (see the following Section 2.3) the so-called Data Center layer.

2.3 Power Management Layers

2.3.1 Why power management

Power management enables the system administrator to save energy and to cut costs by using available tools. Server power management is the principal weapon in the fight against rising energy needs and costs. These capabilities can make a great difference in the energy consumption of huge computing infrastructures, such as Grids and data centers.

Efficiency starts with operations, exactly how the operations manage the services versus how the power is allocated. Effective power management enables us to use less power in the data center, thereby cutting energy costs. This can be observed in one example from a recent performance comparison in Figure 2.1. The top line shows the power consumption of an older server with an older operating system and no power management. The bottom line shows the power consumption of a newer server with a new operating system and with power management enabled. The Y-axis represents power consumption, and the X-axis represents performance. As can be observed, the server with active power management consumed less power: that is, a 30 percent drop at 10 percent utilization, and a 14 percent drop at 100 percent utilization. The difference in throughput is also striking. The modern server with power management engaged demonstrates far better throughput at all levels. There is also a marked improvement in performance. The newer server with power management implemented delivers almost double the performance at less than 90 percent of the power used by the older server. Since servers sometimes sit idle, it is also worth noting that the newer server is much more energy efficient than the older server when operating at idle power settings.

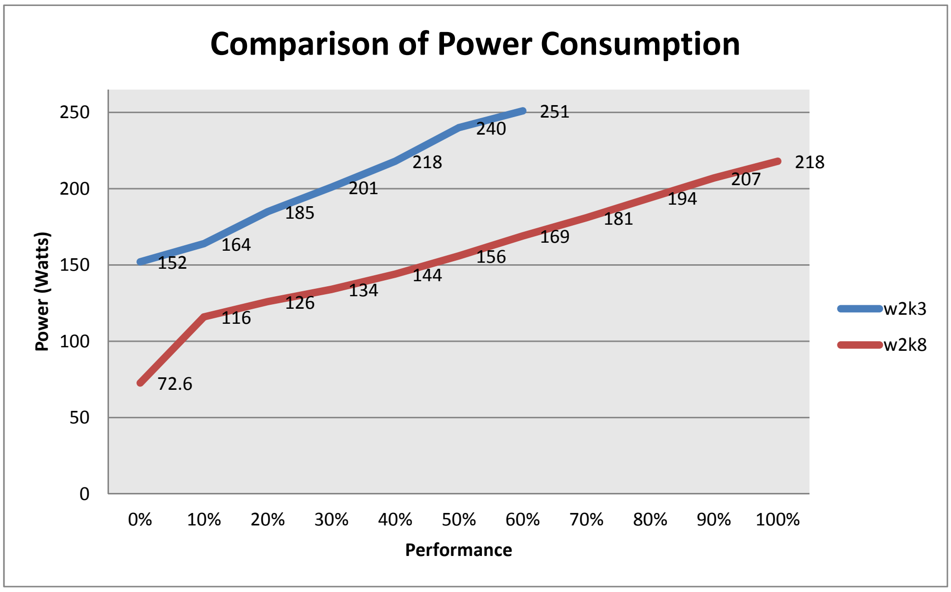

Figure 2.1: Comparison of power consumption between servers.

The benefits of server power management: Effective power management leads to a waterfall of benefits. Like different currents of water rushing together, the benefits of server power management combine, building on each other and multiplying in intensity. Over time, they become strong enough to have a significant impact.

OPEX and CAPEX: Operating expenses or OPEX are the ongoing costs for running a business, a product or system. Its counterpart, capital expenditure or CAPEX is the cost of developing or providing non-consumable parts for the product or system. For example, the purchase of a printer involves CAPEX, while the paper, toner, and power costs are all OPEX.

Efficiency starts with operations, but the cutting of energy expenditure will also trigger another benefit: long-term CAPEX. The less energy is consumed, the less heat is created and therefore the less demand there is for the cooling devices, which in turn involves less consumption of energy and water and increases the useful lifetime of hardware.

Moreover, if the heat generated per server is reduced, then the number of servers per rack can be increased. Hence, when the Grid or the data center receives more demand for services, this feature enables the administrator to fit more servers into the same space and probably prevents the unnecessary purchase of from purchasing new facilities

Productivity: The more servers fitted into each rack, and the more racks in each facility, the more productivity is obtained. Increasing the capacity enables the organization to be more productive and profitable.

Carbon Cost: A reduction in OPEX implies a reduction in CAPEX, an increase in productivity, and also has the potential to reduce carbon cost. If a data center consumes power generated from fossil fuels, the consumptiom of less power will reduce its carbon footprint. Reducing a facility's carbon footprint can help us address environmental concerns by decreasing our contribution to the greenhouse gas emissions created during fossil-fuel-based power generation. If carbon reduction credits are applicable, our company might greatly benefit in terms of tax from a reduction in the consumption of power generated from fossil fuels. Depending on the source of the energy consumed, a greater or lesser quantity of CO_2 is generated. In this thesis, it is assumed that the emissions of CO_2 are of 0.274 kg per kWh which belongs to the production of electricity from oil [84].

Power Management Today: In this way, the waterfall keeps on flowing. Reduced power consumption sets it all in motion. The benefits then build upon each other, by multiplying their impacts, and transforming the data center and organization over time. It all adds up.

Awareness of the tremendous potential of power management is growing, and its importance has been recognized by professionals in major corporations worldwide. Effective power management techniques have been developed, applied, and refined, and new techniques are constantly being developed. The tools of server power management are widespread throughout the data center world.

What you might already be using: Many of these features are within reach of data centers right now. At the component level, manufacturers have improved their chips to perform power monitoring and have enabled them for integration into the functions of power management systems.

Myths: Features of server power management are related to certain drawbacks, although many are simply myths.

- Reliability. The reliability of power-saving features in microprocessors and other hardware devices has been proven through extensive testing and evaluation by vendors. Today, power management constitutes a mature technology and equipment is subjected to rigorous testing to ensure quality and robustness. In fact, vendors are so confident of these features and that they are usually enabled by default.

- Performance. Low-level power management features are only activated when a device or component is idle, and when performance is required, these features are automatically switched off.

- Availability. It is true that low-power states can affect availability, and high-level power management can delay response time of services, and hence policies have to deal with this drawback, by waking-up systems during high-workload periods.

2.3.2 Layers of the Server Power Management

Reducing OPEX, CAPEX, increasing productivity and decreasing carbon costs are tackled from five basic layers of server power management. The basic five layers are explained in the following subsections and are usually shown as a pyramid such as that in Figure 2.2.

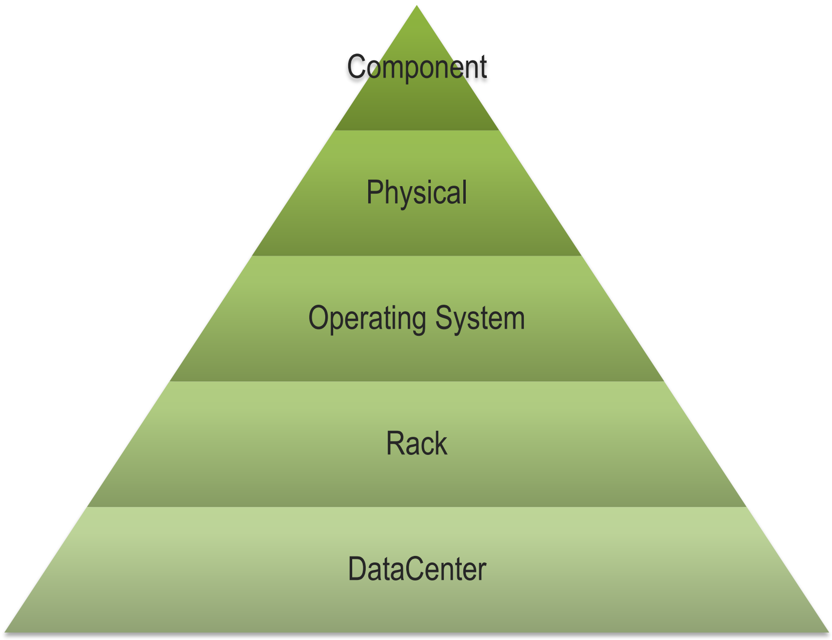

Figure 2.2: Layers of the Server Power Management.

Component Layer: Components are the individual pieces that compound a machine, including chipsets, processors, memory and I/O devices. These components are often manufactured with power management capabilities, such as frequency and voltage scaling. By combining frequencies and voltages, a processor enters into a performance state (P-state). P-states imply reduced performance. C-states are examples of idle states of processors as specified by the Advanced Configuration and Power Interface (ACPI). C-states range from C1 to C6, with C6 using the least power and having the most latency. Other examples of idle states include:

- PPFE, a fast exit state that memory enters when idle
- PPSE, slow exit idle memory state
- Self-refresh, a low-power but long-latency idle memory state, and
- ACPI's B1-B4, D1-D4 and PCIE's L1 to L4 states

Physical System Layer: In the physical system layer, the whole system (i.e., the server) controls the power states of its components. In the ACPI, the terminology assigns a letter to each type of component (B-states refer to I/O buses, L-states to serial such as PCI and G-states, which describe the state of the system as a whole). For each of these types, the "0" state represents the state where the component is fully functional and no power-saving is achieved, and the subsequent states represent the increasing levels of energy saving and the increasing periods of response to return to full power and performance.

Additional power management can be performed at this level by utilizing hardware capabilities, such as the use of blade servers. Blade servers share common resources within a blade chassis, and hence vendors incorporate power-capping technologies into these chassis, by limiting power per blade. The chassis manage the power of the individual blades, regardless of what operating systems the run. The chassis can also optimize power distribution according to the needs.

Operating System Layer: This layer collaborates with the hardware in order to make best choices towards saving energy. This management can occur automatically, as some operating systems are set up in a power-saving mode by default. An example of this is the feature called Core parking, which consists of using only a few cores, thereby allowing other cores to sleep. Within this layer, the power capping also acts, which can be used to prevent systems from consuming more than a specified level of power. This feature artificially limits power consumption of a server or set of servers according to external inputs or policies, and the operating system is in charge of the application of these limits.

Rack Layer: This layer is in charge of managing power consumption of all equipment housed within a given rack. A rack usually includes blade chassis, rack-mount servers, and three-phase power whips. In order to save energy, the power used can be limited for the rack as a whole. Power management tools are needed, which manage limits at previous levels in order to meet the requirements of the rack level. These tools, usually known as Aggregation software, obtain and aggregate power consumption information from a group of servers and other devices. This software facilitates the management of the consumption of multiple servers, and queries the consumption information through the network, via out-of-band communication. The out-of-band data stream is seen as separate from the main, or in-band, data stream and carries instructions than can remotely power the systems. Servers must be equipped with both chip- and system-level power-saving features.

Data Center Layer: This layer includes everything in the data center: all the racks, all the servers in those racks, and all the power-saving capabilities in all the hardware and software in the room. At this level, the key is to look at the whole room, monitoring the overall power consumption and using software to redistribute the workload to reduce power consumption and to control heat dissipation. For example, a manager could consolidate the load on a set of servers and switch other servers off.

Another aspect at this level involves the control of the physical layout of the room, for example increasing the number of servers per rack.

Focus of Power Management Layers: The layers range in increasing complexity from the component layer to the data center layer. The first three (component, physical, and operating system) all have a single-system focus. The rack and data center layers are more complex, have a multi-system focus, and are more concerned with data collection and management. Activities performed in any layer can affect any other layer.

2.3.3 Power Management Policies

Definition of Power Management Policy: Policies must meet the organization's needs and priorities and evaluate performance versus power. This thesis tackles energy-saving policies at the highest layer, that of the data center layer, by evaluating energy consumption for different policies whose main goal is to minimize energy consumption.

Policy Examples: Policies at the data center level can be based on contracts with power providers that dictate a maximum level of consumption. The manager can establish a policy to ensure that power consumption remains below a specified level.

Simple Policies: Policies can be categorized as either simple or complex. Simple policies are triggered by simple rules, for example, turning off a number of servers during late-night hours or periods of seasonal low activity.

Complex Policies: These policies include more factors, and determine what will happen and when based on external factors. Such policies can respond dynamically to events as they happen. For example, a complex policy can respond to the amount of workload by activating or deactivating servers on demand.

The work in this document is focused on these kind of complex policies, which are presented in the papers attached to Part II.

2.4 Grid'5000 at a glance

Grid'5000 has been built upon a network of dedicated clusters. It is not an *ad hoc* Grid. The infrastructure of Grid'5000 is geographically distributed over various sites, of which the initial 9 are located in France: Bourdeaux, Grenoble, Lille, Lyon, Nancy, Orsay, Rennes, Sophia-Antipolis and Toulouse. Porto Alegre, in Brazil, and Luxemburg, are currently being officialy included as the 10th and 11th sites respectively. Reims (France) has been recently added as the 12th site. The project began in 2004 as an initiative by the French Ministry of Education and Research, INRIA, CNRS, the Universities of all the aforementioned cities, and several regional councils. Figure 2.3 shows the geographical representation of the Grid'5000 nodes.

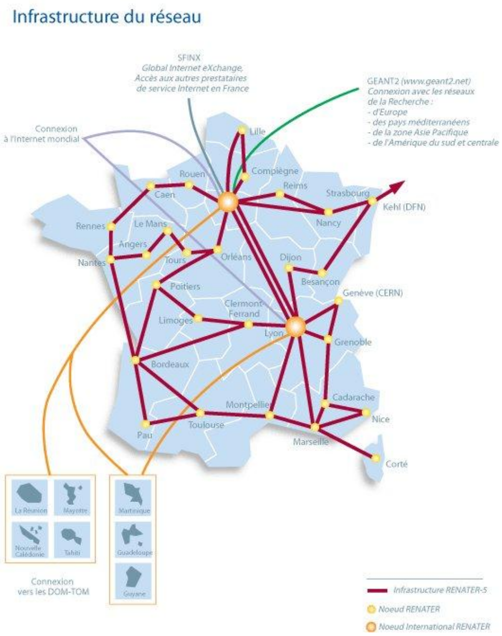

Figure 2.3: Geographical distribution of Grid'5000 nodes.

The initial aim was to achieve 5000 processors on the platform. This objective, adjusted to 5000 cores, was reached during the winter of 2008-2009. On 16th March 2010, 1569 nodes (5808 cores) were in production in Grid'5000. Today the Grid'5000 counts on 8580 cores from 2956 processors. These sites can now connect to each other within the same VLAN at 10Gbps thanks to the dark fibre infrastructure, in an incomplete graph scheme. This network infrastructure is provided by Renater, the French National Telecommunication Network for Technology, Education and Research. It provides interconnection with GEANT-2, overseas territories, and the SFINX (Global Internet exchange).

In terms of the software needed for the use, deployment and management of Grid'5000, the following tools must be mentioned:

- OAR 2. OAR is a resource manager (or batch scheduler) for large clusters. It allows cluster users to submit or reserve nodes either in an interactive or a batch mode.
- Kadeploy 3. Kadeploy is a fast and scalable deployment system for cluster and Grid-Computing. It provides a set of tools for cloning, configuring (post installation), and managing a set of nodes. Currently it successfully deploys linux, *BSD, Windows, and Solaris on x86 and 64-bit computers.
- KaVLAN. VLAN is a manipulation tool for network isolation of experiments.

Grid'5000 enables researh experiments to be carried out at Grid or at cluster level, and guarantees hardware and bandwidth of a more homogeneous nature, although Grid-level experiments are preferred in planning. Each site of Grid'5000 hosts several clusters, since hardware is acquired in incremental steps on each site, whereby clusters are formed at each purchase. Each cluster is composed of two kinds of nodes:

- Compute nodes, which constitute the base elements of a cluster, upon which computations are run.
- Service nodes, which are dedicated to hosting the Grid infrastructure services, such as control and deployment.

Each node can supply several cores, which are the finest granularity of resource in Grid'5000. This means that if a machine has a microprocessor with n cores, it offers n resources to the Grid.

2.4.1 Jobs

The platform can be used in two separate modes: submission or reservation.

- Submission: This is used when a job is submitted to the Grid and the user expects it to be launched immediately. The scheduler decides whether the job can be run, by taking into account the occupation of current resources and the agenda of future jobs. Users usually check these requirements before the submission of a new job through a web interface that presents the state and the agenda of the Grid and its resources.

- Reservation: This is used when a job is to be launched on the Grid in the future. The scheduler checks the requirements of time and resources and decides if the reservation can be made or not. Again, users usually check these requirements before making a reservation.

The software used for task scheduling is the aforementioned OAR. Job information includes submission time, start and stop time, job identification given by the manager software, the owner of the job, and the set of assigned resources which are going to run the job. The job information includes other information which is irrelevant to the objectives of this research.

2.4.2 Resources

The Grid'5000 platform features a variety of machines depending on the location and the cluster they belong to, and on when these machines were included on the platform. Two families can be found: Intel Xeon and AMD Opteron. Each machine offers its CPU cores (usually 2, 4 or 8) to the Grid to execute jobs. Each CPU core is called a resource and each job is related with a set of these resources. Machines are stacked in racks, as shown in Figure 2.4.

Although the performance of each resource is not identical, the assumption that performances are very similar is made, and hence there is no effective difference between running a job on one resource or on another. The same assumption is also made about the consumption of these resources, and therefore each resource uses the same amount of energy. Future work could address this issue which implies taking

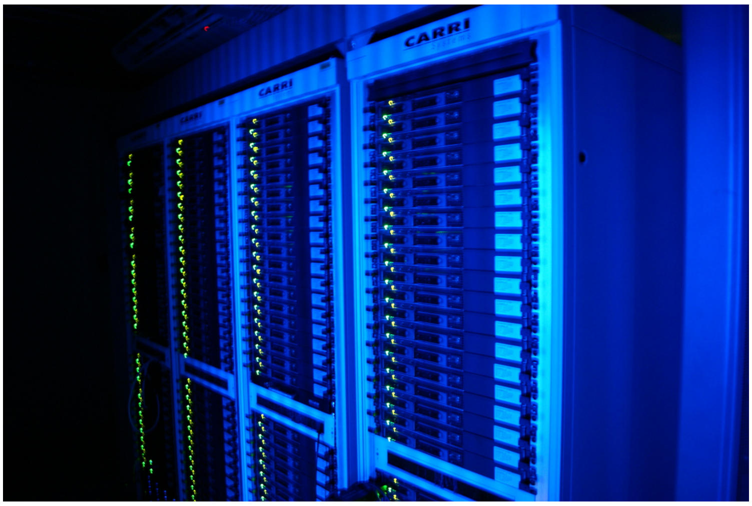

Figure 2.4: Setup of a Grid'5000 node, in racks.

into account which resources consume less energy and attempting to minimize the usage of those resources that waste more energy.

These assumptions enable job resources to be rearranged for energy-saving purposes, without having to consider to which type of resources a job originally belonged; thereby rendering no difference between running a job on one set of resources or on another.

Hence the various states of the resources and their estimated power required are as listed below:

- *On*. A resource is *On* when it is occupied by a job; the resource is running the job. A job is usually deployed over a set of resources. The power a resource needs in this state is approximately 108 watts.

- *Off*. A resource is *Off* when it has been switched off. This means the resource is not occupied with any job. The power needed is approximately 5 watts.

- *Idle*. A resource is *Idle* when it has been switched on and is waiting for new jobs, but it is not presently occupied with any job. The power a resource needs in this state is approximately 50 watts.

- *Booting*. A resource is *Booting* when it is being switched on from *Off* to *On*. The power a resource needs in this state is approximately 110 watts.
- *Shutting*. A resource is *Shutting* when it is being switched off from *On* or *Idle* to *Off*. The power a resource needs in this state is approximately 110 watts.

Figure 2.5 shows the life cycle of the resources where colours are representative of future figures, that is, green for *On*, blue for *Idle*, red for *Shutting*, grey for *Off* and yellow for *Booting*. The time needed (in seconds) for a status change is shown along the edges. Notice that status changes between *Idle* and *On* are immediate, which means that these transitions need 0 seconds. The times $T_{booting}$ and $T_{shutting}$ have been established for simulation purposes as 100 secs and 10 secs respectively.

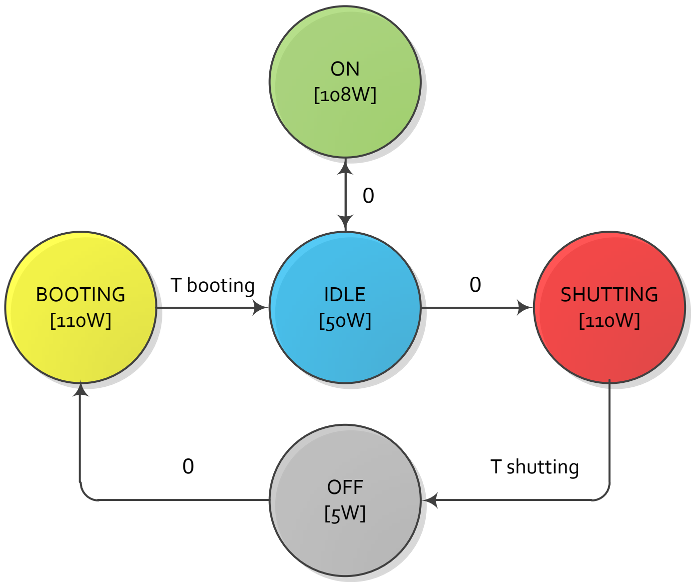

Figure 2.5: Life cycle of the Resource.

2.5 Graphical representation

A graphical representation of what occurs in the Grid is needed for a better understanding of behaviours and issues. Typical representation is based on task-scheduling problems, where the X-axis represents time, and Y-axis represents resources in a discrete form. In the case of Grid-Computing environments, time is usually discretized with a minimum granularity of one second, and in the Y-axis each unit represents one resource (cpu core) of the Grid infrastructure. When a job is submitted to be run on a set of resources, it is represented as a rectangle or a set of rectangles (in the case of submission on non-consecutive resources). The rectangle width starts on the start-time and finishes on the stop-time of the job it represents. Figure 2.6 shows a typical diagram with one job submitted at t_1 on a couple of resources r_2 and r_3 and it is run from t_4 (start-time) to t_7 (stop-time).

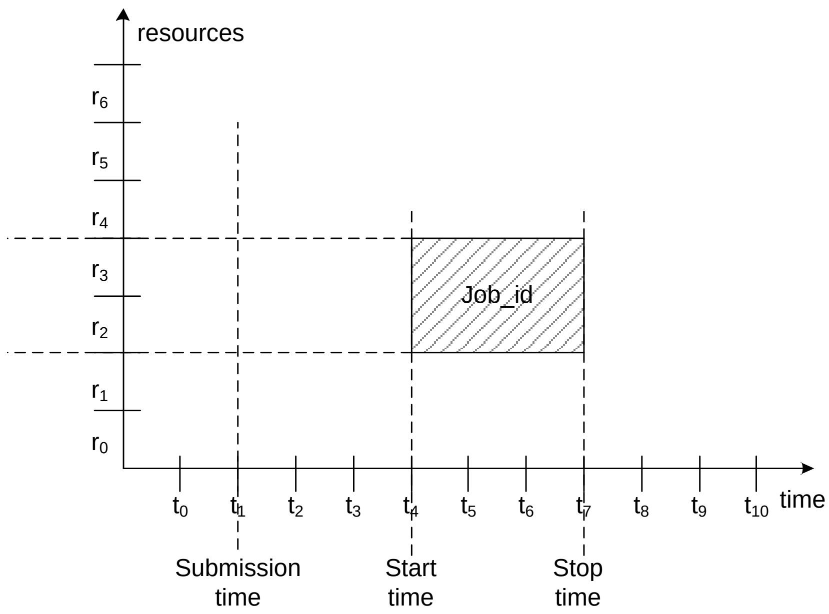

Figure 2.6: Canonical representation of jobs between resources and time.

Despite the lack of colours in this representation, the simulator software developed for this thesis, provides rectangles with colours, thereby representing the state of the resource over time.

2.6 Data envelopment analysis

Data Envelopment Analysis (DEA) is a non-parametric method which provides a relative efficiency assessment (called DEA efficient) for a group of decision-making units (DMU) or for productive efficiency (aka technical efficiency) with a multiple number of inputs and outputs.

DEA has been successfully applied to several sectors. The method establishes a best-practice production frontier (or envelop) based on the empirical input and output data on DMUs. It determines the level of production inefficiency of a DMU by projecting the unit onto the frontier. The original DEA model, introduced in 1978 [28], was set up with input orientation and assumes constant returns to scale (CRS). In an input-oriented model, the desired output level is achieved by minimizing the production inputs. The CRS assumption suggests that an increase in the amount of inputs utilized would lead to a proportional increase in the amount of outputs generated. The original model has been subsequently extended and numerous variations of DEA have resulted. For example, a DEA model can be set up to be output-oriented [27], which attempts to maximize outputs with a set of available inputs. Another significant development of the DEA model by Banker, Charnes, and Cooper (BCC) [11] allows for variable returns to scale (VRS). The VRS assumption suggests that an increase in the amount of inputs utilized can lead to a proportional or non-proportional change in the amount of outputs generated [13].

In recent years, a great variety of applications of DEA have appeared for the evaluation of the performances of many kinds of entities engaged in various contexts. DEA is especially useful when examining the nature of complex (often unknown) relations between multiple inputs and multiple outputs. DEA has been used both in private [45, 44, 7, 30] and in public contexts [54, 2].

Regarding energy efficiency studies, DEA is commonly applied for the study and comparison of the performance and efficiency of energy industries, above all in the electricity industry, see [109], [89], [105], [87] and [103]. More recently, DEA has also been applied to IT companies in [97] and has been popularized in environmental performance measurement due to its empirical applicability.

In this work, DEA is used as a method to compare energy-consumption efficiency between each Grid'5000 location, where productive efficiency is measured as the energy consumed to run Grid'5000 jobs at each location. This analysis is presented in the journal paper *Evaluating decision-making performance in a Grid-computing environment using DEA* included in Part II.

CHAPTER 3

ENERGY-SAVING IN SMART ENVIRONMENTS

$E = \hbar \cdot \nu$

Electromagnetic energy can be emitted only in quantized form.

Max Planck, 1900

Within the current developmental ambit, the main problems of society today include the issue of how to deal with the huge energy consumption that is largely wasted on a daily basis. It should be fully appreciated that energy-saving and energy efficiency constitute two of the principal instruments to achieve economic growth and social welfare.

3.1 Introduction

State efforts to reduce energy wasting in Spain are listed in the "Estrategia Española de Desarrollo Sostenible" approved in 2007 by minister council, and has been put into practice through:

- "Estrategia española de cambio climático y energía limpia. Horizonte 2007-2012-2020" of the Ministry of Environment [77];
- "Plan de Acción 2008-2012 de la Estrategia de Ahorro y Eficiencia Energética en España" of the Ministry of Commerce, Industry and Tourism, [75];
- the new "Plan de Ahorro y Eficiencia Energética 2008-2011" of the Ministry of Commerce, Industry and Tourism [76]; and
- the Ministry of Economy and Competitiveness, which has supported sustainable development projects, such as that of the AFRISOL buildings, which strives towards the construction of totally renewable buildings in a cooperative way with companies, universities and research centers.

In this context, the research provided in this thesis, presented in the paper included within this document in Part II, adapts the utilization of new technologies existent in other domains, in order to improve consumption. Consequently, daily activities, such as switching on lighting, can be adjusted in order to save energy. A software architecture definition (see Chapter 10) forms the foundation upon cornerstone from which these objectives are accomplished.

Buildings in Spain today present a sum total of 3,500 million square metres, and account for 17% of total energy consumption [46]. European authorities approved the new Technical Building Code that requires the installation of solar panels and the use of solar, thermal and photovoltaic energy in new buildings. However, these measures cannot succeed in attaining any real energy saving; they can only satisfy the growing energy demand in each building. This work focuses on how to minimize energy consumption in lighting equipment to obtain a real saving of energy by regulating the resources to attain optimal lighting in buildings. In this sense, the Spanish Association of Home Automation (CEDOM) with the support of the Spanish Institute of Energy Diversification and Saving (IDAE) has published research on energy saving in the residential sector through the installation of home automation [25]. It concluded that energy-saving can be increased to as much as 80% of the present consumption in lighting, 25% in conditioning, and 20% in domestic appliances.

The ideas proposed for the reduction in energy consumption and improvement in efficiency are aimed at developing partial solutions for the scope of energy consumption in residential buildings. Consequently, an intelligent control of residential buildings is composed of lighting control via lighting sensors.

3.2 WSN to sense Smart Environments

Saving energy in smart environment systems is one of the main goals of smart environment research. New approaches to saving energy have arisen thanks to the introduction of Wireless Sensor Networks (WSNs): large networks of embedded devices, containing microcomputers, radios, and sensors. Within the objectives of this study, WSNs are employed to retrieve data on lighting conditions. Several approaches have been proposed in [53, 79] to save energy in this scenario. Nevertheless, the former set of approaches fails to consider user preferences on illuminance, and hence a constant value of illuminance is considered as suitable for every single inhabitant, while the latter approach maintains no knowledge about any type of inhabitants' preferences. Other approaches not based in WSNs, like [86] based on embedded micro-controllers, cannot store any knowledge about inhabitants, and hence it remains unadaptable. Our approach considers inhabitant preferences about lighting and "learns" them in order to automatically adjust lighting to satisfy these preferences. The aforementioned *Technical Building Code* establishes 400 lumens as the optimal quantity of light for a standard office, but makes no mention of how it should be measured. A theoretical computation of how many lumens are provided by our artificial lighting setup can be made. To this end, a theoretical and empirical analysis about how natural lighting affects indoor lighting is carried out and explained in the journal paper *A Study on Saving Energy in Artificial Lighting by Making Smart Use of Wireless Sensor Networks and Actuators* included in Part II.

Moreover, measurements may vary depending on where sensors are located, and upon many other variables, such as type of lights, size of the windows, number of windows, and which direction the windows face. Our approach avoids these difficulties, and makes an analysis of the lighting conditions *in situ* and in real time. The implementation of the experimental case study is based on the ideas presented in [36, 39] who propose a multi-agent approach to control Smart Environments and a paradigm of design based on learning and prediction. The case study stores information according to a model for Smart Environments (see Chapter 9), divided into four categories: device related, inhabitant related, environment related and background.

The devices used are the following: a motion sensor to detect whether someone is in the room, an actuator on the fluorescent lights to switch them on and off, and a couple of *Sentilla Tmotes* sensors.

Let us describe this last device. *Sentilla Tmotes* are devices which measure the quantity of light. The lux (symbol: lx) is the SI unit of illuminance and luminous emittance, and can be detected by either of two different photodiodes, as explained in *Hamamatsu* [58]:

- *S1087 photodiode.* For the visible range of the spectrum, from 320 to 730 nanometers. This range is often called Photosynthetically Active Radiation (PAR). This region corresponds with the range of light visible to the human eye.
- *S1087-01 photodiode.* For the visible range up to infrared, from 320 to 1100 nanometers. This is called Total Solar Radiation (TSR).

Only the PAR unit is considered in this work. The dimensions of the *Sentilla*

Tmotes are of width 8 cm and height 3.2 cm, and are therefore sufficiently small to suit ubiquitous applications and non-intrusive systems. These devices include a humidity and temperature sensor, whose information is also retrieved for future improvement and expansions. In Figure 3.1, the Sentilla Tmote module used in our experiment is shown.

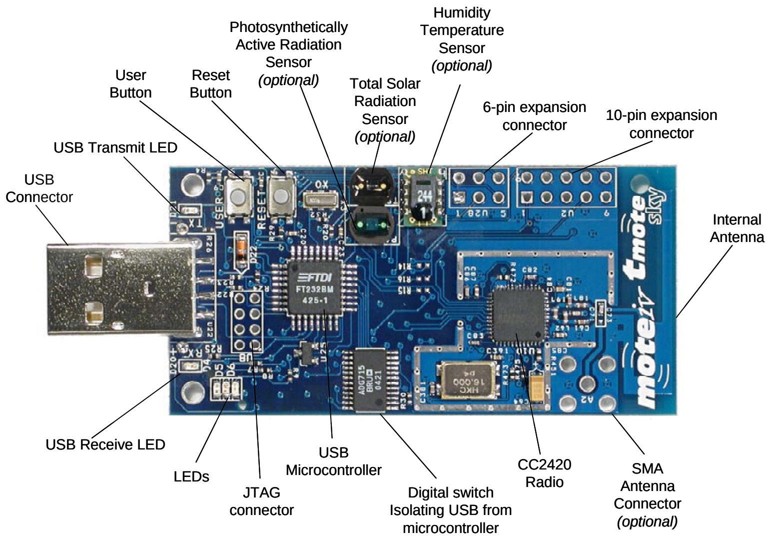

Figure 3.1: Front of the Sentilla Tmote module.

The connectivity of the *Sentilla Tmote* with other motes and computers is executed through the IEEE 802.15.4 (ZigBee) protocol, which minimizes battery consumption. The mesh network protocol implemented by Tmotes software is chosen. In this way, a network to share information and forward it to reach a wider distribution can be designed for the motes.

Nowadays *Sentilla Tmotes* are packaged in a development kit, including an IDE based on Eclipse 3.2 for development in Java. The hardware implements a Java Runtime Environment which can run various applications for the retrieval, processing and transmission of data from sensors.

PART II

Selected research works

Smart Scheduling for Saving Energy in Grid-Computing

Overview

This paper addresses the problem of developing Energy-Saving policies for Grid-Computing Environments. Several policies are developed, tested and then compared, thanks to a software tool called Grid'5000 Toolbox, and results are shown.

Context

This research topic was initiated during the research stages that this PhD candidate carried out at Laboratoire de l'Informatique du Parallélisme of the Ecole Normale Supérieure de Lyon, where permanent researcher Laurent Lefèvre leads the research team on saving energy in Grid-Computing, and on other areas. Thanks to these stages and the help of Laurent Lefèvre and Anne-Cécile Orgerie, these issues could be tackled. This paper is the result of over two years' work in this area.

Journal information

The Journal *Expert Systems with Applications* was selected for the submission of this paper. This Journal is indexed in JCR with an Impact Factor of 2.203 and a 5-Year I.F. 2.455. The Journal stands in ranking Q1 in three categories: Engineering, Electrical & Electronic (41/244); Operations Research & Management Science (5/77); Computer Science, Artificial Intelligence (22/111).

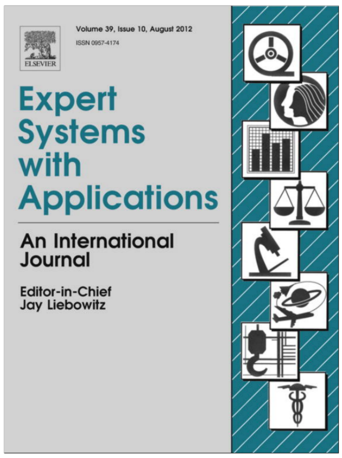

Figure 4.2: ESWA Cover.

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Smart scheduling for saving energy in grid computing

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ARTICLE INFO

Keywords:
Energy policies
Efficiency
Arranging policies
Simulation software

ABSTRACT

Energy saving involves two direct benefits: sustainability and cost reduction. Within the field of Information Technology, clusters, grids and data centres represent the hungriest consumers of energy and therefore energy (saving) policies for these infrastructures should be applied in order to maximize their resources. It is proved in this paper that approximately 40% of energy can be saved in a data centre if an adequate policy is applied. Furthermore, a software tool is presented where simulations can be run and results for real scenarios can be obtained.

1. Introduction

In today's increasingly pessimistic times not only are we faced with major economic issues worldwide, but also with those of sustainability. As a part of sustainability, researchers are encouraged to save energy in all domains, from Information Technology (IT) to transport. Saving energy is directly related with cutting costs and environmental sustainability. Energy efficiency is therefore sought in a wide range of systems from small devices to large-scale computing.

Information Technology energy consumption represents a mere 3–5% of CO_2 emissions worldwide which is similar to that of aviation transport. While apparently trivial in quantity, this usage is symbolic since IT can greatly influence other industrial and research domains (Ruth, 2009). As computing requirements are ever greater, microprocessor manufacturers are doubling the electrical efficiency of computation every year and a half (Sanchez, Wong, Berard, & Koomey, 2011). Nevertheless, energy consumption is still rising despite these good results, with energy consumption of data centres increasing an average of 16.7% over the last decade (Koomey, 2008).

Some companies, such as Google (Ren, Tune, Moseley, Shi, & Hundt, 2010), are committed to increasing energy efficiency in data centres and in cloud computing. The research community has also been searching for improvements in energy efficiency, whereas the majority of companies have focused their efforts on improving facilities.

The huge amount of energy consumed by grid computing provides justification for a study into energy-saving methodologies, either from an economic or ecological point of view. To this end, grid operational policies must be analyzed in order to be optimized.

An experimental grid organization, located in France and called Grid'5000, is analyzed in this paper. Grid'5000 is a scientific instrument designed to support experiment-driven research in all areas of computer science related to parallel, and large-scale and distributed computing and networking. Its purpose is to supply a highly reconfigurable, controllable and monitorable experimental platform to its users.

The rest of this paper is structured as follows: Section 2 includes a brief introduction to Grid'5000 organization and its current energy consumption is analyzed. Various on–off policies, designed to save energy are presented, and a comparison between current energy consumption and the results of each on–off policy are given in Section 3. The way in which jobs can be scheduled between resources is shown in Section 4. Software developed for the testing and simulation is explained in Section 5. Finally, in Section 6, results and conclusions are drawn.

2. Grid'5000 at a glance

Grid'5000 has been built upon a network of dedicated clusters. It is not an *ad hoc* grid. The infrastructure of Grid'5000 is geographically distributed over various sites, of which the initial 9 are located in France: Bourdeaux, Grenoble, Lille, Lyon, Nancy, Orsay, Rennes, Sophia-Antipolis and Toulouse. Porto Alegre, in Brazil, and Luxemburg, are currently being officialy included as the 10th and 11th sites, respectively. The project began in 2004 as an initiative by the French Ministry of Education and Research, INRIA, CNRS, the Universities of on all the aforementioned and several regional councils.

The initial aim was to achieve 5000 processors on the platform. This objective, reframed at 5000 cores, was reached during the

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winter of 2008–2009. On March 16, 2010, 1569 nodes (5808 cores) were in production in Grid'5000. These sites can now connect each other within the same VLAN at 10Gbps thanks to the dark fibre infrastructure which connects them, in an incomplete graph scheme.

Grid'5000 allows experiments at grid or at cluster level, which guarantees a more homogeneous hardware and bandwidth, although grid level experiments are preferred in planning. Each site of Grid'5000 hosts several clusters, since hardware has been acquired in incremental steps on each site, whereby clusters have been formed at each purchase. Each cluster is composed of two kind of nodes:

- Compute nodes, which constitute the base elements of a cluster, on which computations are run.
- Service nodes, which are dedicated to hosting the grid infrastructure services, such as control and deploy.

Each node can supply several cores, which are the finest grains of resource in Grid'5000. This means that if a machine has a microprocessor with *n* cores, it offers *n* resources to the grid.

2.1. Jobs

The platform can be used in two different modes: submission and reservation.

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- *Reservation*: This is used when a job is to be launched on the grid in the future. The scheduler checks the requirements of time and resources and decides if the reservation can be made or not. Again, users usually check these requirements before making a reservation.

The software used for task schedule is OAR. This is a resource manager (or batch scheduler) for large clusters which allows cluster users to submit or reserve nodes either in an interactive or in a batch mode. Job information includes submission time, start and stop time, job identification given by the manager software, the owner of the job, and the set of resources assigned, which are going to run the job. The job information includes other information which is irrelevant to this research.

2.2. Resources

The Grid'5000 platform features different kinds of machines depending on the location and the cluster they belong to, and when these machines were included on the platform. Two families can be found: Intel Xeon and AMD Opteron. Each machine offers its CPU cores (usually 2, 4 or 8) to the grid to execute jobs. Each CPU core is called resource and each job is related with a set of these resources. Although the performance of each resource is not identical, the assumption that performances are very similar is made, and hence there is no effective difference between running a job on one resource or another. The same assumption is also made about the consumption of these resources, and therefore each resource uses the same amount of energy.

These assumptions enable job resources to be rearranged for energy-saving purposes, without having to consider which type of resources a job originally belonged; hence there is no difference between running a job on one a set of resources or on another.

The various states of the resources and their estimated power required are listed below:

- *On*. A resource is *On* when it is occupied by a job; the resource is running the job. A job is usually deployed over a set of resources. The power needed is approximately 108 W.
- *Off*. A resource is *Off* when it has been switched off. This means the resource is not occupied with any job. The power needed is approximately 5 W.
- *Idle*. A resource is *Idle* when it has been switched on and waiting for new jobs, but it is not occupied with any job. The power needed is approximately 50 W.
- *Booting*. A resource is *Booting* when it is being switched on from *Off* to *On*. The power needed is approximately 110 W.
- *Shutting*. A resource is *Shutting* when it is being switched off from *On* or *Idle* to *Off*. The power needed is approximately 110 W.

Fig. 1 shows the life cycle of the resources where colours are representative for future figures, that is, green for *On*, blue for *Idle*, red for *Shutting*, grey for *Off* and yellow for *Booting*. The time needed for a status change is shown along the edges. Notice that status changes between *Idle* and *On* are immediate. The times $T_{booting}$ and $T_{shutting}$ have been established for simulation purposes as 100 sgs and 10 sgs, respectively.

2.3. Performance

Current Grid'5000 behaviour leaves resources *Idle* while waiting for new jobs to run. This policy is the so-called *Always On* policy which is the best for the fast satisfaction of users needs, but the worst in terms of energy consumption. This paper is focused in replacing this current policy with new policies which are presented in the following section.

3. Scheduling energy policies

Energy policies establish the managing of grid resources. While other research attempts to reduce the makespan (Tseng, Chin, & Wang, 2009), the policies shown in this work aim to describe and compute what to do with a resource when it finishes the exe-

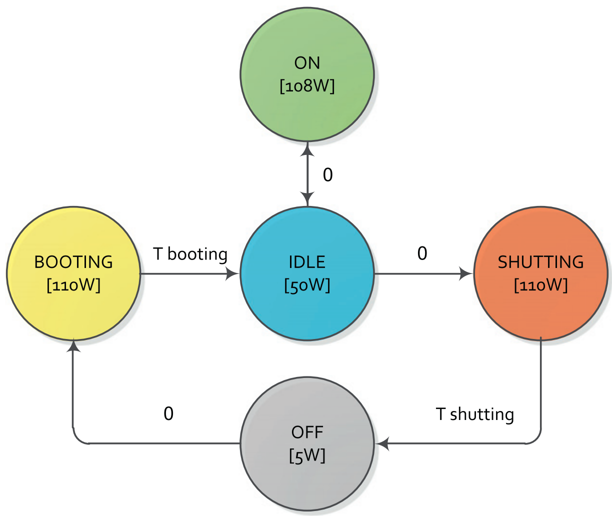

Fig. 1. Life cycle of the resource.

cution of a job. Thus, each energy policy decides to either leave resources switched on or switch them off depending on the purpose of the policy. Each energy policy is illustrated with a screenshot of the Graphical User Interface (GUI) where the horizontal axis is the timeline and the vertical axis represents the resources. The following energy policies are implemented in the Grid'500 Toolbox (Section 5):

3.1. Always On

This is the simplest energy policy, whereby resources are never switched off, under any condition, and therefore resources remain idle, waiting for a new job to be run. Currently Grid'5000 works under this mode, and hence these consumption results are used for comparison with the results of other energy policies in order to determine how much energy can be saved. The number of times resources are switched off or on are always zero, and therefore their stress is minimal. Fig. 2 shows the typical appearance of resources while the Grid'5000 Toolbox is running this energy policy. In this figure, four resources are shown, each resource is denoted by a row, and four jobs have been carried out.

3.2. Always Off

Under this policy, resources are always switches off under any condition, and therefore resources start shutting down after any job finishes, and later they remain switched off. If a new job arrives, the assigned resources have to be booted to run that job. This booting is done within reservation limits, and thus the user is unable to make effective use of the resources until they are booted. This policy is usually the best regarding energy consumption results, but the number of times that booting and shutting is always at a maximum, and therefore the stress produced on the hardware components is the highest, which is not desirable. The typical appearance of resources while the Grid'5000 Toolbox is running under this energy policy is shown in Fig. 3.

3.3. Switch Off Randomly

This policy switches off and randomly leaves the resources idle by following a Bernoulli distribution whose parameter is equal to 0.5 when a job finishes. Hence, the times that resources are switched off or left idle tends towards 50%. Results tend to be half-way between those of the *Always Off* and *Always On* policies regarding the two kinds of results: the times resources are switched off and energy consumption. The typical appearance of resources while the Grid'5000 Toolbox is running under this energy policy is shown in Fig. 4.

3.4. Load

Load can be defined as the percentage of resources that are *On* among the clusters of a location. This policy uses this information and either switches resources off if the load, when finishing a job,

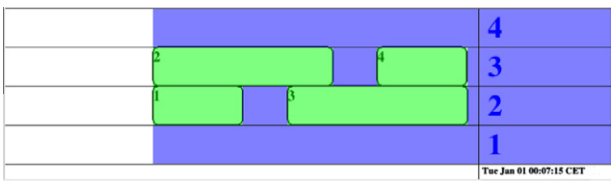

Fig. 2. Example of *Always On* policy. Idle (blue), On (green). (For interpretation of references to colors in this figure legend, the reader is referred to the web version of this article.)

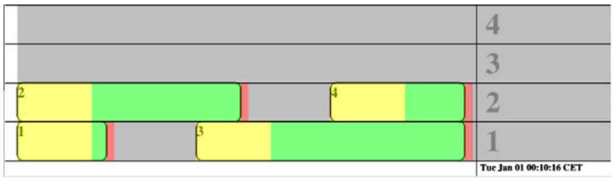

Fig. 3. Example of *Always off* policy. On (green), Shutting Down (red), Off (grey), Booting (yellow). (For interpretation of references to colors in this figure legend, the reader is referred to the web version of this article.)

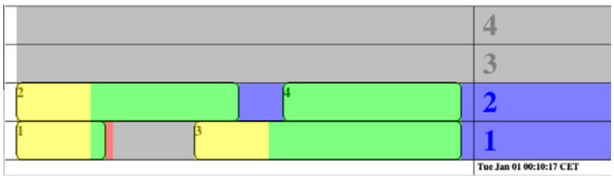

Fig. 4. Example of *Switch off randomly* policy. Idle (blue), On (green), Shutting down (red), Off (grey), Booting (yellow). (For interpretation of references to colors in this figure legend, the reader is referred to the web version of this article.)

is greater than the threshold or leaves the resources idle if the load is less than the threshold. The threshold is a parameter, ranging from 0 to 1, selected from the GUI. The typical appearance of resources while the Grid'5000 Toolbox is running under this energy policy with 0.6 as its threshold parameter is shown in Fig. 5.

3.5. Switch off T_S

T_S is defined *as the minimum time that ensures energy saving if a resource is switched off between two jobs* (Orgerie, Lefèvre, & Gelas, 2008). T_S can be computed as follows:

$$T_S = \frac{E_s - P_{Off} * \delta_{tot} + E_{On \to Off} + E_{Off \to On}}{P_{Idle} - P_{Off}}$$

where P_{Off} and P_{Idle} refer to the power consumption in watts of a given resource when it is *Off* and *Idle*, respectively. $E_{On \to Off}$ and $E_{Off \to On}$ refer to the energy required in joules for a given resource to boot or switch it off respectively. E_S is the energy saved for T_S seconds. Finally, $\delta_{tot} = \delta_{On \to\ Off} + \delta_{Off \to On}$ which is the total time a given resource needs for it to switch itself off and switch itself on.

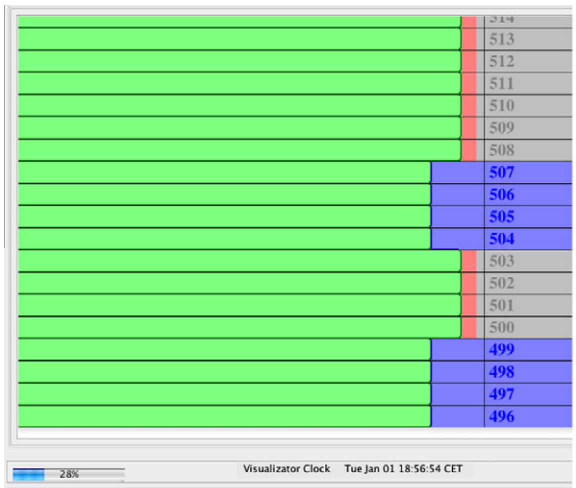

Fig. 5. Example of *Load* policy. Idle (blue), On (green), Shutting Down (red), Off (grey). (For interpretation of references to colors in this figure legend, the reader is referred to the web version of this article.)

This energy policy uses the agenda to check whether the subsequent submitted jobs are going to be run in the grid in less than T_S. This policy computes the number of resources that are needed in a time period less than T_S, and leaves the resources of the recently terminated job idle or shuts them down depending on this computation. In this way, the simulator attempts to minimize booting and shutting-down cycles when no energy can be saved. The typical appearance of resources while the Grid'5000 Toolbox is running under this energy policy, where $T_S = 130$ s, is shown in Fig. 6.

3.6. Exponential

The Exponential distribution, denoted by $Exp(\lambda)$, describes the time between events in a Poisson process, i.e. a process in which events occur continuously and independently at a constant average rate $(1/\lambda)$. Under the hypothesis that the arrival of new jobs follows an Exponential distribution, this energy policy attempts to predict the arrival of new jobs. Thus, to compute the λ parameter, every time a job finishes, the mean time between the last jobs is computed, and denoted by μ. Hence, $\lambda = 1/\mu$ by using the method of maximum likelihood. The probability of the arrival of a new job can then be computed by means of the exponential cumulative density function (cdf) as $cdf(T_s) = 1 - e^{-T_s/\mu}$. Therefore, given a *threshold* value, the following conditions are imposed:

$$\begin{cases} \text{if} \quad cdf(T_s) >= threshold & \text{then leave resources } Idle \\ \text{if} \quad cdf(T_s) < threshold & \text{then switch resources } Off \end{cases}$$

3.7. Gamma

The Gamma distribution, denoted by $\Gamma(\theta, \kappa)$, is frequently used as a probability model for waiting times and presents a more general model than the Exponential. Under the hypothesis that the arrival of new jobs follows a Gamma distribution, this energy policy attempts to predict the arrival of new jobs. The parameters computed every time a job finishes are:

- number of resources available as *resourcesAvailable*. These are the resources that are *Idle* and ready to accept new jobs.
- mean resources used by last jobs as *meanResources*. Total number of resources used by the last jobs is computed and divided by the number of jobs. The number of jobs is a selectable window size.
- mean duration between the previous number of last jobs as *meanDuration*. The sum of the duration of these last jobs is computed and divided by the previous number of last jobs.
- the floor of *resourcesAvailable*/*meanResources* as *z*.

The parameters of the Gamma distribution are then estimated as: $\theta = 1/meanDuration$ and $\kappa = z + 1$. Finally the probability of the arrival of a new job is computed by means of the cumulative density function (cdf) with

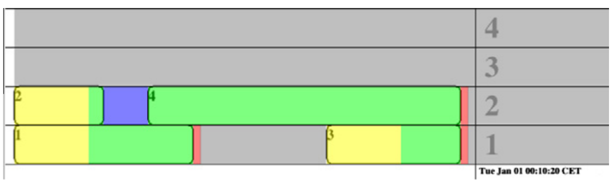

Fig. 6. Example of *Switch off* T_S policy with $T_S = 130$ seconds. Idle (Blue), On (Green), Shutting Down (Red), Off (Grey). (For interpretation of references to colors in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. Example of arranging policies. i) Before jobs have been arranged. Job #3 is about to start, assigned to *Off* resources. (ii) After jobs have been arranged. Job #3 has been moved to available resources. No need to boot resources.

$$cdf(T_s) = \frac{\gamma(\kappa, T_s/\theta)}{\Gamma(\kappa)}$$

Hence, given a *threshold* value, the following conditions are imposed:

$$\begin{cases} \text{if} \quad cdf(T_s) >= threshold & \text{then leave resources } Idle \\ \text{if} \quad cdf(T_s) < threshold & \text{then switch resources } Off \end{cases}$$

4. Arranging policies

Arranging policies establish the arranging of the jobs for their execution. A job can be moved from one set of resources to another, or a planned job execution can even be moved in time in order to take advantage of resources that are already switched on.

- *Do Nothing (DN)*: does not move jobs in time nor from one resource to another; they are executed as defined in the agenda. This together with the energy policy *Always On* offers the current Grid'5000 behaviour.
- *Simple Aggregation of Jobs (SA)*: This policy tries to find resources available (*Idle*) for new jobs. In this way, if a job is assigned to a set of resources which are *Off* and some other resources are available, the time and the energy needed to be switched on can be saved. Notice that this policy does not change start or stop times, and hence it is transparent to users.

An example of these arranging policies can be seen in Fig. 7.

5. Grid'5000 Toolbox Simulator

Grid'5000 Toolbox[1] replays the progress of the real grid regarding the operation of jobs and resources. Grid'5000 Toolbox is able to compute energy consumption of Grid'5000, and enables the user to set up several parameters including: (*a*) simulation start-time, (*b*) simulation stop-time, (*c*) location, (*d*) energy policy and (*e*) arranging policy. These parameters can be set up through the *Configuration* tab as shown in Fig. 8.

Grid'5000 Toolbox (Grid Toolbox, 2011) is a Java Desktop application using libraries to: 1. deal with energy and time magnitudes (JScience Martin-Michiellot, 2008); 2. communicate with RDBMS

[1] This software can be downloaded and executed from the web of the Idinfor research group (Idinfor, 2011).

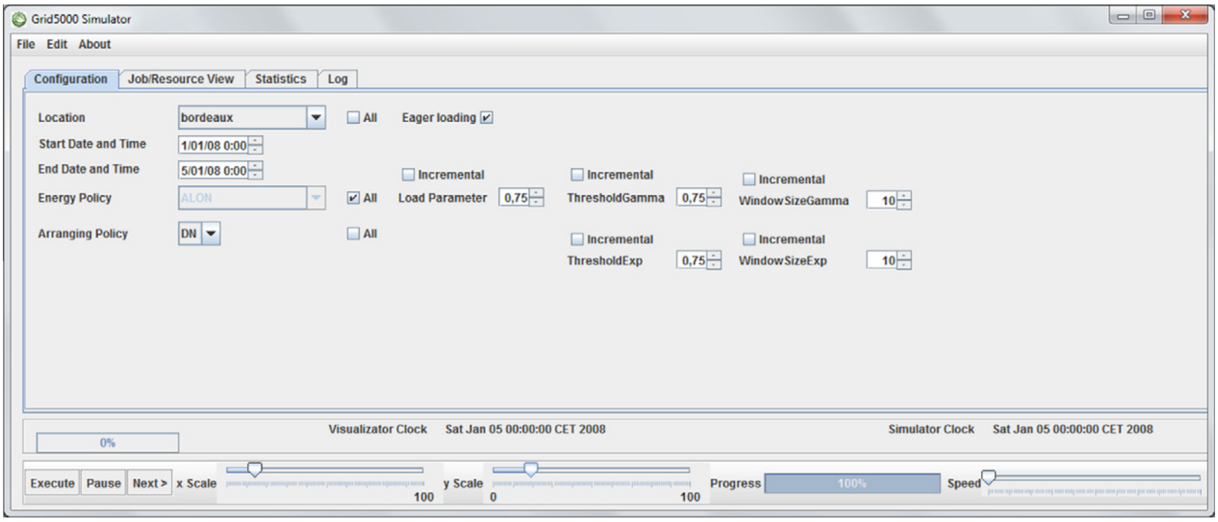

Fig. 8. Configuration tab presenting setup parameters for a batch of simulations.

(JDBC connector API Reese, 2000); 3. annotate database entities (Java Persistence API JPA Keith and Schincariol, 2006; 4. model statistical distributions (JSC Java Statistical Classes Bertie, 2002); 5. logging simulation information (Apache Logging Services Log4Java Gupta et al., 2011); 6. write results in Excel files (JExcel API Khan, 2010); Grid'5000 Toolbox includes a module to parse raw log files from Grid'5000 systems and stores these files in an standard RDBMS through JPA annotations. Each log file is related to one location. The data found in these log files includes: past jobs, resources, machines, clusters, dead-state resources, users, and relations between jobs and resources.

The simulator operation is based on an agenda where jobs are registered and on a list of resources representing the real resources at the sites. The simulator starts querying the agenda from start-time to stop-time. Each query is related to current simulation time, and hence the agenda seeks jobs and events that occur at given current time. Once the agenda returns new events, the simulator processes them and changes resources states as would be needed for execution in the real world, whilst taking into account the policies selected in order to manage resources and jobs. The consumed energy is computed step by step by means of the information on energy consumption of each resource and the resource states detailed in the resource list. The results of simulation executions are stored on a spreadsheet where researchers can find details about consumption, the number of shutting and booting of resources, the comparison between minimal energy consumed and current energy consumed, etc. Results are also shown in the *Statistics* tab in a more visual way (see Fig. 9).

6. Experimentation

In order to present the results, the recommendations for measuring and reporting Overall Data Centre Efficiency (Green Grid, 2011) were taken into account. Results for every combination of energy and arranging policy summarize the behaviour of these policies for each location and for each time period selected. The computed information includes:

- total number of bootings and shuttings,
- total energy consumed
- energy saved as compared with the energy consumed by current Grid'5000 policies (*Always Leave On* and *Do not Arrange* policies)
- comparison between the minimal[2] energy consumable for an execution and actual energy consumed by each combination of policies,
- comparison between the energy consumed by current Grid'5000 policies for an execution and actual energy consumed by each combination of policies,
- saving in energy attained per shutting down, which shows the validity of the shutting down decisions.

6.1. General results

General results compare all possible combinations of energy policies and arranging policies. Grid'5000 Toolbox enables researchers to run a batch of simulations while defining the parameters of each policy. This paper presents a summary of 324 different simulations as follows:

- two different periods of six months. From 1st January, to 30th June and from 1st July to 31st December 2008.
- two arranging policies, *Do Nothing* and *Simple Aggregation of Jobs*
- the seven energy policies listed in Section 3.
- each parameterizable energy policy has been run with various values of for several parameters as follows:
  1. *Load* policy. Load threshold parameter from 0.0 to 1 by 0.3. A total of four scenarios.
  2. *Exponential* and *Gamma*. Threshold probability parameter from 0.0 to 1 by 0.3, and window size from 2^0 to 2^8. Hence there are thirty-six different scenarios for each policy.

From the 324 setups run, the best energy savers have been selected for each policy. Tables 1 and 2 show selected results for the two periods.

With respect to the first period, the minimal energy consumable is 149,202 kW h for a total of 74,035 deployed jobs, and the current energy consumed by Grid'5000 is 217,803 kW h. It can be seen that the simplest energy policy, *Always Off*, is the best in terms of energy saving. However, it is the policy which forces the highest number of power cycles, and hence the stress on the hardware is the greatest. *Load* policy with 0.9 threshold returns very similar results for energy saving and number of power cycles.

[2] The theoretical minimum energy consumed is the sum of the energy needed to run all the jobs of a period. The consumption by the *Idle*, *Booting* and *Shutting Down* states is not computed.

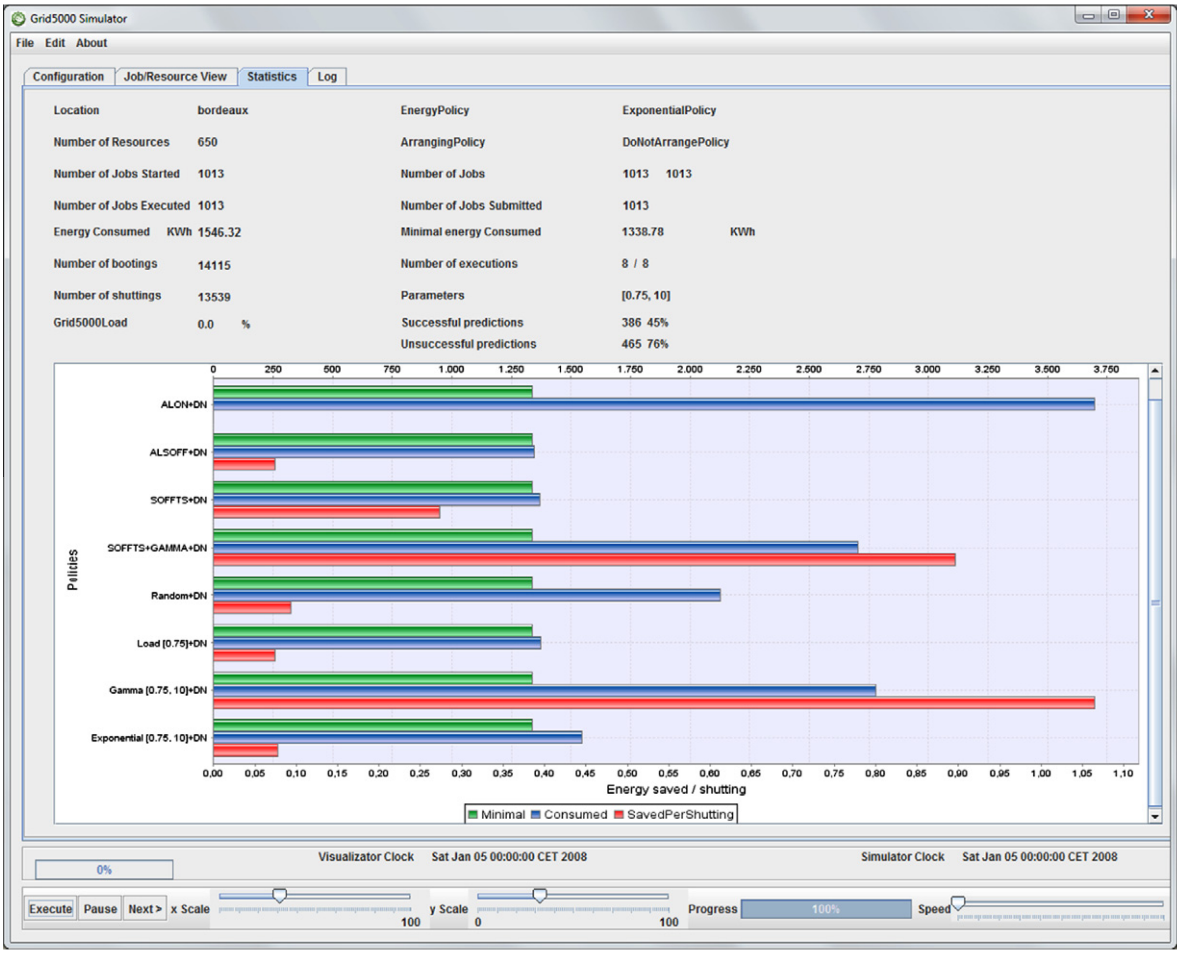

Fig. 9. Statistics tab presenting results for a batch of simulations.

Table 1
Selected results for Bordeaux from 1st January to 30th June, sorted according to energy consumed.

Energy policy		Arranging policy	Boot. + Shutt.	Energy consumed (kW h)	Simulated vs		Saved per shutt.
Name	Params				Min	Curr	
Alwz Off	n/a	*SA*	1,668,900	149,396	100.13	68.59	0.04
Load	[0.9]	*SA*	1,569,934	150,304	100.74	69.01	0.04
S.Off Ts	n/a	*SA*	653,856	150,527	100.89	69.11	0.10
Exp.	[0.9, 16]	*SA*	1,047,198	151,733	101.70	69.67	0.06
S.Off Rdm	n/a	*SA*	890,195	157,645	105.66	72.38	0.07
Gamma	[0.9, 1]	*SA*	183,850	186,929	125.29	85.82	0.17
Alwz On	n/a	*SA*	0	217,921	146.06	100.05	0.00

Table 2
Selected results for Bordeaux from 1st July to 31st December, sorted according to energy consumed.

Energy Policy		Arranging policy	Boot.+ Shutt.	Energy consumed (kW h)	Simulated vs		Saved per shutt.
Name	Params				Min	Curr	
Alwz Off	n/a	*SA*	2,365,598	169,364	100.80	73.61	0.03
S.Off Ts	n/a	*SA*	1,584,070	169,894	101.11	73.84	0.04
Load	[0.9]	*SA*	2,104,456	170,109	101.24	73.93	0.03
S.Off Rdm	n/a	*SA*	1,321,702	173,323	103.15	75.33	0.04
Exp.	[0.9, 1]	*SA*	521,878	175,945	104.71	76.47	0.10
Gamma	[0.9, 1]	*SA*	957,784	193,180	114.97	83.96	0.04
Alwz On	n/a	*SA*	0	230,093	136.94	100.00	0.00

Switch Off Ts policy is the only policy that accesses the agenda for future reservations before deciding what to do. This fact explains why the percentage of prediction success is the greatest. It also returns very good results in terms of energy saving, but with

Table 3
Comparison of the two arranging policies comparison for Bordeaux and a selected set of energy policies.

Energy policy		Arranging policy	Boot.+ shutt.	Energy consumed (kW h)	Simulated vs		Saved per shutt.
Name	Params				Min	Curr	
Load	[0.9]	*SA*	1,569,934	150,304	100.74	69.01	0.04
Load	[0.9]	*DN*	1,561,122	154,141	103.31	70.77	0.04
Load	[0.6]	*SA*	902,932	158,205	106.03	72.64	0.07
Load	[0.3]	*SA*	299,304	177,839	119.19	81.65	0.13
Load	[0.6]	*DN*	892,656	186,406	124.94	85.58	0.04
Load	[0.3]	*DN*	292,025	208,141	139.50	95.56	0.03
Load	[0.0]	*SA*	650	216,386	145.03	99.35	2.18
Load	[0.0]	*DN*	650	216,531	145.13	99.42	1.96
S.Off Rdm	n/a	*SA*	890,195	157,645	105.66	72.38	0.07
S.Off Rdm	n/a	*DN*	879,681	183,073	122.70	84.05	0.04

Table 4
Summary of environmental and economic results for Bordeaux.

Energy policy	Energy consumed (kW h)	Saved energy (kW h)	Euros saved	CO_2 kg saved	Energy Consumed (kW h)	Saved energy (kW h)	Euros saved	CO_2 kg saved	Euros saved	CO_2 kg saved
Alwz S.Off	149,396	68,525	9593	18,776	169,364	60,729	8502	16,640	18,096	35,416
Load	150,304	67,617	9466	18,527	170,109	59,984	8398	16,436	17,864	34,963
S.Off Ts	150,527	67,394	9435	18,466	169,894	60,198	8428	16,494	17,863	34,960
Exp.	151,733	66,188	9266	18,135	175,945	54,148	7581	14,836	16,847	32,972
S.Off Rnd	157,645	60,276	8439	16,516	173,323	56,770	7948	15,555	16,386	32,070
Gamma	186,929	30,992	4339	8492	193,180	36,912	5168	10,114	9507	18,606
Alwz On	217921	0	0	0	230093	0	0	0	0	0
	First period				Second period				Total	

a much lower number of power cycles: about 40% of the number of power cycles of the *Always Off* policy. This implies a great advantage over *Always Off* and *Load*-0.9 policies.

Statistical-based policies, *Exponential* and *Gamma*, perform reasonably well in terms of the percentage of prediction success (as expected), particularly the *Gamma* policy. Energy saving results for the *Exponential* policy are a bit worse than previous policies, and quite high in terms of power cycles. On the other hand, the *Gamma* policy performs modestly in terms of energy saving, although the number of power cycles is the lowest, just 11% of *Always Off*, and hence energy saved per shutting down is the greatest, and the stress imposed on the hardware is the lowest.

With respect to the second period, similar results are found. Thus, the minimal energy consumable is 168,024 kW h for a total of 271,149 deployed jobs, and the current energy consumed by Grid'5000 is 230,087 kW h. It is worth noting that in this case, the *Exponential* policy achieves better results than the *Gamma* policy. This fact can be explained by taking into account that the number of jobs deployed during the first period is one quarter of the number of jobs deployed during the first period.

6.2. Scheduling arranging policies comparison

A set of energy policies has been selected in order to compare results between the two arranging policies: *Do Nothing* and *Simple Aggregation of Jobs*. Results are shown in Table 3.

Notice that the latter policy, *Simple Aggregation of Jobs* is consistently the best since it provokes fewer power cycles, saves more energy, and the energy saved per shutting is increased in general. Therefore, if jobs are arranged, even with simple policies, the results are much better than allowing users to choose resources.

6.3. Environmental and Economic results

In order to summarize energy-saving results, the costs and CO_2 savings are computed for Bordeaux in Table 4. For the computation of these values, a price of 0.14 euros per kW h and a CO_2 generation of 0.234 kg per kW h are considered.

Note that 18,000 euros and 35 tons of CO_2 per year can be saved by implementing the best energy saving policy. Hence, extrapolating results to all 9 locations of Grid'5000, (Bourdeaux, Grenoble, Lille, Lyon, Nancy, Orsay, Rennes, Sophia-Antipolis and Toulouse), **162,000 euros** and **318 tons of** CO_2 per year could be saved.

In terms of energy, up to 129,254 kW h could be saved for Bordeaux and by extrapolating this result to all 9 locations, 1,163,286 kW h. To illustrate how large this quantity of energy really is, it is equivalent to 78 journeys of AVE (high speed rail) train from Madrid to Barcelona, and it is equivalent to the daily energy consumption of 61,314 citizens in the Euro zone.

7. Conclusions and Future work

Various methodologies for tackling energy saving in grid computing environments, which could easily be applied to data centres and massive computing environments are presented.

We have empirically proven that a suitable policy in grid computing could save a considerable mount of energy and reduce the pollution of CO_2 in the atmosphere.

The authors are planning to apply these techniques to these environments in the future, in addition to contributing towards the improvement of energy and arranging policies and their adjustment to new computing environments.

A recent upgrade of Grid'5000 toolbox enables us to retrieve data from the cluster located at *Centro Informático Científico de Andalucía* (CICA), Spain, and hence future work will include external sites for comparison with Grid'5000 sites.

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Evaluating decision-making performance in a Grid-computing environment using DEA

Overview

This paper addresses the problem of comparing efficiency between locations of a Grid-Computing infrastructure. Efficiency is compared thanks to DEA techniques, and the results are shown.

Context

This research topic was based on previous knowledge from PhD Francisco Velasco Morente from the department of Applied Economics of the University of Seville. Thanks to his help, these issues could be tackled. This paper is the result of over one year of work in this area and applies usage information (and data from other sources) from simulations performed for a previous paper titled *Smart Scheduling for Saving Energy in Grid-Computing.*

Journal information

The Journal *Expert Systems with Applications* was selected for the submission of this paper. This Journal is indexed in JCR with an Impact Factor of 2.203 and a 5-Year I.F. 2.455. The Journal stands in ranking Q1 in three categories: Engineering, Electrical & Electronic (41/244); Operations Research & Management Science (5/77); Computer Science, Artificial Intelligence (22/111).

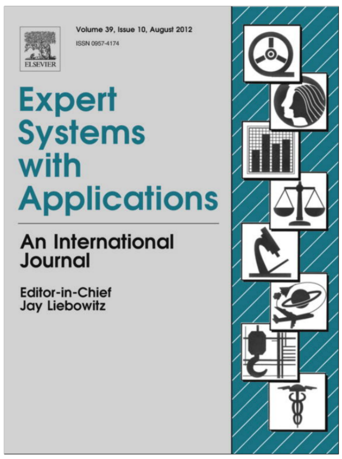

Figure 5.2: ESWA Cover.

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Evaluating decision-making performance in a grid-computing environment using DEA

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Efficiency
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Return-to-scale

ABSTRACT

Energy saving involves two direct benefits: sustainability and cost reduction, both of which Information Technologies must be aware. In this context, clusters, grids and data centres represent the hungriest consumers of energy. Energy-saving policies for these infrastructures must be applied in order to maximize their resources. The aim of this paper is to compare how efficient these policies are in each location of a grid infrastructure. By identifying efficient policies in each location and the slack in inputs and outputs of the inefficient locations, Data Envelopment Analysis presents a very useful technique for comparing and improving efficiency level. This work enables managers to uncover any misuse of resources so that corrective action can be taken.

1. Introduction

Data Envelopment Analysis (DEA) is a nonparametric method to provide a relative efficiency assessment (called DEA efficient) for a group of decision-making units (DMU) or for productive efficiency (aka technical efficiency) with a multiple number of inputs and outputs. DEA was first proposed in Charnes, Cooper, and Rhodes (1978) and is commonly used in operations research and economics to empirically measure productive efficiency of DMUs. In order to determine whether a DMU is efficient is as easy as checking if the DMU is on the "frontier" of the production possibility set. In this way, DEA identifies a "frontier" on which the relative performance of all utilities in the sample can be compared.

In recent years, a great variety of applications of DEA have appeared for the evaluation of the performances of many kinds of entities engaged in various contexts. DEA is especially useful when examining the nature of complex (often unknown) relations between multiple inputs and multiple outputs. DEA has been used both in private (Amirteimoori & Emrouznejad, 2012; Chiang & Hwang, 2010; Eilat, Golany, & Shtub, 2008; Emrouznejad, Parker, & Tavares, 2008) and in public contexts (Afonso, Schuknecht, & Tanzi, 2010; Gonzalez-Rodriguez, Velasco-Morente, & González-Abril, 2010).

Regarding energy efficiency studies, DEA is commonly applied for the study and comparison of the performance and efficiency of energy industries, above all in the electricity industry, see (Pérez-Reyes & Tovar, 2009; Pombo & Taborda, 2006; Tovar, Javier Ramos-Real, & de Almeida, 2011; Vaninsky, 2006; Weyman-Jones, 1991). More recently, it has also been applied to IT companies in Serrano-cinca and Fuertes-calle (2005). Recently, it has also been popularized in environmental performance measurement due to its empirical applicability.

In this work, DEA is used as a method to compare energy-consumption efficiency between each Grid'5000 location, where productive efficiency is measured as the energy consumed to run Grid'5000 jobs at each location.

The rest of this paper is structured as follows: Section 2 includes a brief introduction to DEA methodology used in this paper. Various on–off policies, designed to save energy are presented, and a comparison between current energy consumption and the results of each on–off policy are given in Section 3. The way in which jobs can be scheduled between resources is shown in Section 4. Software developed for testing and simulation is explained in Section 5 and the dataset used for DEA is described and presented. Finally, in Sections 6 and 7, results are given and conclusions are drawn.

2. Data Envelopment Analysis

DEA has been successfully applied to several sectors. The method establishes a best-practice production frontier (or envelop) based on the empirical input and output data on DMUs. It determines the level of production inefficiency of a DMU by projecting the unit onto the frontier. The original DEA model, introduced in Charnes et al. (1978), was set up with input orientation and assumes constant returns to scale (CRS). In an input-oriented model, the desired output level is achieved by minimizing the production inputs. The CRS

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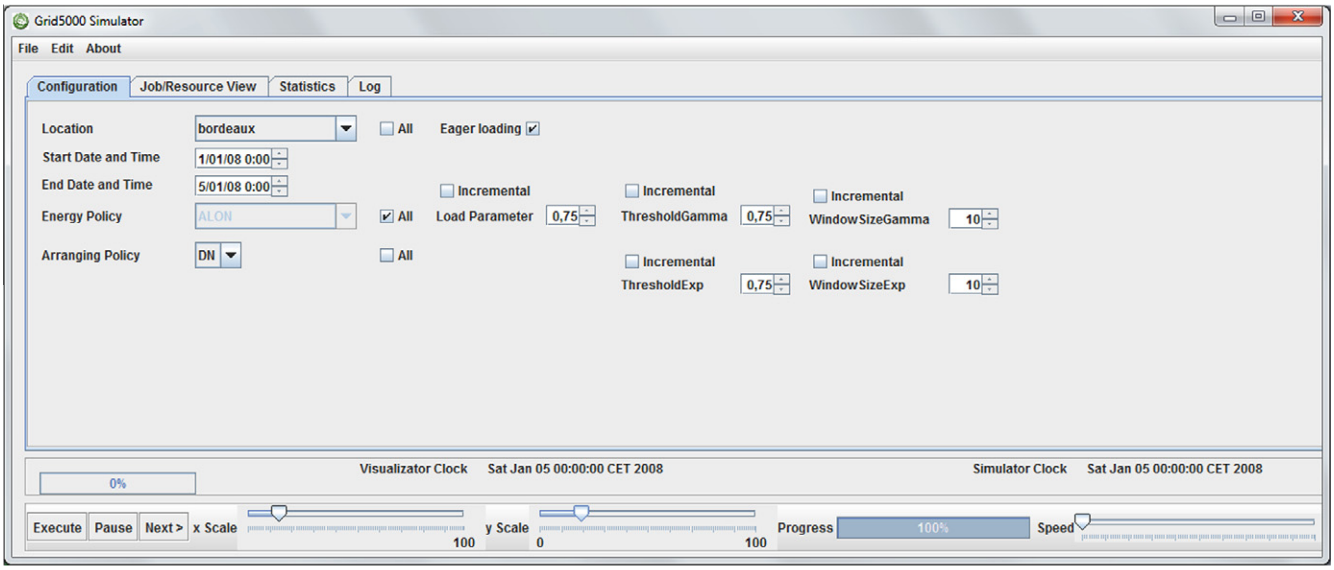

Fig. 1. Configuration tab presenting setup parameters for a batch of simulations.

assumption suggests that an increase in the amount of inputs utilized would lead to a proportional increase in the amount of outputs generated. The original model has been subsequently extended and numerous variations of DEA. For example, a DEA model can be set up to be output-oriented (Charnes, Cooper, & Rhodes, 1981), which attempts to maximize outputs with a set of available inputs. Another significant development of the DEA model by Banker, Charnes, and Cooper (BCC) (Banker, Charnes, & Cooper, 1984) allows for variable returns to scale (VRS). The VRS assumption suggests that an increase in the amount of inputs utilized can lead to a proportional or non-proportional change in the amount of outputs generated (Barkhi & Kao, 2010).

3. Energy policies at a glance

Energy policies establish the managing of grid resources. While other research works try to reduce the make-span (Tseng, Chin, & Wang, 2009), the policies shown in this work try to describe and compute what to do with a resource once a job finishes its execution. Thus, each energy policy decides whether to leave a resource switched on or to switch it off depending on the purpose of the policy. The following subsections show energy policies implemented in Grid'5000 Toolbox.

3.1. Always On

This is the simplest energy policy. It never switches resources off, under any condition, and hence resources stay idle, waiting for a new job to be run. Grid'5000 is currently running this way, and therefor these consumption results can be used for comparison with other energy policies in order to know how much energy would have been saved. The number of times resources are switched off or on are always zero, and therefor the stress upon the resource is minimal.

3.2. Always Off

This policy always switches resources off, under any condition, and hence a resource starts shutting down immediately after any job finishes, and remains switched off. If a new job arrives, resources assigned have to be booted to run that job. This booting is carried out within reservation limits, and hence the user cannot make effective use of the resources until they are booted. This policy is usually the best regarding energy consumption results, but the number of times a resource is booted up and shut down is always maximum, and the stress produced on the hardware components is the highest, which is seldom desirable.

3.3. Switch off randomly

This policy randomly switches resources off or leaves them idle by following a Bernoulli distribution whose parameter is equal to 0.5 when a job finishes. Hence, the number of times resources are switched off or left idle tends towards 50%, and results tend to be half-way between those of the *Always Off* and *Always On* policies (regarding the times resources are switched off and those of energy consumption).

3.4. Load

Load can be defined as the percentage of resources that are *On* among the clusters of a location. This policy queries this information and leaves resources idle or switches resources off if the load when finishing a job is greater than a certain threshold or less than a threshold respectively. This threshold is a parameter selected from the GUI from 0 to 1.

3.5. Switch off T_S

T_S is defined *as the minimum time which ensures an energy saving if a resource is switched off between two jobs* (Orgerie, Lefèvre, & Gelas, 2008). T_S can be computed as follows:

$$T_S = \frac{E_s - P_{Off} * \delta_{tot} + E_{On\rightarrow Off} + E_{Off\rightarrow On}}{P_{Idle} - P_{Off}}$$

where P_{Off} and P_{Idle} refer to the power consumption in watts of a given resource when it is *Off* and *Idle*, respectively. $E_{On\rightarrow Off}$ and $E_{Off\rightarrow On}$ refers to the required energy in joules for a given resource to boot or switch it off respectively. E_S is the energy saved during T_S seconds. Finally, $\delta_{tot} = \delta_{On\rightarrow Off} + \delta_{Off\rightarrow On}$, which is the total time a given resource needs for it to be switched off and switched on.

This energy policy queries the agenda to check if the next submitted jobs are going to be run in the grid in less than T_S. This policy computes the number of resources that are going to be

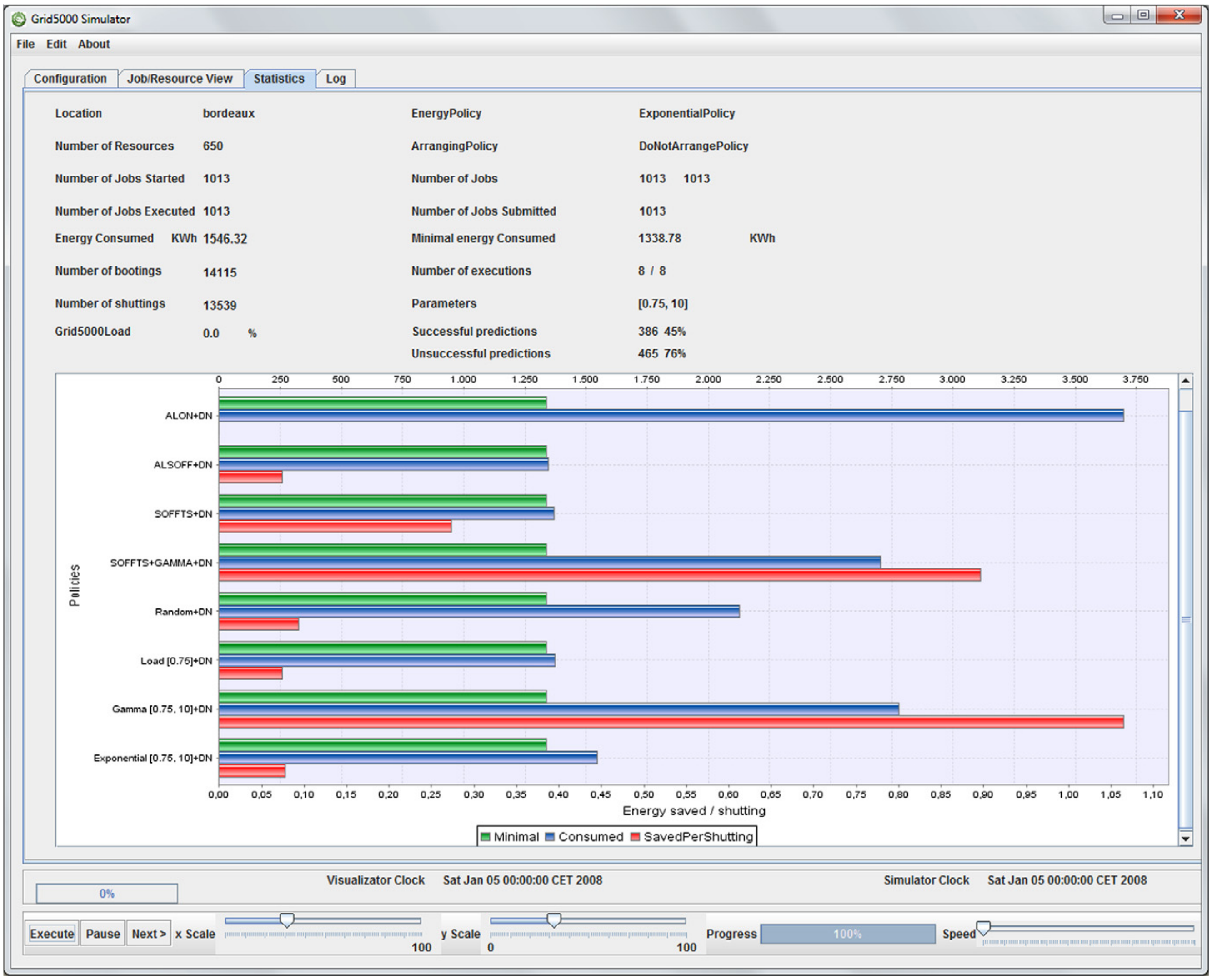

Fig. 2. Statistics tab presenting results for a batch of simulations.

needed within a time period less than T_S, and leaves idle or shuts resources down of the job which has just finished, accordingly. In this way, the simulator attempts to minimize the cycles of booting up and shutting down when these cycles are not going to save energy.

3.6. Exponential

The Exponential distribution, denoted by $Exp(\lambda)$, describes the time between events in a Poisson process, i.e. a process in which events occur continuously and independently at a constant average rate $(1/\lambda)$. Under the hypothesis that the arrival of new jobs follows an Exponential distribution, this energy policy attempts to predict the arrival of new jobs. Thus, to compute the λ parameter, every time a job finishes, then the mean time between the last jobs is computed, denoted by μ. Hence, $\lambda = 1/\mu$ according to the of method of maximum likelihood. The probability of the arrival of a new job is then computed by means of the Exponential cumulative density function (cdf) as $cdf(T_s) = 1 - e^{-T_s/\mu}$. Therefore, given a *threshold* value:

$$\begin{cases} \text{if } cdf(T_s) \geqslant threshold \text{ then leave resources } Idle \\ \text{if } cdf(T_s) < threshold \text{ then switch resources } Off \end{cases}$$

3.7. Gamma

The Gamma distribution, denoted by $\Gamma(\theta, \kappa)$, is frequently used as a probability model for waiting times, and is a more general model than that given by the *Exponential*. Under the hypothesis that the arrival of new jobs follows a Gamma distribution, this energy policy attempts to predict the arrival of new jobs. The parameters computed every time a job finishes are:

- Number of resources available, as *resourcesAvailable*. These are the resources that are *Idle* and ready to accept new jobs.
- Mean resources used by the last jobs, as *meanResources*. The total number of resources used by the last jobs is computed and divided by the number of jobs. The number of last jobs number is a selected window size.
- Mean duration of these last jobs, as *meanDuration*. The sum of the duration of the last jobs is computed and divided by the number of the last jobs.
- The floor of *resourcesAvailable*/*meanResources*, as *z*.

The parameters of the Gamma distribution are then estimated as: $\theta = 1/meanDuration$ and $\kappa = z + 1$. The probability of the arrival of a new job is then computed by means of the cumulative density function (cdf) with

Table 1
Summary of inputs and outputs.

Location	Outputs		Inputs	
	Saved energy (kW h)	# Jobs deployed	# Resources	# Bootings
		Always Off		
Bordeaux	128,697	345,218	650	4,036,514
Lille	238,159	62,451	618	327,408
Lyon	57,715	134,719	322	927,472
Nancy	94,932	73,934	574	1,668,946
Orsay	132,518	89,048	684	2,111,974
Rennes	152,832	57,987	714	2,328,890
Sophia	48,848	57,533	568	2,337,336
Toulouse	86,531	165,995	434	1,754,930
		Random		
Bordeaux	115,539	345,218	650	2,225,174
Lille	220,282	62,451	618	168,398
Lyon	51,771	134,719	322	494,442
Nancy	64,407	73,934	574	904,920
Orsay	105,075	89,048	684	1,141,004
Rennes	141,222	57,987	714	1,205,530
Sophia	39,918	57,533	568	1,198,338
Toulouse	71,738	165,995	434	922,932
		Load		
Bordeaux	127,089	345,218	650	3,675,094
Lille	238,159	62,451	618	327,408
Lyon	57,708	134,719	322	926,028
Nancy	74,616	73,934	574	1,176,234
Orsay	125,703	89,048	684	1,922,154
Rennes	152,832	57,987	714	2,328,890
Sophia	41,063	57,533	568	1,475,640
Toulouse	86,057	165,995	434	1,667,222
		T_s		
Bordeaux	127,018	345,218	650	2,238,318
Lille	236,793	62,451	618	299,846
Lyon	57,299	134,719	322	538,154
Nancy	90,771	73,934	574	1,297,252
Orsay	130,825	89,048	684	1,384,922
Rennes	152,226	57,987	714	1,392,750
Sophia	46,332	57,533	568	1,271,836
Toulouse	85,250	165,995	434	876,026
		Exponential		
Bordeaux	119,779	345,218	650	1,574,410
Lille	237,688	62,451	618	122,680
Lyon	56,349	134,719	322	612,766
Nancy	92,168	73,934	574	1,168,646
Orsay	127,303	89,048	684	1,387,566
Rennes	152,141	57,987	714	1,770,858
Sophia	48,360	57,533	568	1,847,484
Toulouse	86,203	165,995	434	671,122
		Gamma		
Bordeaux	67,374	345,218	650	1,141,048
Lille	159,213	62,451	618	884
Lyon	31,532	134,719	322	131,106
Nancy	18,833	73,934	574	156,116
Orsay	61,581	89,048	684	623,515
Rennes	116,158	57,987	714	644,109
Sophia	20,017	57,533	568	510,400
Toulouse	39,395	165,995	434	153,326

$$cdf(T_s) = \frac{\gamma(\kappa, T_s/\theta)}{\Gamma(\kappa)}$$

Hence, given a *threshold* value:

$$\begin{cases} \text{if } cdf(T_s) \geqslant \textit{threshold} \text{ then leave resources } \textit{Idle} \\ \text{if } cdf(T_s) < \textit{threshold} \text{ then switch resources } \textit{Off} \end{cases}$$

4. Arranging policies at a glance

Arranging policies establish the arrangement of jobs for their execution. A job can be moved from a set of resources to another, or a planned job execution can even be moved in time in order to take advantages of resources that are already switched on.

- *Do Nothing* (*DN*): Neither does this policy move jobs in time nor from one resource to another; jobs are executed as defined in the agenda. This is the current behaviour in Grid'5000. The combination of this arranging policy with the energy policy *Always On* in a simulation offers the current Grid'5000 behaviour, and includes results of energy consumption.
- *Simple Aggregation of Jobs* (*SA*): This policy attempts to find resources available (*Idle*) for new jobs. In this way, if a job is assigned to a set of resources which are *Off* and some resources are already switched on and available, we can save the time and

Table 2
Summary of DEA results for CRS, VRS, and scale efficiency.

		B	Li	Ly	N	O	R	S	T	σ	$\bar{x}$
Alwz. Off	crste	1.000	1.000	1.000	0.516	0.583	0.581	0.303	0.908	**0.255**	0.736
	vrste	1.000	1.000	1.000	0.667	0.650	0.670	0.567	0.938	0.177	0.812
	scale	1.000	1.000	1.000	0.773	0.897	0.868	0.535	0.968	0.151	0.880
Random	crste	1.000	1.000	1.000	0.427	0.521	0.581	0.284	0.889	0.273	0.713
	vrste	1.000	1.000	1.000	0.600	0.608	0.671	0.567	0.906	0.187	*0.794*
	scale	1.000	1.000	1.000	0.712	0.858	0.866	0.500	0.981	0.168	0.865
Load	crste	1.000	1.000	1.000	0.464	0.561	0.581	0.297	0.904	0.264	0.726
	vrste	1.000	1.000	1.000	0.675	0.634	0.670	0.601	0.937	**0.172**	0.815
	scale	1.000	1.000	1.000	0.687	0.885	0.868	0.495	0.965	0.171	0.862
T_s	crste	1.000	1.000	1.000	0.502	0.581	0.582	0.294	0.936	0.261	0.737
	vrste	1.000	1.000	1.000	0.657	0.648	0.670	0.567	0.937	0.178	0.810
	scale	1.000	1.000	1.000	0.763	0.896	0.868	0.519	0.999	0.159	**0.881**
Exp.	crste	1.000	1.000	0.944	0.511	0.572	0.581	0.307	1.000	0.259	**0.739**
	vrste	1.000	1.000	1.000	0.663	0.640	0.670	0.567	1.000	0.185	**0.817**
	scale	1.000	1.000	0.944	0.771	0.893	0.868	0.541	1.000	**0.148**	0.877
Gamma	crste	1.000	1.000	1.000	0.406	0.465	0.653	0.257	1.000	*0.295*	0.723
	vrste	1.000	1.000	1.000	0.667	*0.573*	0.726	0.567	1.000	*0.189*	**0.817**
	scale	1.000	1.000	1.000	0.608	0.812	0.899	0.453	1.000	*0.197*	*0.847*
$\sigma(vrse)$		**0.000**	**0.000**	**0.000**	0.025	0.027	0.021	0.013	*0.035*		
$\overline{vrste}$		**1.000**	**1.000**	**1.000**	0.655	0.626	0.680	*0.573*	0.953		**0.811**

the energy needed for them to be switched on. Notice that this policy does not change start or stop times, and hence is transparent to users.

5. Methodology

In order to compare energy efficiency between the locations of the Grid'5000, a software simulator has been developed. Grid'5000 Toolbox[1] replays the progress of the real grid regarding the operation of jobs and resources. Grid'5000 Toolbox is able to compute energy consumption of Grid'5000, and enables the user to establish several parameters including: (a) simulation start-time, (b) simulation stop-time, (c) location, (d) energy policy, and (e) arranging policy. These parameters can be set up through the *Configuration* tab as shown in Fig. 1.

The simulator operation is based on an agenda where jobs are registered, and on a list of resources representing the real resources at the sites. The simulator queries the agenda from simulation start-time to simulation stop-time. Each query is related to current simulation time (the moment in past-time the software is replaying), and hence the agenda seeks jobs and events that occur at given current time. Once the agenda returns new events, the simulator processes them and changes the states of the resources as would be needed for execution in the real world, whilst taking into account the policies selected in order to manage resources and jobs. The energy consumed is computed step by step by means of the information on energy consumption of each resource and on the resource states detailed in the resource list. The results of simulation executions are stored on a spreadsheet where researchers can find details about consumption, the number of times the resources are shut down and booted up, the comparison between minimal energy consumable and current energy consumed, etc. Results are also shown in the *Statistics* tab in a more visual way (see Fig. 2). A battery of tests has been performed in order to compute energy-saving results based on:

- One period of 12 months. From 1st January to 31st December 2008.
- Two arranging policies, *Do Nothing* and *Simple Aggregation of Jobs*.
- The seven energy policies listed in Section 3.
- Various values of several parameters as follows:
    1. *Load* policy. Load threshold parameter from 0.0 to 1 in steps of 0.3. A total of four scenarios.
    2. *Exponential* and *Gamma*. Threshold probability parameter from 0.0 to 1 in steps of 0.3, and window size from 2^0 to 2^8. Hence there are 36 different scenarios for each policy.

From the 162 setups run, the best energy savers have been selected of each policy. From computed results, we select the following inputs and outputs to measure relative efficiency between locations:

- Inputs:
    1. The number of resources at the location. This parameter remains unchanged between simulations. Resources are the entities that run jobs.
    2. The number of times resources have been switched off and booted during the simulation. Each energy policy shows different behaviour when a job finishes, and therefore this input changes between each energy policy simulated.
- Outputs:
    1. The energy saved, in kW h, using a given energy policy. This is the amount of energy that the location would save if a given energy policy were applied.
    2. The number of jobs deployed at each location.

The following table shows the summary of inputs and outputs for each energy policy for which the DEA methodology is computed using, Coelli software (Coelli, 1996) due to its simplicity usage. Results are compared with those produced by other tools, such as Benchmarking library in R language (Bogetoft & Otto, 2010).

6. Input-orientated DEA results

The results computed are input orientated since firms are able to modify their inputs, and hence our study is focused on reducing inputs while maintaining the level of outputs (see Table 1).

[1] This software can be downloaded and executed from the web of the Idinfor research group (Idinfor, 2011).

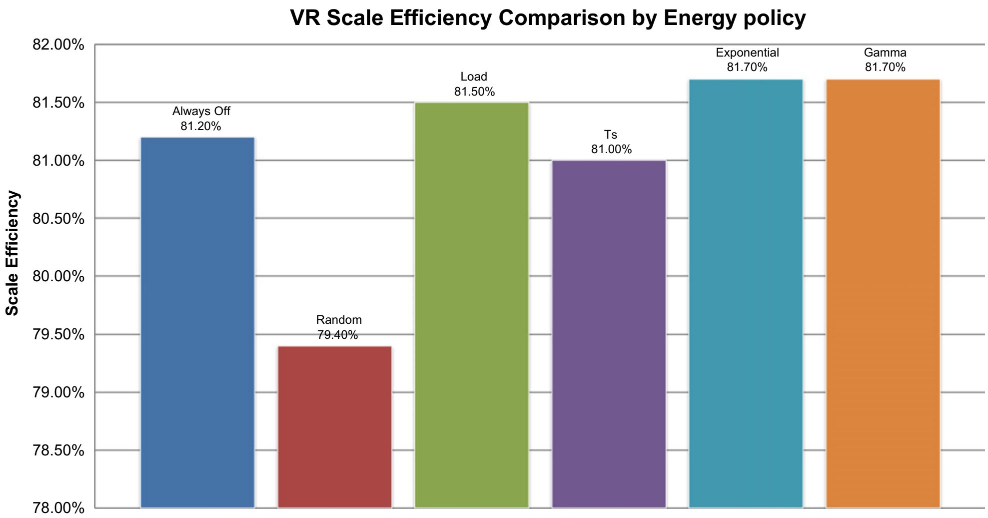

Fig. 3. Comparison of energy policies for VR scale technical efficiency.

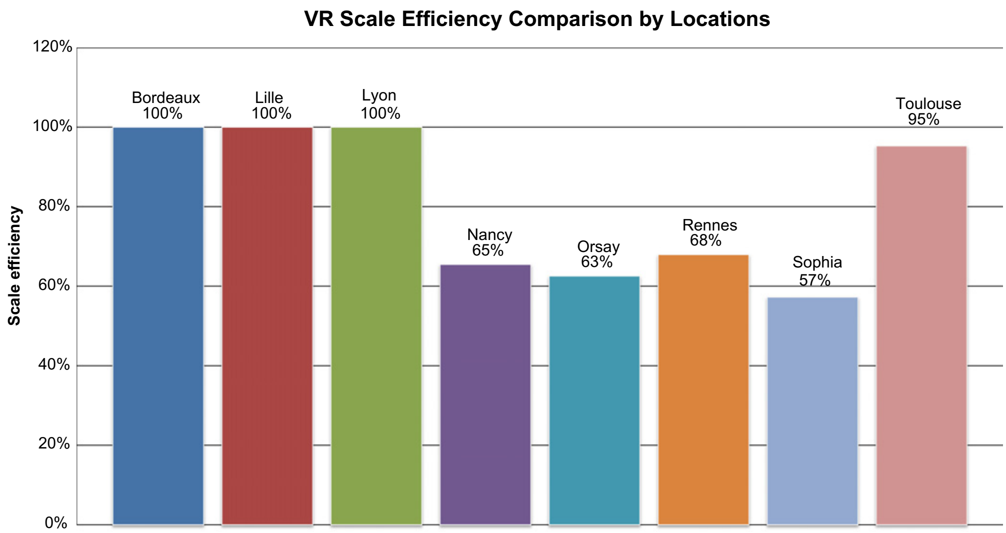

Fig. 4. Comparison of locations VR scale technical efficiency.

Table 2 shows the results generated by the DEA tool (Coelli, 1996) for an input-orientated DEA with 2 inputs, 2 outputs and 8 firms (locations[2]), and these are grouped by energy policy. CRSTE (constant returns-to-scale technical efficiency), VRSTE (variable returns-to-scale technical efficiency) and Scale (scale efficiency) results are shown. Mean and standard deviation are computed for each energy policy and each location.

Results in Table 2 and Fig. 3 show that the most efficient energy policies are those of *Exponential* and *Gamma* (Sections 3.6 and 3.7) in terms of VRSTE ($\bar{x} = 0.817$), followed by the *Load* and *Always Off* energy policies ($\bar{x} = 0.815$). On the other hand, the overall results of *Random* policy show this to be the least efficient ($\bar{x} = 0.754$). In terms of dispersion, the least dispersion is reached using the *Load* policy ($\sigma = 0.172$), which indicates that this policy works homogeneously for any of the policies. Fig. 3 shows a graphical comparison of scale efficiency per energy policy.

In the analysis of locations, it can be observed that Bordeaux, Lille and Lyon are the most efficient locations (VRSTE equals 1.000 for these policies), followed by Toulouse, and that the least efficient locations are Sophia and Orsay, followed by Nancy and Rennes. In terms of dispersion, Bordeaux, Lille and Lyon have the most homogeneous behaviour between policies, followed by Sophia, with Toulouse being the location whose performance is the most dispersed between policies, followed by Sophia, Rennes and Nancy. Fig. 4 shows this graphical comparison of VRSTE per locations.

As a consequence of these analyses, corrections on inputs and outputs can be carried out. Table 3 shows peers per location, including weights and corrections proposed per location/policy. Notice that the type of correction (increase or decrease) remains the same within each location, which constitutes further confirmation of the validity of these corrections. For example, the proposed corrective actions for Nancy are: increase the number of jobs deployed, decrease the number of resources (as they are underused) and decreasing the number of power cycles (since the policies are not working as efficiently as those in other locations).

By taking into account that certain locations are underused, the system manager could better balance the workload through the relocation of jobs from efficient locations to underused

[2] B, Li, Ly, N, O, R, S, and T stand for Bordeaux, Lille, Lyon, Nancy, Orsay, Rennes, Sophia, and Toulouse, respectively.

Table 3
Peers per location and per energy policy and correction proposals.

Policy	Peers	Corrections		
		Jobs	Resources	Bootings
Bordeaux				
Alwz. Off	B (1.000)	↔	↔	↔
Random	B (1.000)	↔	↔	↔
Load	B (1.000)	↔	↔	↔
T_s	B (1.000)	↔	↔	↔
Exp.	B (1.000)	↔	↔	↔
Gamma	B (1.000)	↔	↔	↔
Summary	Bordeaux	↔	↔	↔
Lille				
Alwz. Off	Li (1.000)	↔	↔	↔
Random	Li (1.000)	↔	↔	↔
Load	Li (1.000)	↔	↔	↔
T_s	Li (1.000)	↔	↔	↔
Exp.	Li (1.000)	↔	↔	↔
Gamma	Li (1.000)	↔	↔	↔
Summary	Lille	↔	↔	↔
Lyon				
Alwz. Off	Ly (1.000)	↔	↔	↔
Random	Ly (1.000)	↔	↔	↔
Load	Ly (1.000)	↔	↔	↔
T_s	Ly (1.000)	↔	↔	↔
Exp.	Ly (1.000)	↔	↔	↔
Gamma	Ly (1.000)	↔	↔	↔
summary	Lyon	↔	↔	↔
Nancy				
Alwz.Off	Li (0.206) Ly (0.794)	▲	▼	▼
Random	Li (0.075) Ly (0.925)	▲	▼	▼
Load	Li (0.221) Ly (0.779)	▲	▼	▼
T_s	Li (0.186) Ly (0.814)	▲	▼	▼
Exp.	Li (0.198) Ly (0.802)	▲	▼	▼
Gamma	Li (0.207) Ly (0.793)	▲	▼	▼
Summary	Lille and Lyon	▲	▼	▼
Orsay				
Alwz. Off	Li (0.415) Ly (0.585)	▲	▼	▼
Random	Li (0.316) Ly (0.684)	▲	▼	▼
Load	Li (0.377) Ly (0.623)	▲	▼	▼
T_s	Li (0.410) Ly (0.590)	▲	▼	▼
Exp.	Li (0.391) Ly (0.609)	▲	▼	▼
Gamma	Li (0.235) Ly (0.765)	▲	▼	▼
Summary	Lille and Lyon	▲	▼	▼
Rennes				
Alwz.Off	Li (0.527) Ly (0.473)	▲	▼	▼
Random	Li (0.531) Ly (0.469)	▲	▼	▼
Load	Li (0.527) Ly (0.473)	▲	▼	▼
T_s	Li (0.529) Ly (0.471)	▲	▼	▼
Exp.	Li (0.528) Ly (0.472)	▲	▼	▼
Gamma	Li (0.663) Ly (0.337)	▲	▼	▼
summary	Lille and Lyon	▲	▼	▼
Sophia				
Alwz. Off	Ly (1.000)	▲	▼	▼
Random	Ly (1.000)	▲	▼	▼
Load	Li (0.065) Ly (1.000)	▲	▼	▼
T_s	Ly (1.000)	▲	▼	▼
Exp.	Ly (1.000)	▲	▼	▼
Gamma	Ly (1.000)	▲	▼	▼
Summary	Lyon	▲	▼	▼
Toulouse				
Alwz. Off	B (0.179) Li (0.089) Ly (0.732)	▲	▼	▼
Random	B (0.167) Li (0.055) Ly (0.777)	▲	▼	▼
Load	B (0.179) Li (0.088) Ly (0.733)	▲	▼	▼
T_s	B (0.178) Li (0.086) Ly (0.735)	▲	▼	▼
Exp.	T (1.000)	↔	↔	↔
Gamma	T (1.000)	↔	↔	↔
Summary	Bordeaux, Lille, Lyon, Toulouse	▲	▼	▼

locations. The system manager could also unplug a number of resources at underused locations, in the search for a threshold which guarantees both satisfaction of users and energy saving objectives.

6.1. Detailed analysis of Always Off energy policy technical efficiency

Sophia is selected to illustrate this energy policy. Sophia is the least efficient location in general, and also the least efficient

Table 4
Corrections proposed for Sophia under the *Always Off* energy policy.

Results for firm: Sophia
Technical efficiency = 0.567
Scale efficiency = 0.535 (irs)

Projection summary

Variable		Original value	Radial movement	Slack movement	Projected value
Output	Saved energy	48,848	0	8867	57,715
Output	# Jobs	57,533	0	77,186	134,719
Input	# Resources	568	−246	0	322
Input	# Bootings	2,337,336	−1,012,296	−397,567	927,472

Listing of peers

Peer	Lambda weight
Lyon	1.000

Table 5
Corrections proposed for Orsay under the *Random* energy policy.

Results for firm: Orsay
Technical efficiency = 0.608
Scale efficiency = 0.858 (irs)

Projection summary

Variable		Original value	Radial movement	Slack movement	Projected value
Output	Saved energy	105,075	0	0	105,075
Output	# Jobs	89,048	0	22,811	111,859
Input	# Resources	684	−268	0	415
Input	# Bootings	1,141,004	−447,675	−302,021	391,307

Listing of peers

Peer	Lambda weight
Lille	0.316
Lyon	0.684

Table 6
Corrections proposed for Nancy under the *Load* energy policy.

Results for firm: Nancy
Technical efficiency = 0.675
Scale efficiency = 0.687 (irs)

Projection summary

Variable		Original value	Radial movement	Slack movement	Projected value
Output	Saved energy	74,616	0	22,948	97,564
Output	# Jobs	73,934	0	44,823	118,757
Input	# Resources	574	−186	0	387
Input	# Bootings	1,176,234	−382,423	0	793,810

Listing of peers:

Peer	Lambda weight
Lille	0.221
Lyon	0.779

performing under the *Always Off* energy policy. The corrective actions recommended for this location and policy are detailed in Table 4. This location presents a CRS technical efficiency of 0.303 and a VRS technical efficiency of 0.567, and hence in order to achieve overall efficiency and to belong to the efficient frontier it must reduce input and increase output. This means that number of bootings and shuttings should be reduced by in 1.4 million (−60%), and, most importantly 246 resources (−43%) should be removed. In addition, these measures have to be followed by an increase of 77,186 (+134%) in the number of jobs run at this location and a reduction of 8867 kW h (−18%) in energy consumption.

The peer for this location is Lyon, which belongs to the segment of the production frontier where Sophia has to tend. Within these new dimensions, Sophia will make the most of its resources and will become efficient in the means of production. The other non-efficient locations should be corrected in a similar way.

6.2. Detailed analysis of Random energy policy technical efficiency

Orsay is selected to illustrate this energy policy although it is not the least efficient location for this energy policy. The corrective actions recommended for this location and policy are detailed in Table 5. Orsay presents a CRS technical efficiency of 0.303 and a VRS technical efficiency of 0.521, and hence in order to achieve overall efficiency and to belong to the efficient frontier it must reduce input and increase output. This means that the number of bootings and shuttings in must be reduced by 749,696 (−65%), and most importantly, 268 resources (−39%) should be removed.

Table 7
Corrections proposed for Toulouse under the T_s energy policy.

Results for firm: Toulouse
Technical efficiency = 0.937
Scale efficiency = 0.999 (irs)

Projection summary

Variable		Original value	Radial movement	Slack movement	Projected value
Output	Saved energy	85,250	0	0	85,250
Output	# Jobs	165,995	0	0	165,995
Input	# Resources	434	−27	0	406
Input	# Bootings	876,026	−55,393	0	820,632

Listing of peers

Peer	Lambda weight
Lille	0.086
Lyon	0.735
Bordeaux	0.178

Table 8
Corrections proposed for Rennes under the *Exponential* energy policy.

Results for firm: Rennes
Technical efficiency = 0.670
Scale efficiency = 0.868 (irs)

Projection summary

Variable		Original value	Radial movement	Slack movement	Projected value
Output	Saved energy	152,141	0	0	152,141
Output	# Jobs	57,987	0	38,556	96,543
Input	# Resources	714	−235	0	478
Input	# Bootings	1,770,858	−584,429	−832,549	353,879

Listing of peers

Peer	Lambda weight
Lille	0.528
Lyon	0.472

Table 9
Corrections proposed for Nancy under the *Gamma* energy policy.

Results for firm: Nancy
Technical efficiency = 0.667
Scale efficiency = 0.608 (irs)

Projection summary

Variable		Original value	Radial movement	Slack movement	Projected value
Output	Saved energy	18,832	0	39,073	57,906
Output	# Jobs	73,934	0	45,857	119,791
Input	# Resources	574	−190	0	383
Input	# Bootings	156,116	−51,909	0	104,206

Listing of peers

Peer	Lambda weight
Lyon	0.793
Lille	0.207

In addition, these measures have to be followed by an increase of 22,811 (+25%) in jobs run at this location.

The peers for this location are Lyon and Lille, which both belong to the segment of the production frontier where Orsay has to tend. Within these new dimensions, Orsay will make the most of its resources and will become efficient in the means of production. The other non-efficient locations should be corrected in a similar way.

6.3. Detailed analysis of Load energy policy technical efficiency

Nancy is selected to illustrate this energy policy although it is not the least efficient location for this energy policy. The corrective actions for this location and policy are detailed in Table 6. Nancy presents a CRS technical efficiency of 0.464 and a VRS technical efficiency of 0.675, and hence in order to achieve overall efficiency and to belong to the efficient frontier it must reduce input and increase output. This means that the number of bootings and shuttings must be reduced by 382,423 (−32%), and, most importantly 186 resources (−32%) should be removed. In addition, these measures have to be followed by an increase of 44,823 (+60%) in the jobs run at this location and a reduction of 22,948 kW h (+30%) in energy consumption.

The peers for this location are Lyon and Lille, which both belong to the segment of the production frontier where Nancy has to tend. Within these new dimensions, Nancy will make the most of its resources and will become efficient in the means of production. The other non-efficient locations should to be corrected in a similar way.

6.4. Detailed analysis of T_s energy policy technical efficiency

Toulouse is selected to illustrate this energy policy although it is not the least efficient location for this energy policy. The corrective actions recommended for this location and policy are detailed in Table 7. Toulouse presents a CRS technical efficiency of 0.936 and a VRS technical efficiency of 0.937, and hence in order to achieve overall efficiency and to belong to the efficient frontier it must reduce input but it has no needs of increasing output. This means that the number of bootings and shuttings must be reduced by 55,393 (−6%), and most importantly 27 resources (−6%) should be removed.

The peers for this location are Lyon, Lille and Bordeaux which belong to the segment of the production frontier where Toulouse has to tend. Within these new dimensions, Toulouse will make the most of its resources and will become efficient in the means of production. The other non-efficient locations should be corrected in a similar way.

6.5. Detailed analysis of Exponential energy policy technical efficiency

Rennes is selected to illustrate this energy policy although it is not the least efficient location for this energy policy. The corrective actions for this location and policy are detailed in Table 8. Rennes presents a CRS technical efficiency of 0.581 and a VRS technical efficiency of 0.670, and hence in order to achieve overall efficiency and to belong to the efficient frontier it must reduce input and increase the output 'number of jobs'. This means that the number of bootings and shuttings must be reduced by 1.4 millions (−80%), and most importantly 235 resources (−32%) should be removed. In addition, these measures have to be followed by an increase of 38,556 (+66%) in the jobs run at this location.

The peers for this location are Lyon and Lille which belong to the segment of the production frontier where Rennes has to tend. Within these new dimensions, Rennes will make the most of its resources and will become efficient in the means of production. The other non-efficient locations should be corrected in a similar way.

6.6. Detailed analysis of Gamma energy policy technical efficiency

Nancy is selected to illustrate this energy policy although it is not the least efficient location for this energy policy. The corrective actions recommended for this location and policy are detailed in Table 9. Nancy presents a CRS technical efficiency of 0.406 and a VRS technical efficiency of 0.608, and hence in order to achieve overall efficiency and to belong to the efficient frontier it must reduce input and increase output. This means the number of bootings and shuttings must be reduced by 51,909 (−33%), and most importantly 190 resources (−33%) should be removed. In addition, these measures have to be followed by an increase of 45,857 (+62%) in the jobs run at this location and a reduction of 39,073 kW h (+207%) in energy consumption.

The peers for this location are Lyon and Lille which belong to the segment of the production frontier where Nancy has to tend. Within these new dimensions, Nancy will make the most of its resources and will become efficient in the means of production. The other non-efficient locations should be corrected in a similar way.

7. Conclusions

The hypothesis that DEA methodology can be useful for the analysis of technical efficiency in Grid computing environments has been proved. Data Envelopment Analysis enables Grid managers to detect which grid locations present the best and worst performance in terms of energy consumption and efficiency. This methodology also enables several energy policies to be analyzed with regard to their behaviour and the potential differences between running a certain policy at one particular location or another.

By means of DEA methodology, system managers are armed with knowledge of which locations are underused and hence decisions regarding the switching off of resources and the relocation of underused locations can be made in order to achieve a better utilization of the Grid infrastructure as a whole.

Acknowledgements

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A Study on Saving Energy in Artificial Lighting by Making Smart Use of Wireless Sensor Networks and Actuators

Overview

This paper addresses the problem of developing Energy-Saving policies for Smart Environments. A WSN was deployed in two offices of the University of Seville to *sense* lighting conditions and to learn about user preferences in order to save energy in lighting appliances.

Context

This research topic was initiated during the first years of research by the PhD candidate. Certain topics within Ubiquitous Computing and Ambient Intelligence constituted the main focus of study. This paper is the result of several years of acquiring a wide range of knowledge in these fields.

Journal information

A special issue of the *IEEE Network Magazine* in Digital Home Services was selected for the submission of this paper. This Journal is indexed in JCR with an Impact Factor of 2.148 (JCR-2009), JCR-5 3.529. The Journal stands in ranking Q1 in four categories: Computer Science, Hardware & Architecture (9/49); Computer Science, Information Systems (25/116); Engineering, Electrical & Electronic (37/246), Telecommunications (8/77).

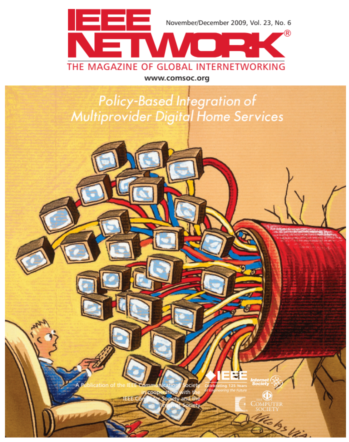

Figure 6.2: IEEE Network Cover.

A Study on Saving Energy in Artificial Lighting by Making Smart Use of Wireless Sensor Networks and Actuators

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Abstract

This article is focused on adapting lighting conditions to user lighting preferences. A theoretical analysis of lighting conditions is carried out, and a case study is shown by means of the setup of an experimental environment and an empirical analysis of lighting conditions. Finally, a methodology for saving energy, which adjusts luminance to user preferences, is presented, and a study of the consumption results is given.

The Earth is at risk of irreversible damage. The greater the increase in world population, the higher the natural resource consumption. There is an abundance of clear evidence of significant changes in climate conditions, which affect ecosystems of flora, fauna, and, of course, humankind. These changes generate an incentive to find ways to better manage natural resources in order to preserve our current quality of life.

As in many developed economies, Spanish residential energy consumption continues to rise, accounting for about 20 percent of the nation's total energy usage. The Spanish authorities approved the new *Technical Building Code* in accordance with the European Parliament Directive 2002/91/CE, which requires the installation of solar panels and the use of solar, thermal, and photovoltaic energy in new buildings. However, these measures alone will not succeed in attaining real energy saving; they only curb the growing energy consumption in new constructions. The methodology proposed attends to obtain real energy savings by regulating the resources to reach optimal lighting conditions in buildings.

Saving energy in smart environment systems is one of the main goals of smart environment research. Wireless sensor networks (WSNs) — large networks of embedded devices, containing microcomputers, radios, and sensors — open new methods and approaches to saving energy. WSNs are used to retrieve data on lighting conditions. Several approaches have been proposed in [1, 2] to save energy in this scenario. Nevertheless, the first approach does not consider user preferences in illuminance; hence, a constant value of illuminance is considered suitable for every single inhabitant, and the last approach maintains no knowledge of inhabitants' preferences. Other approaches not based on WSNs, like [3] based on an embedded microcontroller, cannot store any knowledge about inhabitants, so it is not adaptable. Our approach considers inhabitant preferences about lighting and *learns* them in order to automatically adjust lighting to satisfy these preferences.

The aforementioned Spanish Technical Building Code establishes 400 lumens as the optimal quantity of light for a standard office, but makes no mention of how it should be measured. A theoretical computation of how many lumens are provided by our artificial lighting setup can be made. To this end, a theoretical and empirical analysis about how natural lighting affects indoor lighting is carried out in the next sections.

Moreover, measurements may vary depending on where sensors are located, and on many other variables: type of lights, size of windows, number of windows, which direction the windows face, and so on. Our approach, as put forward later, avoids these difficulties, and makes an analysis of the lighting conditions in situ and in real time. The implementation of the experimental case study is based on the ideas exposed in [4, 5], which propose a multi-agent approach to control smart environments and a paradigm of design based on learning and prediction. The case study stores information according to [6], a model for smart environments divided in four categories: device related, inhabitant related, environment related, and background.

We then compute how much consumption can be saved by adjusting lighting to user preferences. This computation is based on the case study of a standard office at the Department of Computer Languages of the University of Seville. Conclusions are drawn in the final section.

Theoretical Analysis

In order to study how artificial lighting alters lighting conditions in an indoor environment, a mathematical analysis is carried out that relates the luminance of a room with the lights alternatively switched off and on. Let us suppose in this study that the artificial light has constant power (e.g., 100 W).

A function $y = f(x)$ is considered where x and y denote the quantity of light, measured by the same device, with artificial

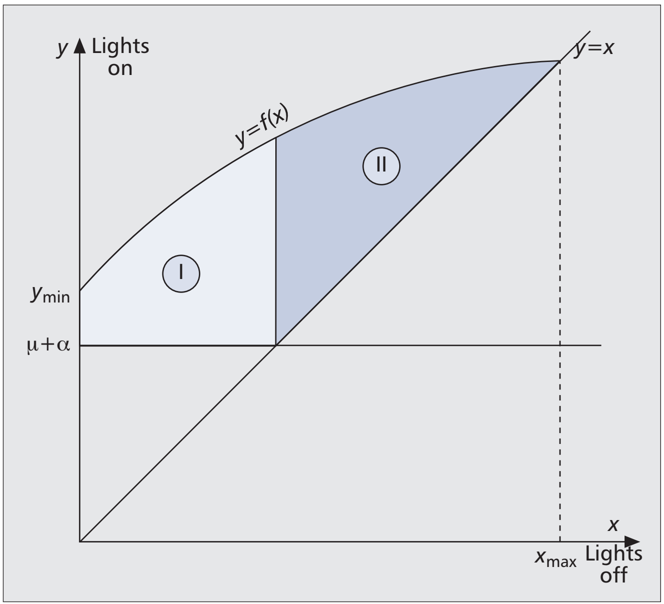

Figure 1. *The relationship between lights off and lights on.*

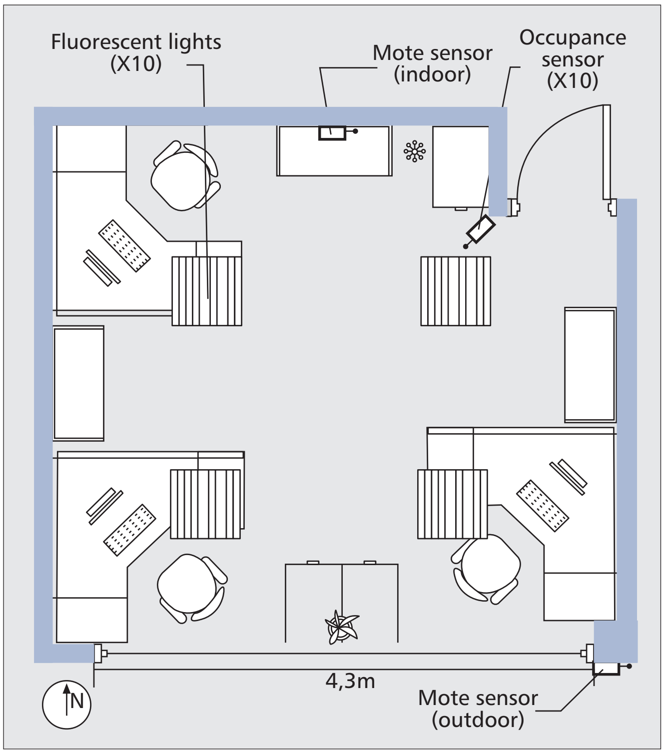

Figure 2. *Room setup.*

lights first switched off and then on (both in the same unit). Clearly, the illumination with the lights on is equal to or greater than that with the lights off; therefore, the inequality $0 \leq x \leq y$ holds.

Let x_{max} denote the maximum quantity of light the device can measure. This value is finite, and does not depend on whether lights are on or off; hence, $x_{max} = f(x_{max})$.

The function $f(x)$ is an increasing function, so its first derivative is non-negative. The reason for this result is due to theoretical properties of light, and the fact that artificial light has constant power such that for any $0 \leq x_1 < x_2 \leq x_{max}$, $f(0) \leq f(x_1) \leq f(x_2) \leq f(x_{max})$. Hence, $0 \leq x \leq x_{max}$ and $0 \leq y_{min} \leq y \leq x_{max}$, where $y_{min} = f(0)$. Note that y_{min} denotes the minimum quantity of light with the lights on and is reached when, in an indoor environment, only artificial light contributes to the lighting measurements.

With respect to the second derivative of $f(x)$, this must be non-positive since if it were positive, the first derivative of $f(x)$ would be an increasing function, which is impossible since artificial light has constant power.

On the other hand, let μ denote the lighting threshold of an inhabitant, which means that μ is the minimum quantity of light a user considers sufficient to render additional lighting unnecessary. This value depends on the preference of each user and can vary greatly depending on various factors, such as eye color, ocular difficulty, different habits, and different use of the space. Nevertheless, an interval $I = [\mu - \alpha, \mu + \alpha]$ is considered in this article due to the uncertainty of the human perception of lighting conditions. Therefore, the most important value is $\mu + \alpha$, which must be estimated for each user; this value permits us to ensure that the user has sufficient light.

The luminance of the artificial light must be such that $y_{min} \geq \mu + \alpha$ since it must guarantee that the lighting preferences of the user can always be satisfied. Clearly, the artificial light must attain at least the value $\mu + \alpha$, since otherwise, the artificial light would have to be changed. This characteristic should be borne in mind when carrying out maintenance of a lighting system. It should be noted that the value y_{min} depends solely on the power of artificial light.

In Fig. 1 an example of function $f(x)$ can be seen that verifies all theoretical conditions given. It is worth noting that the lighting preferences of the user are exceeded in the zones denoted I and II in Fig. 1. Thus, a regulator of light can be installed (zone I), and a motion sensor can then be configured to switch off the light when it is turned on while no people can be detected indoors (zone II). Therefore, electricity consumption can be reduced with these two devices. Nevertheless, some empirical problems must be solved in order to achieve these energy savings.

Case Study

In this section a particular case is studied that covers all the theoretical aspects mentioned above. Thus, an experimental environment has been designed in order to carry out an empirical study.

Experimental Environment

A standard office has been set up at the Department of Computer Languages and Systems of Seville University to obtain a real dataset. This office is intended to be used by three people, who could be visited by colleagues or students. The system of lighting consists of natural light from one large window, and four groups of four artificial fluorescent lights (16 in total) of model F18W/154 T8 manufactured by Sylvania [7], which can act as a complement to the natural light or as the sole source of light. In Fig. 2 the distribution and setup of the room can be studied. It can be observed that the geographical position of the city of Seville was taken into account in the design of the building since the window faces south, which maximizes the quantity of light received during the day. This fact alone implies great savings in consumption. It is worth noting that since any room can face any cardinal direction, the consumption saving and lighting threshold may vary, depending on user preferences (e.g., the position of the user's desk is in front of the windows, and the user prefers to close the blinds and have the light on since the user finds direct sunlight uncomfortable); hence, these factors must be considered when comparing results. For this reason, in order to study the dependence of lighting on these conditions, the need to retrieve data using several devices was placed in the proposed layout.

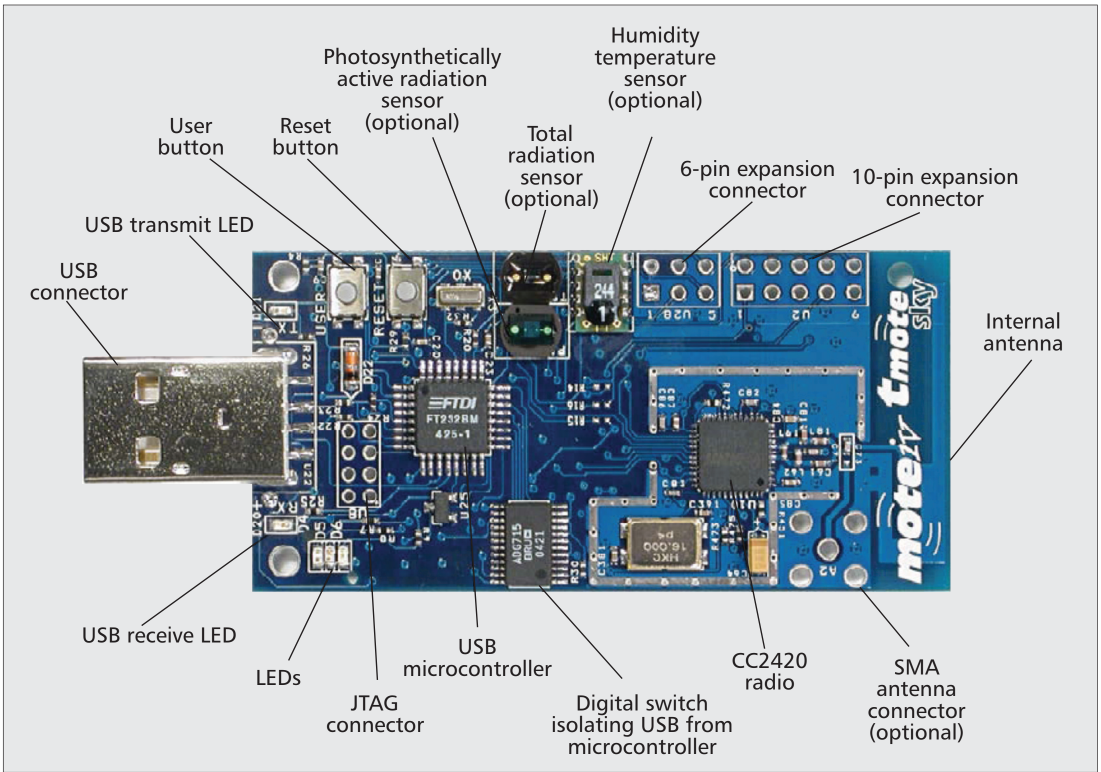

Figure 3. *Front of the Sentilla Tmote module.*

The devices used are the following: a motion sensor to detect whether someone is in the room, an actuator on the fluorescent lights to switch them on and off, and a couple of *Sentilla Tmotes* sensors.

Let us describe this last device. Sentilla Tmotes are devices that measure the quantity of light. The unit of illuminance is a *lux* and can be detected by either of two different photodiodes, as explained in *Hamamatsu* [8]:

- *S1087 photodiode*: For the visible range of the spectrum, from 320 to 730 nm. This range is often called *photosynthetically active radiation* (PAR). This region corresponds with the range of light visible to the human eye.
- *S1087-01 photodiode*: For the visible range up to infrared, from 320 to 1100 nm. This is called *total solar radiation* (TSR).

Only the PAR unit is considered in this article. The dimensions of the Sentilla Tmotes are 8 cm × 3.2 cm, so they are sufficiently small to suit ubiquitous applications and nonintrusive systems. These devices also include a humidity and temperature sensor, whose information is also retrieved for future improvement and expansions. In Fig. 3 the Sentilla Tmote module used in our experiment is shown.

The connectivity of the Sentilla Tmote with other motes and computers is executed through the IEEE 802.15.4 (ZigBee) protocol, which minimizes battery consumption. The mesh network protocol implemented by Tmotes software is chosen. In this way, a network to share information and forward it to reach a wider distribution can be designed for the motes.

Nowadays Sentilla Tmotes are packaged in a development kit, including an integrated development environment (IDE) based on Eclipse 3.2 for developing in Java. The hardware implements a Java Runtime Environment, which can run different applications for retrieving, processing, and sending data from sensors.

As can be seen in Fig. 2, two Sentilla Tmotes are installed, one indoor and another outdoor, although only those measurements given by the indoor Tmote are taken into account in this article.

User Preference Threshold

Furthermore, the threshold μ of an inhabitant needs defining. This threshold is the minimum quantity of light a user considers sufficient to stay in the room; hence, an experiment with four different inhabitants labeled *AFM*, *JAN*, *IN* (who share the office described in Fig. 2), and *JAA* (who works in a single office) is carried out. Each inhabitant independently completes a questionnaire about lighting conditions in the room every two hours for ten working days. The question is: "*Is this quantity of light enough for you*?"; each inhabitant answered either *Yes* or *No*. A complete threshold analysis can be found in [9]. According to the questionnaire, the preferences for each inhabitant are:

- **AFM**: The lowest satisfying value for PAR is 90 luxes, and the greatest non-satisfying value for PAR is 83 luxes, that is, $\mu + \alpha = 90$ and $\mu - \alpha = 83$ for this user.
- **JAN**: The lowest satisfying value for PAR is 95 luxes, and the greatest non-satisfying value for PAR is 88 luxes.
- **IN**: The lowest satisfying value for PAR is 89 luxes, and the greatest non-satisfying value for PAR is 75 luxes.
- **JAA**: The lowest satisfying value for PAR is 101 luxes, and the greatest non-satisfying value for PAR is 92 luxes.

Empirical Analysis

An analysis of the lighting data retrieved in the environment above is carried out. The main objective in this experiment is to study lighting conditions when lights are switched on and when lights are off. The data is obtained from an indoor mote via the S1087 photodiode (i.e., the PAR is used).

Tests, which include switching on and off lights at different moments of the day and night and pairing the luminance measures, are carried out 50 times. Let x and y be the retrieved data (the full dataset is available in [9]) of the luminance when lights are off and on, respectively.

In order to achieve a function that relates the x and y data, the linear correlation coefficient r is calculated. Since $r =$

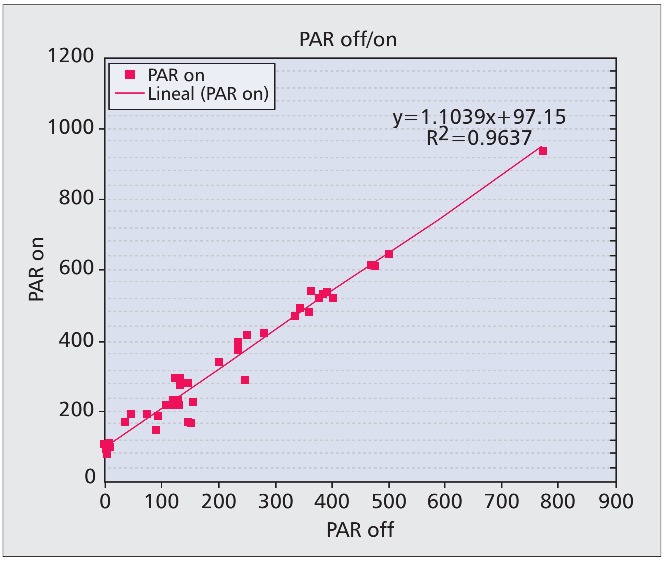

Figure 4. *PAR Off/PAR On relation.*

0.9827 is near 1, a linear model is obtained by using the least squares methods (Fig. 4): $y = f(x) = 1.1039x + 97.15$. It is worth noting that this function is increasing and that $y_{min} = 97.15$.

The linear regression of x with respect to y is $x = f^*(y) = 0.873y - 77.15$. That is, if y is denoted PAR_{On} and is known, an estimated value of x, denoted $PAR_{OffEstimated}$, can be obtained.

Saving Energy

Under the conditions stated above, it can be guaranteed that $\mu + \alpha$ is the quantity of light an inhabitant considers. Therefore, in order to save energy, indoor artificial lights can be adjusted to this $\mu + \alpha$ value.

The main goal of the current work is to use the knowledge learned to save energy. Data from motes have been retrieved over several months in different periods of the year and data has been stored in a relational database as described in [10]. The methodology proposed used only one part of the dataset. This subset is shown in the list below:

- **Indoor lighting PAR**: This variable represents the quantity of light received from the indoor Sentilla Tmote S1087 photodiode. It is a continuous variable that ranges from 0 lux upward.
- **Indoor light state**: This variable represents the state of the lights of the room received from the X10 appliance module. It is a discrete variable, with value 0 for lights off and 1 for lights on.
- **Motion**: This variable represents the detection of motion sent by the MS13A X10 device. It is a discrete variable, with value 0 for no motion and 1 for motion detected.

From this dataset, several statistical analyses of lighting usage are made; for example, how long lights are left on and off, or when the quantity of light (PAR) is greater or less than user preference (μ_{PAR}). This analysis is shown in Table 1.

As can be observed in the table, the lights are on for 18.84 percent of the total time, that is, about 4.8 hours a day or 33.6 hours a week (non-working days are also included). The most important value to focus on is the number of instances that the lights are on while PAR values are greater than μ_{PAR}, since this means that the lighting conditions exceed those necessary to satisfy the preferences of an inhabitant, and hence energy is being wasted. Abnormal behavior of the illuminance sensor is present in the table since 0.15 percent of the instances have a value less than μ_{PAR} when the lights are on. These instances should be considered as error values, although the percentage is negligible. These values are computed for the μ_{PAR} of the AFM inhabitant (note that TSR analysis has been omitted but can be found in [9]).

The next task is to compute the quantity of luxes in all the instances of the database where the lights are on (PAR_{On}):

$$\sum_{lights=On} \left(PAR_{On} - PAR_{OffEstimated}\right),$$

where $PAR_{OffEstimated}$ is the estimated PAR value by regression $f^*(PAR_{On})$ with the lights off.

The wasted luxes can now be calculated (Fig. 1) as

$$\sum_{lights=On} \left[PAR_{On} - \max\left(\mu_{PAR}, PAR_{OffEstimated}\right)\right]$$

Notice that the maximum between μ_{PAR} and $PAR_{OffEstimated}$ is subtracted from the illuminance detected by sensors. This is the borderline between zones I and II shown in the theoretical analysis in Fig. 1.

The energy consumed by the lights is calculated as follows:

$$\text{totalTimeOn} * \#\text{tubes} * (\text{wattsPerTube}/1000) = \text{Total kWh},$$

and the undesired CO_2 generated is

$$\text{Total kWh} * 0.274 \text{ kg/kWh} = \text{total kg of } CO_2.$$

By supposing a linear relation between generated luxes and their consumption, the total *waste of lighting* can be computed as about *72 percent of consumption*. Making a smart adjustment of the lights could save about 340 kWh, 93 kg of CO_2, and €46 (€0.14/kWh) a year per standard office, based on the data retrieved for the case study and the methodology proposed.

It is worth noting that the adjustment of lights is not trivial; fluorescent lights are generally suitable for dimming, so a discretization of lights is carried out. A total of 16 fluorescent lights are employed so that some or all of them can be switched on at any time. Moreover, the regression line of the relation PAR On/Par Off can be used (instead of Par Off/Par On as shown in the previous section). In this way, the quantity of luxes ($PAR_{OffEstimated}$) when the lights are off can be estimated before any action is executed. See Table 2 for an analysis of the results.

	Total		PAR			
			PAR > µPAR		PAR < µPAR	
	#instances	%	#instances	%	#instances	%
Lights on	13,810	18.84	13,710	52.53	70	0.15
Lights off	59,490	81.16	12,390	47.47	47,100	99.85
Total	73,300	100	26,100	100	47,170	100

Table 1. *Study of lighting behavior.*

	Interval			Per year		
Days computed	101.8			365		
Days with lights on	19.2			68.77		
Total Luxes generated	167,010,000			598,775,280		
Total Luxes wasted	119,715,110			429,210,527		
	kWh	CO_2 (kg)	Euros	kWh	CO_2 (kg)	Euros
Total consumption	132.6	36.3	17.9	475.32	130.24	64.24
Total waste	95.0	26.0	12.8	340.72	93.36	46.05

Table 2. *Light consumption and wasting per interval and year.*

Conclusions

In this article it has been shown that electricity consumption can be reduced by incorporating two devices (a regulator of light and a motion sensor) in an indoor setup. Hence, any saving obtained in electricity consumption can be greater if the preferences of users and the environment are set up by following an optimal criterion. Thus, we have proved that in a experimental room, the waste of lighting is about 72 percent of consumption in spite of the optimality of the geographical orientation. Furthermore, the methodology proposed is adaptable to any environment and any user, due to the fact that lighting conditions are not predefined but learned by a smart environment system.

Acknowledgments

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PART III

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Editor: Anthony D. Joseph ■ UC Berkeley ■ adj@eecs.berkeley.edu

Pervasive Computing Approaches to Environmental Sustainability

EDITOR'S INTRO

In this issue's Works in Progress department, we have eight projects with a focus on environmental sustainability. The first three projects explore sensing and pervasive computing techniques for monitoring environmental conditions in outdoor situations. The next four projects use pervasive computing in indoor environments to inform individuals about their energy and resource consumption with the goal of positively influencing their behaviors. The final project aims to develop an energy-generation infrastructure that combines multiple types of renewable energy sources.

—*Anthony D. Joseph*

A DECISION SUPPORT SYSTEM FOR CROP MANAGEMENT

Rolando A. Cardenas-Tamayo and J. Antonio García-Macías, *CICESE Research Center*

The agricultural sector is one of the most important sources of income and production worldwide. Agriculture is directly related to sustainability issues such as water availability and soil conservation, so using these resources efficiently is important. Continuous monitoring systems can maximize their proper use. Such environments are highly dynamic, and systems that support the decision-making process are valuable tools. However, these systems need large amounts of information that must be provided continuously; additionally, they require constant attention by their users.

Therefore, we designed and implemented a decision-support system for monitoring crops using pervasive computing technologies such as wireless sensor and actuator networks. The prototype we implemented includes tools that provide real-time information about crop status and the surrounding environment, contributing to the use of techniques such as fertigation (the application of fertilizers, soil amendments, or other water-soluble products through an irrigation system).

We carried out an experimental evaluation of our prototype with a group of potential users based on the technology acceptance model (TAM), gathering the users' perceptions about usefulness, ease of use, and intention. We believe that our proposal has the potential to reduce costs and, by using precise information, improve resource management for crop production. We've begun long-duration field tests that will enable a better assessment of our proposal.

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ADAPT: AUDIENCE DESIGN OF PERSUASIVE TECHNOLOGY

Timothy M. Miller, Patrick Rich, and Janet Davis, *Grinnell College*

Although many recent research efforts have used pervasive computing to persuade people to use less energy in the course of their everyday activities, stakeholders have rarely been involved in those design efforts. In response, we held a series of participatory design events at Grinnell College to involve potential users in designing an ambient persuasive display that targets an energy-consuming behavior. We used an exploratory game to help participants find places where they consume. We then introduced them to sensor and actuator technology through the Phidgets rapid prototyping framework (www.phidgets.com), engaged them in building mockups, and invited them to critique prototypes of several designs. Ultimately, we designed an interactive sculpture as part of a staircase in the science building, intended to attract people to the stairs from a nearby elevator. The system uses glowing LEDs embedded in hand-sized wire sculptures to evoke fireflies along the walls and stair railings. Participants can "catch" the fireflies, which are equipped with vibration sensors, by tapping them—thus triggering a celebratory animation. Users can race

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the fireflies up the stairs, showing that most people can walk faster than the nearby elevator. A smaller display near the elevator directs people to the sculpture in the stairway.

We're currently gathering baseline data on stair and elevator use and preparing to install the system. We plan to evaluate the system with respect to frequency of stair and elevator use, frequency of interactions with the system itself, and self-reports regarding the system's effectiveness in promoting behavior and attitude change.

For more information, contact Janet Davis at davisjan@cs.grinnell.edu.

REALNET: AN ENVIRONMENTAL WIRELESS SENSOR NETWORK

***Joan Albesa, Manel Gasulla, Jorge Higuera, María Teresa Penella, and José Garcia**, Universitat Politècnica de Catalunya*

Wireless sensor networks (WSNs) have recently emerged as a feasible technology in several fields, including environmental monitoring and control. We're deploying an environmental WSN, called REALnet, at our campus to monitor physical parameters from the air, water, and soil and to act on the environment in a more sustainable way. We're investigating several topics that can be critical barriers to developing WSNs:

- Power consumption: Implementing new low-power measuring methods; synchronizing nodes by compensating for the clock drifts to reduce duty cycle and power consumption.
- Power supply of sensor nodes: Energy harvesting as an alternative to primary batteries; using efficient energy and power management techniques.
- Interoperability: Implementing suitable wireless standards such as IEEE 802.15.4, Zigbee, and 6LoWPAN (IPv6-based low-power wireless personal area network); implementing IEEE 1451 on top of them to interoperate the diverse networks.

We've already deployed five nodes: one coordinator node, powered from the mains; one sensor node, powered by primary batteries, that monitors the campus pond's water level and temperature; and three router nodes, powered by solar cells, that route data from the sensor node to the central node. Router nodes also transmit data about the level of solar irradiation, temperature, and battery level. We'll soon add nodes to monitor a tiny weather station and low-power sensors to measure the soil temperature and moisture. We're implementing the IEEE 1451 standard and will save data on a database server for access through the Internet.

For more information, contact Manel Gasulla at manel.gasulla@upc.edu.

AUTOMATING SMART-ENVIRONMENT SYSTEMS

***Alejandro Fernández-Montes**, Universidad de Sevilla*

This work focuses on learning user preferences about lighting and air conditioning to plan actions that an automated smart-environment system should perform to satisfy these preferences. However, the system must also detect inhabitants' wasteful behaviors such as turning on lights when natural light is available or abusing the air conditioning system when it's not necessary. The system must then teach the inhabitants to save energy by avoiding those behaviors.

My research group proposes a general software architecture that can guide developers in building smart-environment solutions with sustainability features. I have empirically tested this architecture, using it to develop a smart-environment solution for learning users' lighting preferences.

This proposal is based on the goals of ubiquitous computing as Mark Weiser proposed them in the late 1980s. Taking this as a starting point, we believe that automation in smart environments should be organized as continuous interaction between three main tasks: perception, reasoning, and acting.

The system perceives the environment's state by means of the physical components distributed throughout the environment. It then reasons about the state and produces a list of possible actions to take. Finally, it carries out these actions, each of which is made up of several processes. A policy manager can guide developers to deploy green policies in order to save energy.

To test this general software architecture, we're developing a smart solution that covers tasks of perception, reasoning, and acting. This is a Java solution built on top of the Sentilla Development Kit. It has been very useful in polishing this architecture proposal.

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WIRELESS SENSOR NETWORKS FOR EMERGENCY APPLICATIONS

***Maria-Angeles Grado-Caffaro**, Sapienza Studies*

The European Union's Sixth Framework Programme is funding the WINSOC project (*wi*reless sensor *n*etworks with *s*elf-*o*rganization *c*apabilities for critical and emergency applications). This research started in September 2006 and is due to finish in February 2009. The project aims to radically improve sensor networks' performance using a biologically inspired design.

The system can self-assemble into organized structures in which the sensor nodes behave as biological entities that are able to make decisions on the basis of their local environments and their own individual states. These nodes are small calculating machines (much simpler than the current ones) in the network that need to carry out only very simple rules, thus eliminating the need for the inefficient, complex

WORKS IN PROGRESS

Figure 1. The shower prototype. An ambient display can help people by giving immediate and direct feedback regarding water consumption.

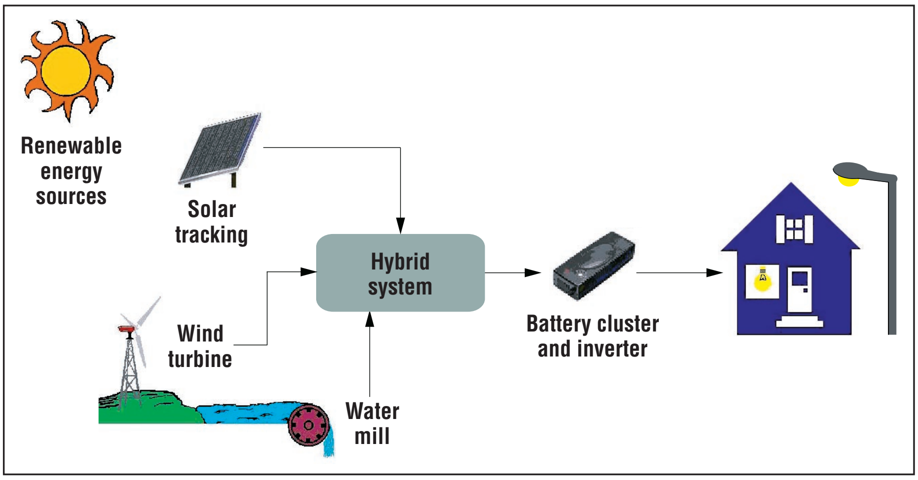

Figure 2. Schematic view of the hybrid energy production and delivery system.

protocol interactions used for end-to-end communications. This approach lets us build distributed detection and estimation capabilities that are crucial for understanding a WSN scenario and eliminates the need for sending all the data to a fusion center.

This technology is attractive for a wide range of environmental purposes; so far, the WINSOC team has analyzed landslide and wildfire applications. In India, our Amrita University partner has deployed sensors to monitor humidity and porosity in the terrain as well as the forces involved in terrain displacements. The system sends this information to a satellite, which then conveys it to a control center. Also, our Czech Center for Science and Society partner has introduced sensors in a forest to detect and locate heat and smoke sources. A simulation of a spreading fire, developed by the WINSOC team, provides monitoring and alerts.

Selex Communications (Italy) coordinates the WINSOC project. Other partners include the University of Rome "La Sapienza" (Italy), the Ecole Polytechnique Fédérale de Lausanne (Switzerland), Intracom Telecom (Greece), the Commissariat per l'Energie Atomique-LETI (France), the Czech Center for Science and Society (Czech Republic), Dune (Italy), Universitat Politècnica de Catalunya (Spain), the Indian Space Organization (India), Amrita University (India), and the science and technology consultancy firm Sapienza Studies (Spain).

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AN AMBIENT WATER CONSUMPTION DISPLAY

Karin Kappel and Thomas Grechenig, Vienna University of Technology

Water is becoming a scarce resource worldwide. Nevertheless, according to the United Nations, water usage has grown at twice the rate of population growth during the past century. There is an urgent need for people to change their water usage behavior. Ambient displays can help people by giving immediate and direct feedback regarding their consumption while at the same time blending in with the environment.

Water consumption for one shower varies heavily depending on the user's shower habits, so the potential for water conservation is great. We built a prototype of an ambient water consumption display system for the shower, which gives the user feedback and an impression of the amount of water going down the drain (see Figure 1). This impression is achieved by using the metaphor of the drain being closed and the water level increasing within the shower. The imaginary water level is visualized in the form of LEDs that are vertically assembled on a stick. One additional LED lights up for every five liters, thus delivering direct feedback.

Two initial tests in two-person households show promising results. A couple used to argue over who used more water. After we installed the display, they learned that the woman used only half as much water even though she spent more time in the shower. This discovery stimulated the man to use even less water. Overall, each subject, depending on the individual goal, made different efforts to act more sustainably after having installed the ambient water consumption display.

For more information, contact the authors at karin.kappel@inso.tuwien.ac.at.

HYBRID ENERGY PRODUCTION AND DELIVERY USING MULTIPLE RENEWABLE SOURCES

Ilhan Umut, *Kırklareli University*
Erdem Uçar, *Trakya University*

This study investigates energy production from renewable energy sources such as solar, wind, and water and storage of the produced energy in batteries before consumption. The processes take place simultaneously. The hybrid system shown in Figure 2 will be able to supply energy uninterrupted. When one or more of the resources ceases functioning, the other sources will

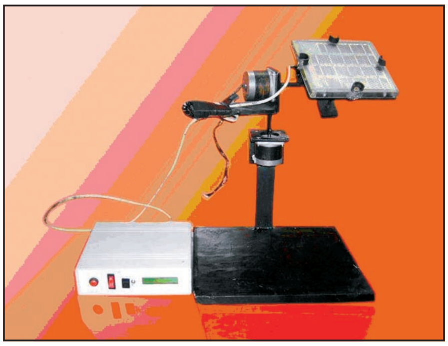

Figure 3. The solar tracking device and other system components.

be able to feed the system. The main advantage of this type of system is the energy production's independence from the electricity network. Therefore, we will be able to supply energy for environmental lighting and security systems, even in rural areas.

The system's solar module is already in use (see Figure 3). We designed this module in such a way that the system follows the sun automatically. The studies for the other modules are continuing. We'll conduct tests for the other modules once we can find a convenient location where we can produce energy from all three sources.

It will also be able to instantly measure the quantity of produced energy and send that data to a computer through a cable or wireless connection. The software will be able to express the amount of produced energy from each source as daily, monthly, and yearly totals. The system will record the data, monitor system status, and control the system.

For more information contact the authors at erdem@trakya.edu.tr.

OPTIMAL DISTRIBUTED CONTROL FOR SUSTAINABLE BUILDINGS

Josh Wall and John Ward, *CSIRO*

With the building sector contributing 30 to 40 percent of global CO_2 emissions, sustainable building technologies have been identified as one of the most cost-effective approaches for reducing carbon emissions. Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) believes that advances in optimal, distributed building controls will help realize significant savings while maintaining or even improving indoor climates.

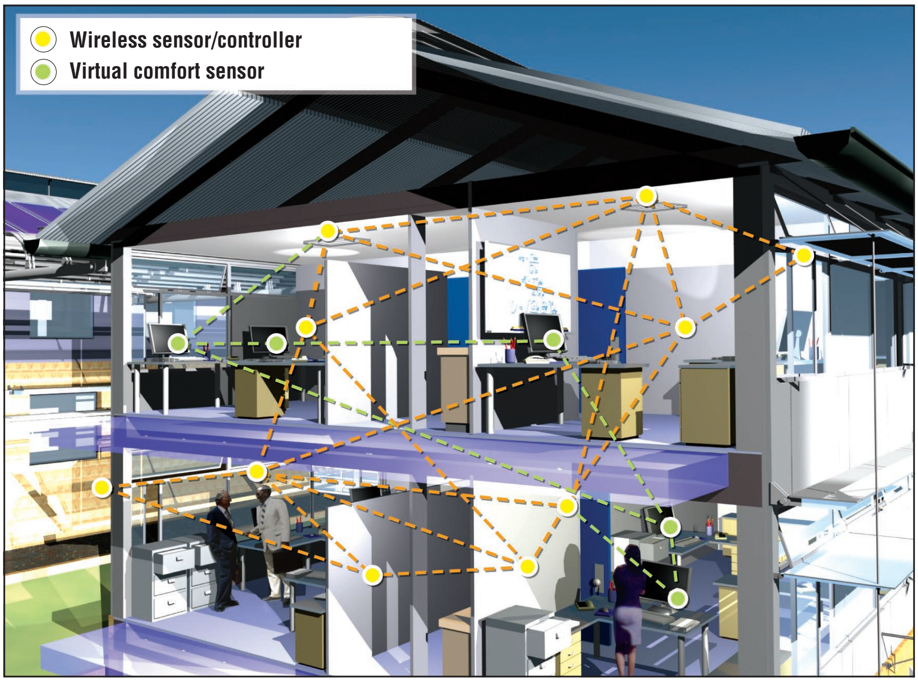

Figure 4. Integration of wireless sensors/controllers and virtual comfort sensors for optimal, distributed control of sustainable buildings.

CSIRO focuses on four key areas in intelligent building controls: optimizing the trade-off between user comfort, operating cost, and carbon emissions; forecasting building conditions; applying localized control responses; and identifying anomalous conditions that might represent faults or inefficiencies. The application of pervasive computing technologies is enabling these developments. Specifically, by using high-spatial-resolution mesh networks, we can obtain detailed condition, operation, and energy mappings for use both at a local sensing and control level and when aggregated for whole-building optimization.

CSIRO is extending its optimal building control technology to wireless sensor networks to facilitate low-cost, ubiquitous controls. With low energy consumption and robust ad hoc communications, such controls are ideal for retrofits to existing building stock—which is crucial for maximizing carbon reductions. Using distributed, embedded hardware, intelligence can be immersed into building sensor and control networks using localized data as input to optimized adaptive control routines with fast response and low network and computational overhead. This input can be combined with real-time comfort feedback from occupants via pervasive PC-based virtual comfort sensor software (see Figure 4). This technology has the potential to break through traditional comfort barriers by improving thermal satisfaction—not only from the direct physical effect of occupant adjustments on indoor climate but also from the empowerment of the occupants.

Supported by ever-evolving software architectures and embedded hardware platforms, possibilities for optimal, distributed control of sustainable buildings are growing dramatically, with significant potential energy savings and reduction of carbon emissions becoming reality.

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Knowledge-Based Intelligent Information and Engineering Systems

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Smart Environment Vectorization
An Approach to Learning of User Lighting Preferences

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Abstract. The automation of smart environment systems is one of the main goals of smart home researching. This paper focus on learning user lighting preference, considering a working field like a standard office. A review of the smart environment and devices setup is done, showing a real configuration for test purposes. Suitable learning machine techniques are exposed in order to learn these preferences, and suggest the actions the smart environment should execute to satisfy the user preferences. Learning machine techniques proposed are fed with a database, so a proposal for the vectorization of data is described and analyzed.

1 Introduction

Smart home technologies are often included as a part of ubiquitous computing. Mark Weiser [1] outlined some principles to describe Ubiquitous Computing (ubicomp) from which we emphasize that the purpose of a computer is to help you do something else.

Home technologies have tried to help home inhabitants since its creation. Nowadays, due to the popularization of computational devices, ubiquitous computing is called to be the revolution to develop smart systems with artificial intelligence techniques.

Domoweb [2] was a research project originally developed as a residential gateway implementation over the OSGi (Open Services Gateway Initiative) service platform. Nowadays Domoweb conform a great platform where researchers from different disciplines converges and where we can deploy, develop and test smart home related solutions, due to the component based model, and the service oriented architecture that Domoweb and OSGi supports.

This article focuses on modeling smart spaces to apply machine learning techniques. We have focused in the learning of user preferences for the lighting of a space. In order to interact with the space and retrieve these preferences, an office at the department of Computer Languages of the University of Seville has been provided of several devices to accomplish these tasks.

Artificial intelligent methods can be supported by this model like machine learning algorithms where is centered this article. Some techniques are presented

I. Lovrek, R.J. Howlett, and L.C. Jain (Eds.): KES 2008, Part I, LNAI 5177, pp. 765–772, 2008.

to accomplish this goal in section 3. Finally we propose some expansions which could be studied in order to cover other cases.

2 Experimental Environments

Two different environments are used for data collection. The first one is a simulated environment developed in Java that allows researchers to generate simulated and synthetic databases.

Second one is a standard office at the department of Computer Languages is used for data collection during the experiments. This office is intended to be used by a single person, who could be eventually visited by other work mates or students. It is illuminated by natural light from the window and four artificial fluorescent lights which can act as a complement of the natural light or like unique source of light.

Figure 1 shows the distribution and setup of the room.

As you can see, the orientation of the window is south, so it maximizes the quantity of light that receives during a day. This fact must be considered when analyzing results.

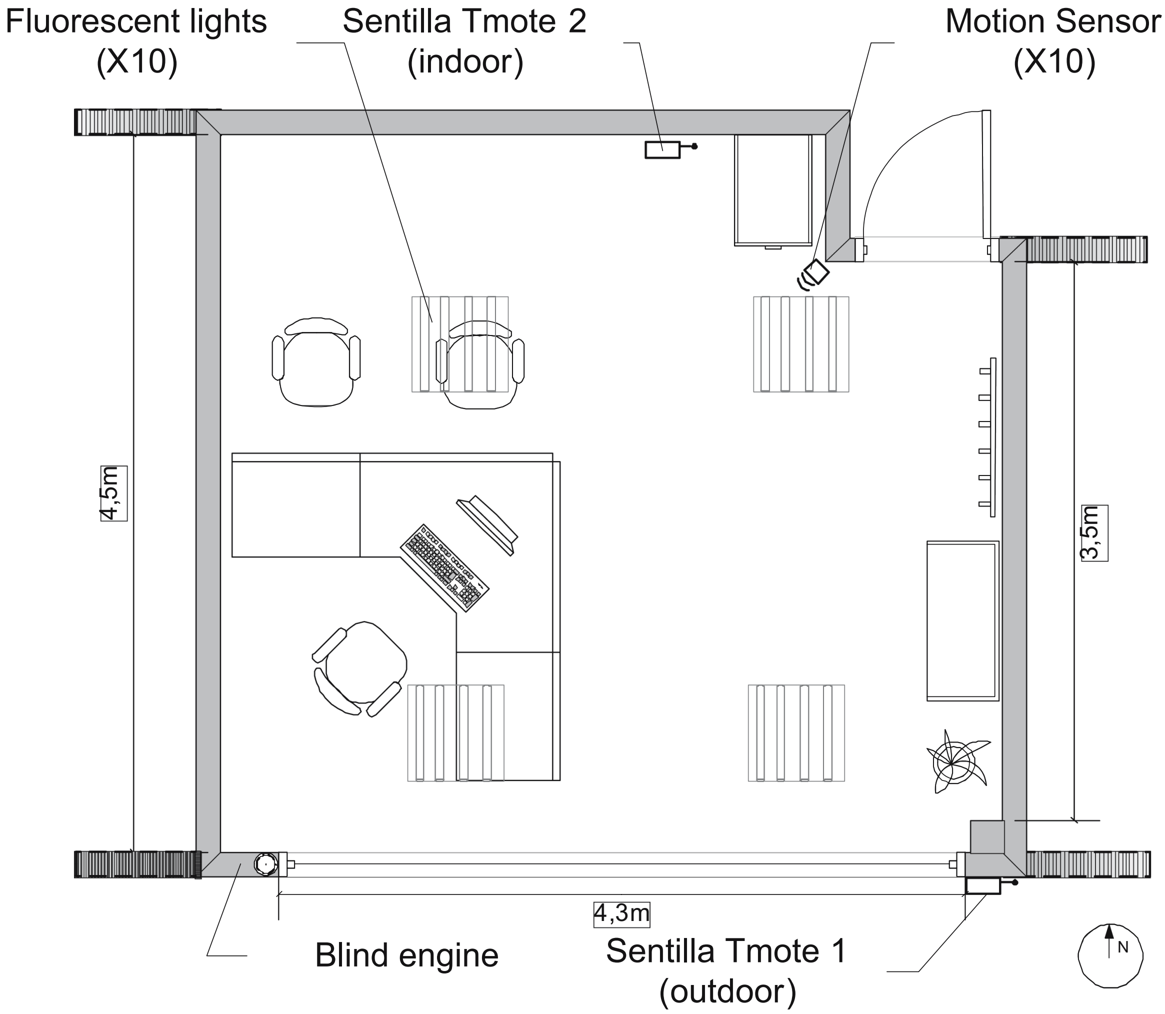

Fig. 1. Room setup

3 Related Devices

In this section we present the devices which will interact in the setup proposed. The concrete model and manufacturer of the devices are detailed although the learning system should be independent of these details.

3.1 Sentilla Tmote

Sentilla Tmotes are the devices which detects the quantity of light. In this setup we propose to install one mote indoor, and another outdoor. This way we can compare the preferences of the user indoor with the quantity of light outdoor. We'll be able to deduct some weather parameters in real time too. The dimensions are 8 cms. of width and 3.2 cm. of height, so it is quite small to suit ubiquitous applications and non intrusive systems. These devices also implement a humidity and temperature sensor, which could be requested for future improvement and expansions. The figure 2 shows the Sentilla *Tmote* module:

The connectivity with other motes and computers is done through the IEEE 802.15.4 (ZigBee) protocol, which minimizes battery consumption. Zigbee supports mesh networking so this is the topology we will adopt and this way the *motes* can create a network to share information and forward it to reach wider areas.

Nowadays Sentilla *Tmotes* are packaged in a beta development kit, including an IDE based on Eclipse 3.2 for developing. The hardware implements a Java Runtime Environment which can run different applications to retrieve, process and send information from sensors.

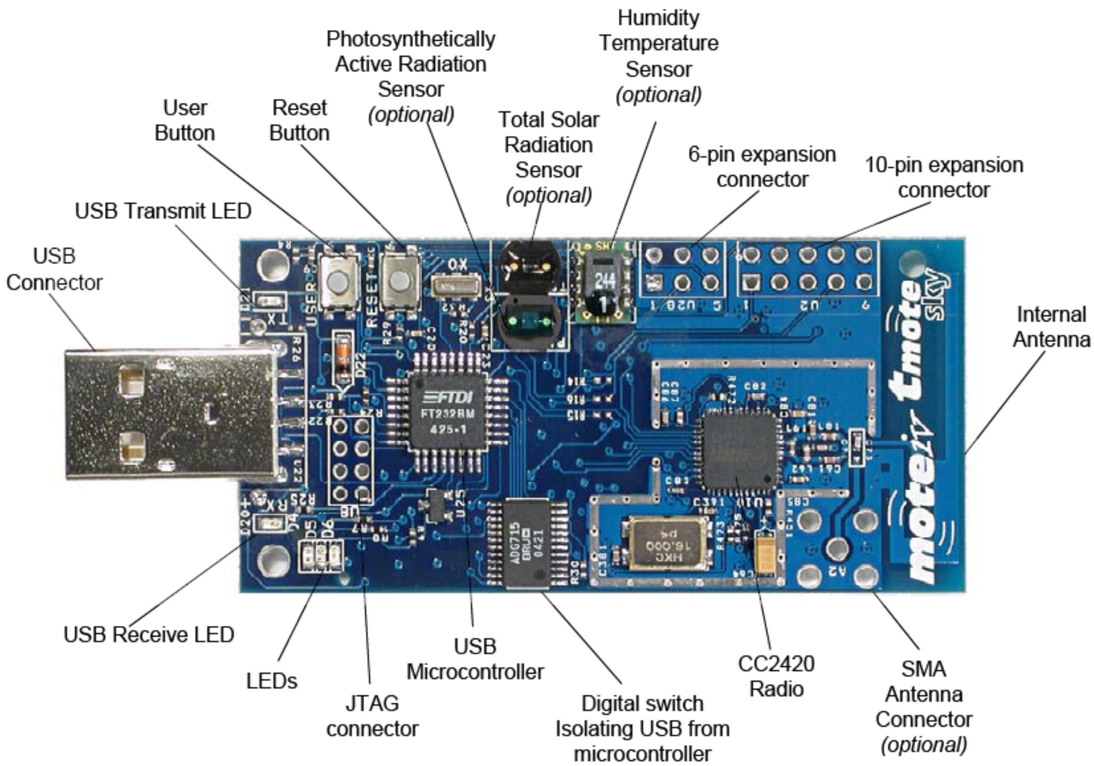

Fig. 2. Front of the *Tmote* module

3.2 Motion Sensor

A motion sensor is indispensable to determine when a user is at the room. This could act as a trigger of the learning algorithm to retrieve, process and send the information from sensors.

Domoweb project implemented an OSGi platform with software components to interact with X10 devices. The figure 3 shows the MS13A, a wireless device which interacts with a gateway that routes wireless messages over the electrical cable using X10 protocol. Notice that, although X10 protocol is an old-fashioned technology, it carries out its purpose perfectly.

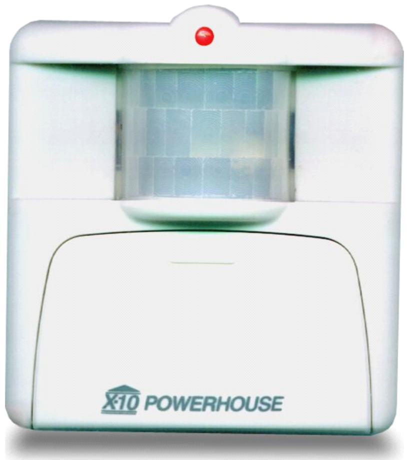

Fig. 3. Front of the MS13A. X10 Wireless Motion Sensor.

3.3 Fluorescent Light

These lights are activated with an X10 actuator, like the Appliance module AM486 in order to determine when a light has been switched on and off, and its current state.

3.4 Blind Engine

Lighting preferences are directly related with the quantity of light that goes through the window. Therefore the state of the blind or curtain will affect the lighting of the room. Some devices are under study but at the moment of writing this article none satisfied our requirements of wirelessly communication and standardized protocols.

4 Framework of Learning

As exposed before, our goal is the learning of the lighting preferences of a single user. This machine learning is done over the statistical data retrieved at the environment shown in sections 2 and 3. In general, we will retrieve a set of data X called *input*

$$X = \{x_1, x_2, \ldots, x_n\}$$

and we will have a set of data Y called *output*.

$$Y = \{y_1, y_2, \ldots, y_m\}$$

The process of learning tries to search a functional dependence between both sets of data. The framework is based on V.N. Vapnik [3] model of learning with examples. The model is composed by three elements as shown in the figure 4.

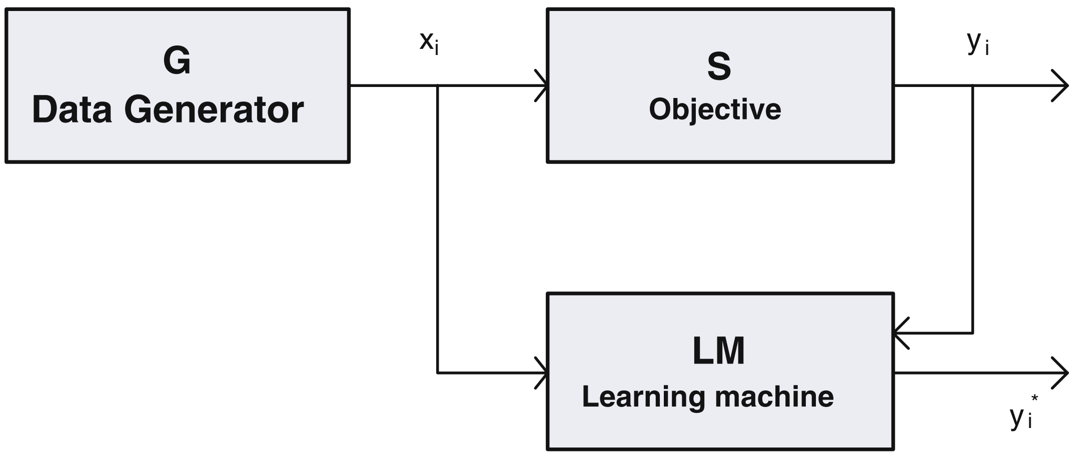

Fig. 4. Learning model

1. **Data generator.** Samples of X, retrieved by the infrastructure proposed.
2. **Objective** (aka supervisor)**.** User preferences.
3. **LM.** Learning machine.

The learning can be carried out due to the dependence of the user preferences with his habits. Normally we have the same lighting preferences. These preferences must be learned at every environment, due to its dependence with the location, orientation of the window, devices setup and so on.

4.1 Techniques

Two families of algorithms, related with learning machine, can be considered although both are going to be supervised.

Support vector machine (SVM) and Neural networks (NN) are the selected techniques to learn user lighting preferences. The main advantage of these techniques is that always offer an output. On the other hand it is hard to interpret or understand their outputs which is an important feature that prediction algorithms should implement as expounded in [4].

The other family of algorithms considered is the machine learning techniques based on rules. These algorithms provide an output easier to understand and interpret, but their main disadvantage is that if no rule matches current state, these algorithms don't offer an output.

4.2 Input and Output

Table 1 shows the input variables X proposed and two sample input data:

Table 1. Input sample

Outdoor lighting $[0,1]$	Indoor lighting $[0,1]$	Indoor light state {0,1}	Blind state $[0,1]$	Motion {0,1}	Action over light {-1,0,1}	Action over blind $[-1,1]$	Threshold $[0,1]$
0.9	0	0	0	1	0	0	0.5
0.9	0.7	1	0.5	1	1	0.5	0.5

- **Outdoor lighting.** This variable represents the quantity of light received from the outdoor Sentilla *Tmote* sensor. Continuous variable from 0 to 1.
- **Indoor lighting.** This variable represents the quantity of light received from the indoor Sentilla *Tmote* sensor. Continuous variable from 0 to 1.
- **Indoor light state.** This variable represents the state of the lights of the room received from the X10 appliance module. Discrete variable, 0 for lights off, and 1 for lights on.
- **Blind state.** This variable represents the state of the blind or curtains. Continuous variable from 0 to 1. 0 for totally closed and 1 for totally open.
- **Motion.** This variable represents the detection of motion sent by the MS13A X10 device. Discrete variable, 0 for no motion, 1 for motion detected.
- **Action over light.** This variable represents the action done by the user over indoor light. Discrete variable, -1 lights switched off, 0 no action, +1 lights switched on.
- **Action over blind.** This variable represents the action done by the user over the blind/curtains. Continuous variable, -1 means the user closed it totally, 0 no action, +1 means the user opened it totally.
- **Threshold.** Represents the current user lighting preference. 0 represents minimum room lighting, 1 represents maximum room lighting.

Notice that Sentilla *Tmotes* offer the quantity of light received in luxes. We have to standarize this data to a $[0,1]$ interval.

Table 2 shows the output variables Y proposed and two sample output data:

- **Action over light.** Represents the action over indoor light predicted by the learning machine in order to satisfy user lighting preferences. Discrete variable, -1 lights switched off, 0 no action, +1 lights switched on.

Table 2. Output sample

Action over light {0,1}	Action over blind $[-1, 1]$	Action over threshold $[-1, 1]$
0	0	0
0	0	α

– **Action over blind.** Represents the action over the blind/curtains predicted by the learning machine in order to satisfy user lighting preferences. Continuous variable, -1 means the machine closed it totally, 0 no action, +1 means the machine opened it totally.
– **Action over threshold.** Represents the correction the machine must done in order to adapt current user threshold. Negative values reduce threshold, 0 represents no action, and positive values represent an increase correction over threshold. The value α of the correction must be determined with care, in order to avoid infinity jumps around user preference, and converge to the real user preference.

5 Future Work

Comparative results must be done between machine learning techniques proposed in section 4.1. Next step should focus in enlarge action field, to other rooms with different users, locations, orientations, and so on. This way we could compare results obtained with these techniques in different (but similar) environments, and create a wider *motes* mesh network.

Other field of action could be applying these techniques and algorithm to learn user preference over conditioning. Sentilla *Tmote* devices also include sensors to retrieve temperature and humidity, useful to learn conditioning preferences.

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Modeling Smart Homes for Prediction Algorithms

A. Fernández-Montes, J.A. Álvarez, J.A. Ortega, M.D. Cruz, L. González, and F. Velasco

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Abstract. This paper reviews the goals of the Domoweb project and the solutions adopted to achieve them. As a result we enjoy a great support to develop smart home techniques and solutions. As a consequence of the acquired experiences a Smart home model is proposed as a division of four main categories. In relation with the smart home model, we show the essential features a smart environment prediction algorithm should satisfy and a procedure to select relevant information from the model to achieve artificial intelligence based solutions.

1 Introduction

Smart home technologies are often included as a part of ubiquitous computing. Mark Weiser [1] outlined some principles to describe Ubiquitous Computing (ubicomp) from which we emphasize that the purpose of a computer is to help you do something else.

Home technologies have tried to help home inhabitants since its creation. Nowadays, due to the popularization of computational devices, ubiquitous computing is called to be the revolution to develop smart systems with artificial intelligence techniques.

Domoweb [2] is a research project which was originally developed as a residential gateway implementation over the OSGi (Open Services Gateway Initiative) service platform. Domoweb implements the standard services any residential gateway must have like http server, web interfaces, device manager, user manager and other basic services.

Nowadays Domoweb conform a great platform where researchers from different disciplines converges and where we can deploy, develop and test smart home related solutions, due to the component based model, and the service oriented architecture that Domoweb and OSGi supports.

This article focuses on modeling smart homes and the features the prediction algorithms should implement. A good smart environment model must represent the

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properties, states, attributes and any other characteristic that could be useful in building smart environments solutions as is proposed in section 2.

Artificial intelligent methods can be supported by this model like prediction algorithms where is centered this article. The features these algorithms must be aware of are defined in section 3 and finally a procedure to discriminate significant information is released in section 4.

2 Smart Home Model

Artificial intelligence algorithms need a solid base of knowledge to work. This fact demands us a great effort for building a model of the smart home and its environment. Other projects have helped us to compose the model [3-5] which has been arranged in four main categories explained in next sections and expounded in table 1.

2.1 Device Related

This category is the most obvious one so is related with the main elements in a smart home environment. Ambient intelligence algorithms should be aware of next main fields:

- **Status.** Algorithms must know the current states of devices installed on the smart home. Obviously this is essential for these algorithms, and one of the most important domains to build future predictions.
- **Location.** Devices usually occupy a location for a long time and this location may be useful for ambient intelligence algorithms. The model must be able to consider non-still devices as well, like motorized cleaner robots and others.

2.2 Inhabitants Related

Smart home algorithms must be aware of the inhabitants' status to offer appropriate predictions for any user or for the whole group of inhabitants. On this line we discuss some of the necessary fields to infer inhabitants-aware predictions:

- **Personal data.** This field includes all the data concerning to a particular person like name, age, sex and so on.
- **Location.** Inhabitants can move over the home rooms, so smart home systems have to know where each inhabitant is, and should be able to identify them.
- **Physical state.** This field is related with the illness or injuries that an inhabitant can suffer during his life. Smart home technologies must adapt to this situations and offer appropriate replies.
- **Mental state.** The state of mind of a person can be defined as a temporary psychological state. A depressed inhabitant behavior usually differs from a euphoric one, so smart home must be consistent with these circumstances.

Table 1. Smart Home Model

CATEGORIES	FIELDS	DESCRIPTION	EXAMPLE
DEVICE RELATED	Status	Current state the devices are.	Sensor temperature is at 25ºC
	Location	Where the devices are.	Cleaner robot is in Living room.
INHABITANTS RELATED	Personal data	Name, Age, sex.	Diane is 45.
	Location	Where the inhabitants are.	Mark is at bedroom.
	Physical state	Illness, injuries, and others states inhabitants are.	Roy has a cold.
	Mental state	Psychological state the inhabitants are.	David is depressed.
ENVIRONMENT RELATED	Date, time	Temporary information	Current time is 13:36.
	Environmental conditions	the phenomena that currently occur in the atmosphere	It's rainy
HOME BACKGROUND	Inert entities location	Where these entities are.	Sofa is at living room.
	Home limits properties	The properties of the home structure and limits.	Bedroom window opacity is 70%

2.3 Environment Related

This category probably is the most diffused due to it covers heterogeneous and difficult-to-limit fields as we discuss in the following list:

- **Date, time, season.** Obviously smart home behavior should be different in different temporal conditions and it may depend in these temporal factors as the air condition policies will differ between summer and winter.
- **Environmental conditions.** This field comprises current environmental conditions (sunny, cloudy, rainy and others). Smart home should make a request for a weather forecast as well, which could be significant to assess future decisions.

2.4 Home Background

This category must comprise all the relevant things concerned to inert entities and its properties or qualities. This could be the less relevant category discussed, but anyway could be significant in some concrete applications. We propose a couple of fields related in next listing:

- **Furniture location and position.** Furniture occupies space at home and can be moved. Location (room where the furniture is) and position (place where the furniture is placed in a room) should be known by the smart home systems due to it could be useful by concrete applications like robot movement related algorithms, or presence detection related algorithms.
- **Home limits properties.** The texture of a floor, the color of a wall, or the opacity of the windows could be significant in several cases such as temperature adjustment applications.

3 Features of Prediction Algorithms

In this section we present the features that a smart home system must implement, specially related with the prediction algorithms the systems may have. The article doesn't focuses on artificial intelligence techniques like the studies of [5-10] do, but on what are the most important and indispensable features that must be considered to develop prediction algorithms. Much of the ideas presented below could be useful to implement others smart home algorithms.

3.1 Prediction Supported by Last Events and States

Prediction algorithms should consider as input data two main aspects. First it should analyze the last events occurred in the home's performance field which have changed the home status in any manner.

Second it should analyze current state and previous states as well. This way the algorithms should determine last changes in the home status, and which events have been involved in these changes.

In section 5 we discuss further about these aspects and propose a way to consider states and events.

3.2 Predictable by the Inhabitants

Smart homes should learn inhabitant behaviors and habits, and build predictions, but it has to be predictable by the inhabitants to achieve no unexpected behaviors.

3.3 Understandable Decisions

Prediction algorithms have to offer an explanation of their predictions and/or actions. This way the inhabitants will be more trusted with the decisions the system took. This will improve the user acceptance of the smart home predictions.

3.4 Wrong Decisions Detection and Related Improvement

If the smart home executes a wrong decision it should be aware of this failure and be able to learn from its errors. A possible scenario should be when someone arrives home at night and the system orders the hall lights to switch on, but immediately the user performs the opposite action (which should be switch off the lights). The system has to notice this failure and extract some knowledge from this experience to face future similar situations with guarantees of success.

3.5 Anomalies Detection

In some scenarios, the smart home should consider that a wrong decision executed as a consequence of a wrong prediction could be produced due to an anomaly. We can consider this scenario, an inhabitant wake up all working days at 7.00 a.m., so smart home switch on the coffee-maker some minutes before. But when the wake-up alarm goes off, the smart home detects no movement so it could be desirable to request an emergency service with a standard phone call or other mechanism.

3.6 Quick Response When Required

Some situations require the smart home prediction algorithms to return a response with time limits. These algorithms are responsible for detection of this situations and they must be able to adapt to these circumstances in order to provide a quick response.

3.7 General Policies and User Adaptation

Smart homes technologies should implement the mechanisms to support some home policies like security, energy or comfort. These policies can be collected in different levels. The inhabitants could define some general policies which could be customizable by concrete inhabitant preferences. We can discuss the following scenario; inhabitant A gives preference to energy consumption over comfort. To satisfy these preferences smart home system should try to minimize the energy consumption produced as a result of its predictions. On the other hand, inhabitant B gives preference to comfort over energy consumption, so algorithm has to adapt to this user preferences policy.

This way if the prediction algorithm determines that inhabitant A arrives home, it will switch on air conditioner system only at the arrival of the inhabitant, however if the inhabitant B is going to arrive home, the smart home should switch on the air conditioner system sometime before the arrival of the inhabitant.

4 Window of States

Smart home prediction algorithms usually make use of last states and events occurred at home environment. A state can be defined as the whole set of pairs field-value according to the model presented in section 3. We could also distinguish subsets of these states for each category so we shape the related sub-states. This way we can consider sub-states to include devices related, inhabitants related, environment related and background related information.

Events can be defined as something that happen at a given place and time. In smart home contexts, we can add to this definition that the event must cause a state change of the smart home. Events that do not cause a state change shouldn't be considered by smart home algorithms as something significant.

When building a smart home solution we can discuss what states and events should be considered. To resolve this situation we propose the use of a window which envelops the states (and events) that are going to take part in the giving response as shown in figure 2.

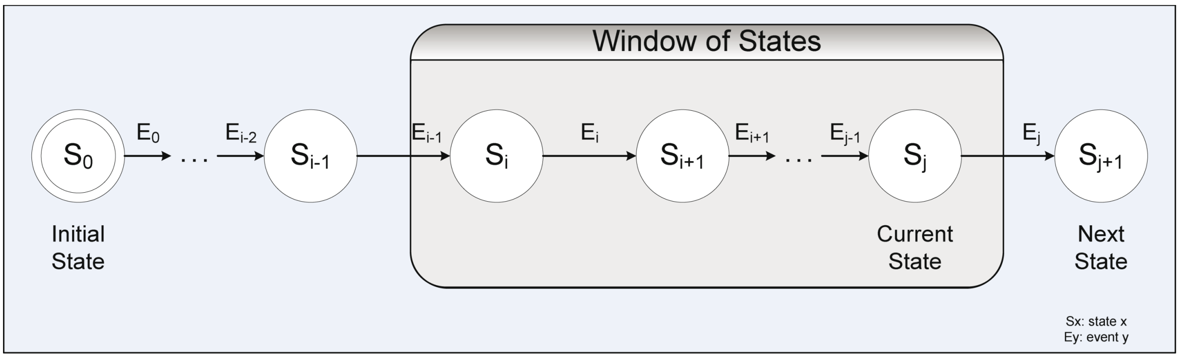

Fig. 1. Window of states

States are represented as circumferences labeled from S_0 to S_{j+1}, transitions between states as arrows labeled with the event which caused the state change.

Reader should notice that states from S_0 (initial state) to S_{j-1} are past time states, S_j is the current state and S_{j+1} is the next state which is currently unknown.

The size of the window $\boldsymbol{n}$ equals to the number of states and events to be processed. This size is deduced from the equation $\boldsymbol{n = j\text{-}i\text{+}1}$.

4.1 Dynamic vs. Static Window

Two approaches can be considered related with the size of the window. Algorithms designer could prefer the use of a static and predefined size of this window to build smart predictions. This approach can be useful in non-complex solutions, so it's easy to implement. The size could be estimated by means of empirical techniques and the own designer experience.

However dynamic window size is a more powerful approach for determining the size in real time. Algorithms could extend and reduce the size of the window depending on the requisites of current application like time of processing, hardware capabilities, solution accuracy and others.

5 Conclusions and Future Work

The previous sections have discussed some basis related with smart environments methods. A first model approach have been proposed as a start point to develop successful solutions, and prediction algorithms features form a guideline to implement these algorithms.

Prediction algorithms promise to be applicable to many areas within the smart home and smart environments so future work should be centered in the study of the methods and artificial intelligence techniques for prediction as in the improvement of the model definition.

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Smart Environment Software Reference Architecture

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***Abstract*—Nowadays ubiquitous computing is spreading to all scopes of our lives. Smart environments are present at every location such us homes with automation and control devices, offices full of control networks to assist workers, or hotels with even more control devices in order to save energy and satisfy guests preferences.**

This paper focus on the proposal of a Reference Architecture for developing Smart Applications and deploy them in Smart Environments. The proposal consider three main process in the Software Architecture of these applications: *a*) perception, *b*) reasoning and *c*) acting.

***Keywords*-Smart environments, software architecture, ubicomp.**

I. Introduction

We can define a smart environment as *one that is able to acquire and apply knowledge about the environment and its inhabitants in order to improve their experience in that environment* [1].

Smart home technologies are often included as a part of ubiquitous computing. Mark Weiser [2] outlined some principles to describe Ubiquitous Computing (ubicomp) from which we emphasize that the purpose of a computer is to help you do something else.

Home technologies have tried to help home inhabitants since its creation. Nowadays, due to the popularization of computational devices, ubiquitous computing is called to be the revolution to develop smart systems with artificial intelligence techniques.

Domoweb [3] was a research project originally developed as a residential gateway implementation over the OSGi (Open Services Gateway Initiative) service platform. The experiences obtained from this project allow us to face an even more challenging project, the proposal of a General Software Reference Architecture to develop smart applications where all the components of a smart environment can interact flawlessly and reach automatism objectives.

Typical components of a smart environment are widely studied over the literature, but we can emphasize the approach of D.J. Cook, and S.K. Das at [4] which shows a general organization of these components. These are divided in four layers: *a*) physical, *b*) communication, *c*) information and *d*) decision. This approach joins hardware with software agents, so very heterogeneous elements appear in the same component model such as a *decision maker* and *sensors* or *actuators*. All these components must collaborate to achieve the goals of automatism that a smart environment is required. This is the main motivation of current work, so a Reference Software Architecture is proposed.

Other interesting approaches have been proposed. Costa [5] presents a model where each issue is matched with the characteristics that address it. Weis [6] shows a high level programming language for rapid prototyping of pervasive applications. The approaches from Rehman [7] and Bannach [8] are focused in interactive context-aware applications and prototyping of activity recognition applications respectively. In contrast with these approaches, ours is a General **Software** Architecture for Smart (pervasive) Applications.

II. Reference Architecture

The proposal of a General Reference Software Architecture to develop smart applications is based in the goals of the ubiquitous computing subject proposed by Weiser [2]. Taking this as a starting point, we believe that automation in smart environments should be organized as a continuous interaction between three main tasks: *a*) perception, *b*) reasoning and *c*) acting. (see figure 1).

The perception of the state of the environment is performed by means of the physical components distributed through out the environment, reasoning must be done about the state and it produces possible actions to take, finally these actions must be carried out.

III. Perception

The perception process should be divided in different tasks in order to provide an accurate *perception* of the real world (see figure 2).

It has to deal with low-level details to retrieve data from real world and adapt it to a knowledge base which must agree the smart environment model proposed in [9]. This process have to clear this data of erroneous, insignificant or redundant values in order to achieve the accuracy required by next process.

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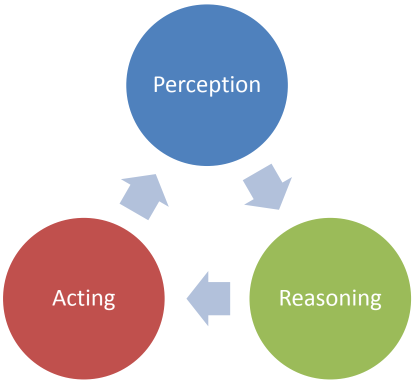

Figure 1. The cycle of the automation process in a smart environment.

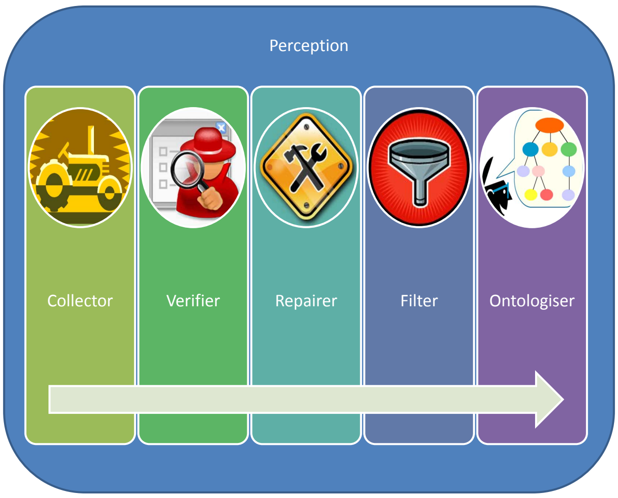

Figure 2. Tasks of the perception process.

A. Collector

This is the lowest-level task, so its main objective is to retrieve data from physical devices. It will usually have to deal with gateways devices of every technology deployed over the smart environment.

The properties of the environment suitable to be captured by these sensors are listed in [9]. Actually a subset of these properties could be selected to achieve any particular application or automation process (e.g. put lights off when nobody is at home does not need conditioning information from the environment).

Sensors must be deployed in an organized manner to avoid redundant or insignificant information and reduce costs. When developing the *Data Collector* we have to consider if devices should be programmed or not (or if both types of sensors are present in the environment).

Majority devices are pre-programmed and can't extend its basic functionality (e.g. X-10 Motion sensor), so developers have to adapt to them. On the other hand more and more devices have the ability to extend or modify their performance (e.g. Sentilla *Tmote*).

The latter are much more challenging for developers due to they can be adapted to current needs for a concrete application or circumstances. In this case, Data Collector task covers daemons developed to retrieve information and small applications running on devices as well, so both elements have to agree what information is sent, periodicity of these requests and so on.

B. Verifier

The main purpose of the *Verifier* task (as its name means) is to *verify* that the data (which is currently being received by the *Data Collector*) is correct. But the challenge now is how the *Verifier* can determine if the data is correct or not. There is no unique solution for all possible environments, so the verification has to adapt to each environment dynamically.

We propose the *Verifier* to maintain a rule engine where verification rules can be deployed, modified and used in order to determine where data is right or wrong for current environment. The rule engine will have to offer programmers a flexible way to read, add, modify and delete rules.

By the way this task has to work side by side with the *Repairer* when incorrect data is received in order to fix invalid data. The mechanism of communication between the *Verifier* and the *Repairer* must be determine. Typical implementations of this mechanism would be the publication of a *repair service* by the *Repairer* that will be invoked by the *Verifier*.

We can conclude the *Verifier* can be seen as a filter applied over all the data received, and it can be used to reject data for any reason (incorrect, redundant and other reasons).

C. Repairer

The *Repairer* task will try to fix incorrect data detected by the *Verifier*. The corrections applied to data can be done in very different ways such us:

- **Ignore data**. First option is to ignore data, it means to set it with unknown value. The *Ontologiser* will save that value as required by storage system (e.g. Weka-arff '?' character, or SQL null value).
- **Adjust data**. If a value is incorrect, but its distance with a correct value is less than a threshold (previously customized) the value could be adjusted to nearest correct value.
- **Replace data**. Other option is to replace data with previous correct data. (e.g. if temperature sensor returns 100 Celsius, and previous data is 25, we could replace current value with 25).
- **Reject data**. If current values are not suitable to be repaired, the repairer will reject it.

Once a set of data has been received, verified and repaired, it has to be sent to the *Ontologiser* to be organized and stored.

D. Ontologiser

Artificial intelligence algorithms need a solid base of knowledge to work. The main goal of the Ontologiser is to organize data to conform a model of the real world.

This fact demands us a great effort for building a model of a smart environment. Other studies have helped us to compose the model [10] [11] [12] which has been arranged in four main categories explained in [9].

Synchronization. *Ontologiser* will have to synchronize data from a world full of asynchronous devices and events. Automation applications usually need sets of data composed from multiple devices values. Data from different devices must by synchronized for a latter aggregation, so this task will have to define the rules to synchronize values from multiple and very heterogenous sources.

Implementations of the synchronization process will vary depending on the goals of a concrete smart application, but all implementations will share some elements such as:

- **Data buffer** will store data received that is waiting to be paired with other data.
- **Garbage collector** will supervise the size of the buffer, and will periodically clean the buffer from data that couldn't be paired.

Aggregation. Once data is synchronized it must be joined in a set of data for a concrete application. Each attribute should conform the Smart Environment Model [9].

When data is aggregated it is ready to be stored in the knowledge base that feeds the reasoning tasks and learner process. The knowledge base format will be any of the *de facto* standards like arff, or any relational database.

IV. Reasoning

Reasoning process in smart environments can be separated in several tasks (see figure 3) which interact to achieve three main goals: *a*) learn, *b*) reason and *c*) predict.

Learning can be done through any of the techniques commonly known and widely studied in the literature. Attending to the scope of this work we can separate these techniques in two main categories: *a*) rule based and *b*) *black-box* based .

Rule based algorithms offers the advantage to be readable and easily understandable by humans. Rule-based techniques are studied in [13] and applied to automation of smart environments in iDorm [14] or combined with temporal reasoning in ADB [15].

On the other hand *black-box* based techniques don't offer a comprehensible model of the knowledge that is being learned, but these techniques have been successfully used in pattern recognition and learning in general. Neural Networks or Support Vector Machine are studied as a general technique by authors like [16], [17], [18] and applied to automation of smart environments in the Neural Network House [19], House_n [20] and Mav Home [10].

Figure 3. Typical tasks of the reasoning process.

A. Learning Agent

This task can be seen as the glue that joins any other task proposed to achieve the objectives of the Reasoning process. It has to deal with:

- *Data Mining* task to extract patterns,
- *Situation Recognition* task to label patterns recognized,
- *Prediction* task to find future actions to be taken and
- *Error detector* task to detect wrong decisions and to make related improvements over the entire process.

The learning can be carried out due to the dependence of the user preferences with his habits. For instance normally we have the same lighting preferences in our offices so these preferences must be learned at every environment, due to its dependence with the location, orientation of the window, devices setup and so on.

Learning techniques. Two families of algorithms, related with learning machine, can be considered although both are going to be supervised.

Support vector machine (SVM) and Neural networks (NN) are some of the techniques we can use to learn user lighting preferences. The main advantage of these techniques is that always offer an output. On the other hand it is hard to understand their outputs which is an important feature that prediction algorithms should implement as expounded in [9].

The other family of algorithms considered are the machine learning techniques based on rules. These algorithms provide

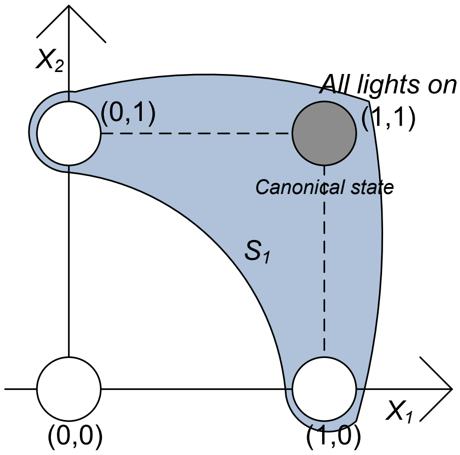

Figure 4. States for variables x_1 and x_2

an output easier to understand and interpret, but their main disadvantage is that if no rule matches current state, these algorithms don't offer an output.

B. Data Mining

Data mining task works side by side with the learning agent to extract information and find patterns from the data stored by the *Perception* (see section III) process.

Smart Environment Vectorization Data mining is fed with a stream of data with a concrete format. This is usually so-called the vectorization of data. This fact forces every concrete smart application to propose a vectorization of the environment and configure all the reasoning process with it.

C. Situation recognition

A situation is defined as a set of states which have similar values. This set can be defined by:

- a canonical state as a representative state of all the states in the set
- a distance function which define how to measure the difference between two states
- a threshold which define the maximum distance between the canonical state and the states of the set.
- a weight for each element of a state between [0,1]. A weight of zero represent that an element must not be considered.

The following example illustrates the definition of a situation. Let x_1 be the variable which represents the state of a light, and let x_2 be the variable which represent the state of another light. These variables are discrete, and its range is $0, 1$ which represent the states off and on respectively.

The figure 4 shows all the states that these variables can constitute.

We would like to define the situation S_1 where any of the lights is on. The canonical state of S_1 is $\{1, 1\}$ (all lights on)

Table I
STATES THAT BELONG A SITUATION.

State		Canon. State		Weights		d	Thresh.	$\subset S_1$
x_1	x_2	y_1	y_2	w_1	w_2			
0	0	1	1	1	1	2	1	no
0	1	1	1	1	1	1	1	yes
1	0	1	1	1	1	1	1	yes
1	1	1	1	1	1	0	1	yes

for the variables x_1 and x_2 respectively. A typical distance function could be defined as:

$$d([x_1, x_2], [y_1, y_2], [w_1, w_2]) =$$

$$= \sqrt{(x_1 - y_1)^2 * w_1 + (x_2 - y_2)^2 * w_2}$$

Where $[x_1, x_2]$ represent a state, $[y_1, y_2]$ represent the canonical state and $[w_1, w_2]$ represent the weights of x_1 and x_2 respectively which should be $[1, 1]$ for the situation S_1 any of the lights is on due to both lights should be considered. The threshold can be set to 1.

Table I shows the set of states that belong to the situation. If the distance is less or equal to the threshold, the state belongs to the situation. In other cases we can conclude the state will not belong to the situation.

D. Prediction

The knowledge acquired during the process of learning of the agent will be useful to make predictions about future actions that should be taken in order to achieve any automatism objective. These actions can be considered as the output of smart algorithms as explained in [21].

Desirable features of prediction algorithms. The features that a smart home system must implement are listed, specially related with the prediction algorithms the systems may have. So we don't focus on artificial intelligence techniques like the studies of [11], [22], [23] do, but on what are the most important and indispensable features that must be considered to develop prediction algorithms for smart environments which are briefly studied in [9] and just listed below: *a*) Prediction supported by last events and states, *b*) Predictable by the inhabitants/users, *c*) Understandable decisions, *d*) Wrong decisions detection and related improvement, *e*) Anomalies detection, *f*) Quick response when required and *g*) General policies management.

E. Error detector

The main purpose of this task is to supervise the actions taken by the inhabitants in order to detect opposite decisions between the machine and them. Therefore it will have to keep last actions taken by the smart environment and compare them with actions taken by the inhabitants.

The comparison of these actions is usually a complex operation where lots of elements take part into, and it has to take into account how many actions are going to be considered to make the comparison, how long these actions are going to be considered, or if actions over different devices could be opposite (e.g. open the window could be opposite to switch off the lights). All these aspects make the detection of wrong decisions much more challenging.

V. Acting

Finally, to close the cycle, Smart Environments have to act automatically to achieve a concrete smart application. This is the main purpose of the process of *Acting*. As shown in figure V the decisions and concrete tasks ordered by the *Reasoning* process have to pass through three main tasks *a*) policy manager, *b*) task scheduler and *c*) task runner1.

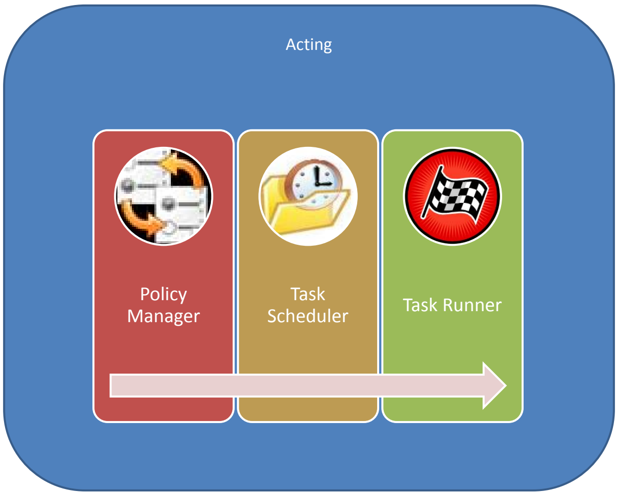

Figure 5. Tasks of the acting process.

A. Policy Manager

The decision of carrying out a task must be supervised by the Policy Manager. A smart environment may have defined policies about energy saving, security or comfort. This manager may implement the software artifacts necessary to define, store and query these policies such as Rei policy language [24] or a more extensive work of [25].

This process must be also suitable to change its policies in real time, so inhabitants preferences may vary (i.e. during vacation periods energy saving and security could be a priority in the smart environment).

B. Task Scheduler

Once an action has been ordered by the reasoning process, and has passed through the filter of the policy manager it has to be scheduled.

The scheduler has to consider that some tasks could have a time limit to be executed, and also has to consider its priority. The implementation will typically implement a queue where action will wait.

C. Task Runner

The task runner is the last task of the *Acting* process. It has to deal with low level protocols to send orders to devices. This task will receive a set of orders for a set of devices and it will have to translate them to low-level instructions.

This task must be a very light process with almost no-lag so its time xcomplexity should be lineal.

VI. Case study

We have already shown the Reference Architecture proposed, and the developing environment in [21] so it's time to present the applications developed during this work to validate the Architecture.

We have focused on developing an implementation of the Perception process (first of the Reference Architecture) which main objective is the *perception* of data about localization of workers, luminosity, temperature and humidity of an office at the LSI department at the University of Seville.

A. Mote Sensor Report

This application belongs to the *Data Collector* task. As it was presented in section III-A this task has the responsibility of the low-level interaction with devices, and it could be distributed between central stations of the Smart Environment and the devices themselves. Mote Sensor Report is a pervasive application developed on Sentilla Work IDE and deployed over Sentilla Tmotes.

Sentilla Tmotes implement a JVM called Sentilla Point so it can run Java applications. In order to access the hardware capabilities of the device, Sentilla offers a java library which give you access to the data gathered by the sensors and other elements such us extension port or leds.

The java application developed access to sensor data and send it through the Zigbee interface. The sensors conform a mesh network where motes act as repeaters. This type of network makes possible to cover wider areas even though Zigbee protocol has a 10m. radio.

When developing this application we realized that luminosity captured by sensors fluctuated if the fluorescent lights of the office were on. The reason of this behavior is that fluorescent bulbs are always turning off and on although it is not noticeable by humans due to its short frequency. However this behavior was a problem, so we had to tackle it and we included a part of the *Repairer* task (see section III-C) at this point, due to the reparation couldn't be possible in a later moment so it has to be tackled at this point.

The solution is quite simple, instead of retrieving just one value, n values are retrieved and the average of them is calculated and then sent to the Sentilla Gateway plugged into the central station.

B. Mote Dashboard

In order to receive all the information from the Sentilla *motes* an application has been developed. It shows the information that is being received from the motes in real time. This application carries out three main tasks:

- **Data Collector**. An execution thread is responsible of managing the reception of data from the motes, using the mote gateway supplied with the Development kit.
- **Verifier**. A simple verifier has been developed and performs simple tests, similar to preconditions, over data received. (e.g. $luminosity >= 0$).
- **Repairer**. When the verifier task detects erroneous data Mote Dashboard choose between two options:
  - Replace. If previous correct data was received short time before, concrete erroneous values are replaced with previous values. The time difference is customizable.
  - Reject. On the other hand, if previous correct data was received long time before, current erroneous data is rejected.
- **Ontologiser**. Finally correct data is processed by the ontologiser task. It performs three operations:
  - Synchronization. It keeps a buffer of data received from every *mote*. When information from outdoor and indoor *motes* was taken at approximately same time it is composed by the aggregation task.
  - Aggregation. Once data is synchronized, it is added to the same instance of the input data.
  - Store. Finally, Dashboard stores all instances in *arff* format and *SQL* database (useful for machine learning tools like Weka [13]).

Mote Dashboard has other minor functionalities:

- **Show information**. It shows the information received from the motes in a GUI (Fig. VI-B), and a list of active motes in the mesh network.
- **Reset**. Resets the dashboard GUI. This doesn't affect stored data, but cleans buffers and GUI from data received.

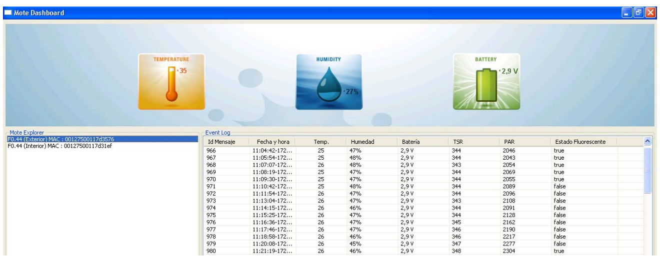

Figure 6. Mote Dashboard GUI.

VII. Conclusions

We have shown a General Software Reference Architecture to develop Smart Environment Applications which is very useful for developers of Smart Environments solutions. We have answered questions like: *a*) How should the applications/software be divided?, *b*) Which process should be present for these smart solutions?, *c*) How these process should interact? .

Future work has to focus on continue developing smart applications to provide more feedback to the Reference Architecture in order to continue improving it. Another interesting challenge is to consider not only the ability of the smart environment to fit user preferences but using Smart Environment to change behaviors in the individual. The increasingly pressure requirement of sustainability points out that future smart environments will *teach* the inhabitants to be more conscious with the world and its environment and we believe that it has to be the way future smart environments must work.

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LECOMP: Low Energy COnsumption Mesh Protocol in WSN

Juan A. Ortega, Alejandro Fernandez-Montes, Daniel Fuentes,
and Luis Gonzalez-Abril

Abstract. LECOMP is a mesh network protocol that is focused on minimizing battery consumption of nodes in a Wireless Sensor Network (WSN). This paper is a improvement of a first approach [1] which proposes a method to extend the lifetime and the reliability in a WSN balancing transmissions saving energy throughout different nodes in order to consume homogeneously nodes' batteries, and taking into account distances and hops of routes. First, a central node analyzes messages from nodes during a training period to determine new routing rules for each sensor. Second, the server configures the network adding the computed rules to the nodes. Third, central server can reconfigure the network routes when new balance of load is needed.

1 Introduction

Since sensors are battery powered in Wireless Sensor Networks applications, it is essential to minimize energy consumption so lifetime of the global network can be extended to reasonable times. The establishment of WSNs have grown in both research and real-world applications so improvements and solutions are required. Nowadays, energy-efficient sensor networks is a common topic in research works and the main directions to energy conservation are discussed. Some studies deal with the topology control which refer to the techniques that are aimed to super-imposing a hierarchy on the network organization to reduce the consumption [2]. In this sense, the location and the distance between the nodes are critical aspects. Some studies determines that multi-hop communication in mesh networks consumes less power than the traditional single-hop long distance radio communication in star networks

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[3]. Other studies propose an efficiency power management in the network using sleep/wakeup protocols at the application or network layers [4, 5], or strictly integrated MAC [6] protocols. There are multiple application environments of energy-efficient wireless sensor networks and different routing techniques for them [7, 8]. Others methods save energy by reducing the number of sensor transmissions. In [9], sensor transmissions are sorted according to the magnitude of their measurements, and the sensors with small magnitude measurements, less than a threshold, do not transmit. However, in [10] the data compression allows the reduction of the data length. On the other hand, battery analysis is another approach to balance the transmissions and maximize lifetime of the network[11]. In this paper some of the described techniques are combined to achieve a energy-efficient communication in a mesh WSN. Specifically, the batteries levels, sensor distances and message routes are analyzed to balance load and to optimize the routes from nodes to the central station. In Section 2 we provide an overview of the objectives then, in Section 3, we describe our energy-efficient routing proposal LECOMP. Implementation and test results are related in Section 4 and finally, concluding remarks are made in Section 5.

2 Routing Proposal

The primary goal of LECOMP protocol for WSN is to increase the lifetime of the network saving batteries. Moreover, secondary goals are: decreasing the load of the netwrok by minimizing configuration messages needed to setup sensors routing constraints in an automated and live way, and on the other hand, to free the administrator from manually setup the network. The architecture of our sensor network is illustrated in figure . We consider next elements:

- A set of n motes or sensors, $S_1, S_2, ..., S_n$. Devices that sense on aspects of the physical world like the humidity or temperature levels. These sensors are typically battery powered and this information can be spread throughout the network.
- The central server (aka end node), H that stores aspects of the mote network state and acts as a proxy to communicate between mote network and client applications.
- A set of client applications, A that interfaces with the host server to communicate with nodes, to manage existing applications or deploy new ones.

We assume that sensors initially interact each other through a standard mesh network that tries to maximize the reliability of the network broadcasting packets to all nodes in order to reach the end node.

A message from a sensor can be captured by all sensors that are into its scope. The server can communicate with sensors within its scope, but client applications only communicate with the server. The size of a message is limited but it can be configured and modified to include or exclude information.

The main goal of this routing proposal is the optimization of the number of messages copies traveling through the network and the improvements of routes in order

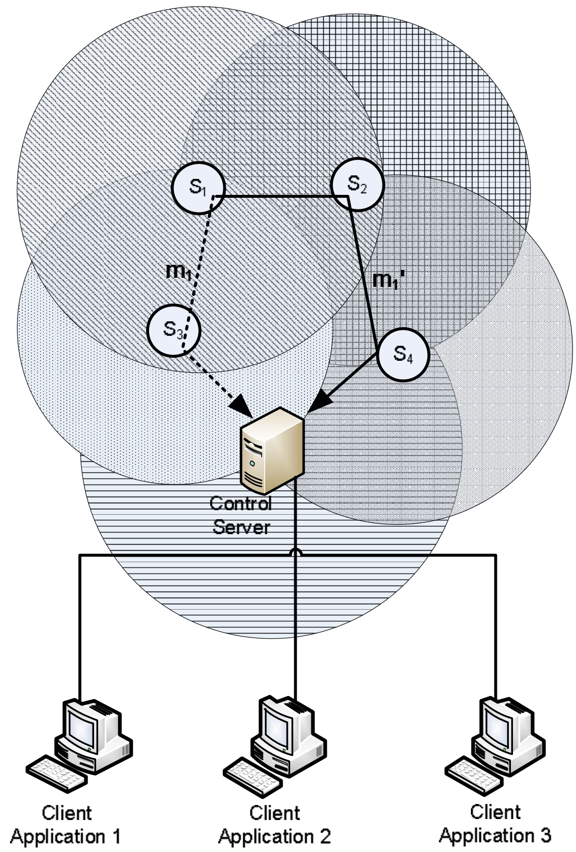

Fig. 1 Representation of typical WSN. A message is sent from S_1 node to H server.

to save batteries in the nodes by a previous training period. This way the H server computes rules for each sensor to determine when is necessary to forward a received message.

When the training-time begins, all the sensors start sending messages to the server. In every message, the description of the route (nodes list, where a message has been routed) is attached to the message. When a message arrives to the H server, the message contains the whole route from the origin sensor to the server H. With this information, the H server can establish some rules to improve the communication between the nodes. This rules are computed by an implementation of the A* algorithm for pathfinding. A* algorithm [12] uses a distance-plus-cost heuristic function $f(x)$ which is a sum of two functions:

- $g(x)$ The path cost function. We assume this function returns the standardized weight (power in watts needed) of the edge between two nodes. This weight is the quantity of power needed to make the transmission between two nodes.
- $h(x)$ The heuristic function. Our solution uses the minus geometric mean of battery levels (in [0-1]) of current path. This way we are taking into account battery levels of a path in order to benefit paths where battery levels of nodes are higher. Notice that geometric mean is used to detect paths where at least one of the nodes has a very low battery level.

Comparing with Dijkstra or others algorithms for pathfinding, A* includes both cost function and heuristic function so it mixes depth-first search and breadth-first search. A* is equals to Dijkstra algorithm if $h(x) = 0$. For example, let's consider two routes R_1 and R_2 of two copies m_1 and $m2$ of the same message respectively:

$$R_1 = [S_1, S_2, S_4, H]$$

$$R_2 = [S_1, S_3, S_4, H]$$

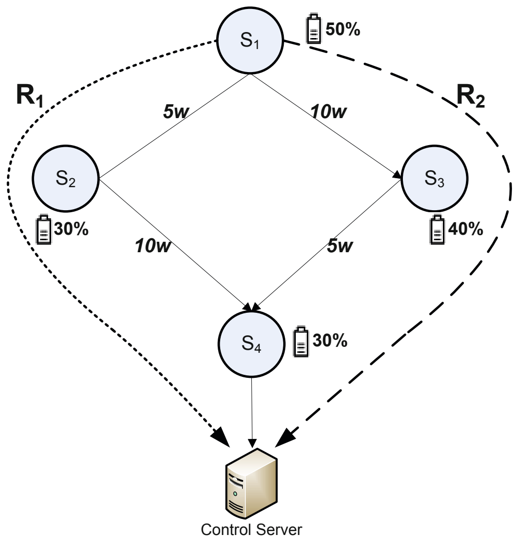

Fig. 2 Case study for 4 nodes and two possible paths

Nodes, routes, costs and battery levels are shown in figure 2. Once the server receives paths, costs and battery levels computes best paths. In the situation shown route R_1 final cost is computed bellow:

$$f(1) = g(1) + h(1) = 0 - 0.5 = -0.5$$
$$f(2) = g(2) + h(2) = 0.5 - \sqrt[2]{0.5 \cdot 0.3} = 0.11$$
$$f(4) = g(4) + h(4) = 1 - \sqrt[3]{0.5 \cdot 0.3 \cdot 0.3} = 0.64$$
$$Cost(R_1) = f(1) + f(2) + f(4) = -0.5 + 0.11 + 0.64 = \mathbf{0.25}$$

And for route R_2:

$$f(1) = g(1) + h(1) = 0 - 0.5 = -0.5$$
$$f(3) = g(3) + h(3) = 1 - \sqrt[2]{0.5 \cdot 0.4} = 0.56$$
$$f(4) = g(4) + h(4) = 0.5 - \sqrt[3]{0.5 \cdot 0.4 \cdot 0.3} = 0.1$$
$$Cost(R_2) = f(1) + f(3) + f(4) = -0.5 + 0.56 + 0.1 = \mathbf{0.16}$$

With these paths, the server can detect that it is not necessary that the S_3 sensor forwards the message m_2 (which is a copy of m_1). Hence, the rule *"Don't forward a message if the previous nodes sequence is* $[S_1]$*"* will be established for the S_3 sensor when the server reconfigure the network. In this manner, the server H continues receiving messages and computing new rules until a time threshold is exceeded. In this case, the nodes stop sending messages to the server and the reconfiguration of the nodes starts. In this stage, the server establishes the computed rules to the nodes and the network starts using this new configuration.

This way we can achieve energy saving by three actions:

- reducing message hops and avoiding copies.
- prioritizing the route where costs are lower.
- balancing load to maximize general battery levels.

Obviously, during the training time, the decrease of the energy consumption is null. However, after this period, the key limitations of WSNs, the storage, power and processing, are treated. The server reconfigures the nodes with the calculated rules and the communication in the network. With this optimization, in the last example the message m_2 will not arrive to server. Hence, duplicated messages in the network are avoided and consequently, the information load in buffers, the time processing and the battery consumption in sensors are reduced and, consequently, the lifetime of the network is increased. Furthermore, by deleting data redundancy and minimizing the number of data transmissions, there is less data load in the network, the possibilities of an overload are lower and the message management is simplified.

```
// Called when the Dispatcher receives a message for this
   protocol.
begin public void stackReceive [Receiver rcvr]
    // Gets the message
    RoutedMsg msg=(RoutedMsg)rcvr.getData();
    // Check hasn't been received already and route is
       allowed
    if (!msg.equals(prevMessage) &&
    !msg.currentRoute.equals(restrictedRoute)) then
        // Adds current sensorId to the route
        msg.currentRoute.addElement(id);
        // Not-relevant operations
        TestReceiver meta=new TestReceiver();
        meta.addMetadata(rcvr);
        meta.data = msg.data;
        // This will forward the received data
        ds.dispatch(meta);
        prevMessage = msg;
    end
end
```

Algorithm 1. Routine running on sensor nodes that checks if message forwarding is needed

As batteries drain the *H* server computes new rules, and periodically, the *H* server reconfigures the routing rules to balance batteries of the whole network. In addition to this reconfiguration if a node stops working due to an attack, the lack of battery or another external factor it will not send any reply. In this case, the *H* server will check affected paths and compute new paths to replace invalid ones.

3 Implementation, Tests and Results

For test purposes we have implemented the routing proposal in Sentilla Work, the IDE supplied with Sentilla Development Kit. The real implementation is an extension of one of the protocols supplied by Sentilla, therefore the algorithm shown it was written in Java.

Results are shown in Table 1 below where the base mesh protocol, the first version of the method called LECOMP-1 [1] and present method LECOMP-2 are compared. Tests have been done at the WSN deployed at Computer and Systems Languages department of the University of Sevilla. It consists on 9 Zigbee sensors deployed in 9 offices. The number of avoided messages in LECOMP-1 and LECOMP-2 is calculated through an approximation between the number the time computed and the duplicated messsages received in the base case. Table 1 shows that in case of LECOMP-1 the sensor network lifetime is 421h and for LECOMP-2 439h. Compared to 360h when no LECOMP is applied this is an improvement of approximately 17% in case LECOMP-1 and 22% of LECOMP-2 in terms of sensor network lifetime. That implies that when LECOMP-1 is used the WSN runs 2,5 days longer and in case of LECOMP-2 over 3 days longer than when no intelligent routing applied. Moreover, we would like to emphasize the improvement of about 7% in avoided messages and 10% in avoided steps in this proposal comparing with the first version of the method. In figure 3, the battery life and the (no-duplicated) received messages

Table 1 Base-Protocol, LECOMP-1 and LECOMP-2 comparison

	Base	LECOMP-1	LECOMP-2
#sensors	9	9	9
timeComputed	360h.	421h.	439h.
#msgsPerHour	30	29.5	29.7
#msgs	10800	12425	13044
trainingTime	0h.	1h.	1h.
#duplicatedmsgs	1944	5	5
avgStepsPerMsg	2,3	2,02	2,12
#msgsReceived	12744	12430	13049
#msgsAvoided	0	2249	2945
%avoidedMsgs	0	**18,1**	**22,5**
#Steps	29311	25524	27933
#StepsAvoided	0	7368	9020
%avoidedSteps	0	**25,1**	**35,9**

in the three cases are compared. Using our method the number of received messages and the lifetime of the WSN increments.

Figure 3 the battery life and the (no-duplicated) received messages in the three cases is compared. Using our method the number of received messages and the lifetime of the WSN increments.

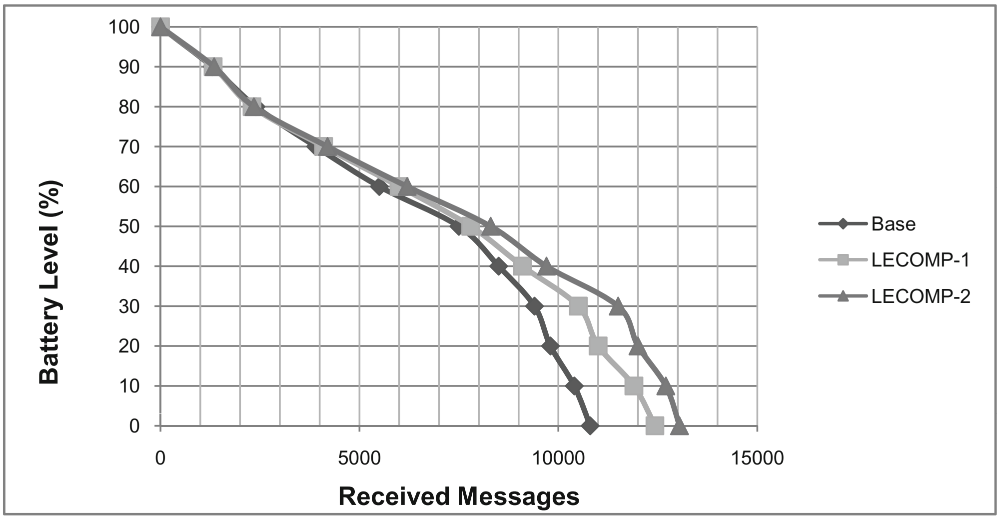

Fig. 3 Comparison Graphic between Base Mesh protocol, LECOMP V1 and LECOMP V2

4 Conclusion

In this paper, we have presented a energy-efficient method for mesh wireless sensor networks. We have got to save up energy by reducing the forwarding of messages. First, the central server determines the rules through the information of the messages routes, the battery levels and the distance between sensors. Second, the network is reconfigured avoiding duplicated messages and balancing the load. The described practical experiences with over Sentilla sensors and Zigbee technology shows an improvement in the WSN lifetime of 22% compared with the base protocol.

Acknowledgements. This research is supported by the MCI I+D project ARTEMISA (TIN2009-14378-C02-01).

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PART IV

Final remarks

CHAPTER 12

CONCLUSIONS AND FUTURE WORK

The law of conservation of energy tells us we can't get something for nothing,

but we refuse to believe it.

Isaac Asimov, 1988

12.1 Conclusions

This thesis focuses on the problem of the growing energy consumption worldwide, which presents major difficulties in the short and medium-term. This obstacle has two bases: on one hand, economic costs of energy, which can prevent companies and populations from developing. On the other hand, it is known that energy sources are limited, and that the current growth of energy consumption remains not sustainable.

Moreover, this work analyzes both energy consumption in Grid-computing and Smart environments, and provides solutions to save the maximum energy. It has been proved that Grid facilities can save up to 40% of energy and that up to 72% of energy in lighting conditioning can be saved by making use of proper policies.

Furthermore, the cost of applying these energy-saving policies is insignificant in comparison to the saving in costs involved with less energy consumption.

Simulation software has been developed in order to compute energy consumption at Grid locations, whereby several energy-saving and aggregation policies have been applied. This tool has been widely tested in order to obtain reliable results, and has been published online through the Idinfor web page, thereby making it available worldwide for researchers interested on these issues.

Finally, the innovation of the thesis is also presented in the use of Data Envelopment Analysis, which is applied in order to compare the efficiency between various Grid-Computing locations. This innovation has proved itself to be a useful tool for Grid-system administrators in the evaluation of efficiency and performance of locations, who in turn recommend actions that should be carried out for the location to become as efficient as the most efficient locations. Location efficiency varies from 57% to 68% in comparison with the most efficient locations (100%). These non-efficient locations are encouraged to decrease their number of resources and increase the number of jobs run.

12.2 Future work

In terms of energy saving in Grid-Computing and Smart Environments, future work will focus on six topics:

- Adapting energy policies to take into account the variety of energy consumption of resources. To date, every resource has been assumed to consume the same amount of energy. However energy consumption may differ from one resource to another. This fact can make slight differences between energy policies and an arranging policy that attempts to maximize the usage of more efficient resources could provide better results.

- Adapting models to issues of data centers. Here, we have provided solutions for Grid-Computing Environments, where jobs are deployed for periods from minutes to hours, and deployed to resources numbering from two to several. Data centers usually process atomic queries by means of a single resource. For example, Google data centers have to process web searches which usually are resolved within one second.

- Creation of new policies. With respect to adapting models to issues of data centers, policies should be adapted to this new model in meeting objectives for the saving of energy. Moreover policies analyzed in this thesis work can also be combined and the results of these combinations can be analyzed. For example, we could establish a new policy combining *Load policy* and *Exponential policy*. In this way, if the current load is low, then *Load policy* would shut resources down, and subsequently *Exponential policy* could be applied in order to decide what to do with the resources.

- Exporting techniques to other supercomputing infrastructures. Since 2009 the *Centro Informático Científico de Andalucía* (CICA) cluster for supercomputing has been logging information about jobs, deployments and usages, and hence we have started to apply these energy-saving policies to simulate this cluster in order to test how much energy could be saved, and to check whether the performances of these policies would present similar behaviour in other supercomputing environments.

- Within the context of Smart Environments, we are planning to share our experience and knowledge with the University of Reutlingen and the HTWG Konstanz in order to build a new model of Smart Environment where biometric information on inhabitants is considered, such as the level of stress.

APPENDIX A

CURRICULUM

A.1 Published papers

During last years, a set of research papers has been developed, within both Grid and Smart Environments and most of them related to energy saving.

[**2007**]**:** During 2007 the research was focused on modeling smart environments and offering applications which make use of the control of these environments. We also applied for a national researching project called InCare to improve services for dependant people.

[**2008**]**:** In 2008, we focused our efforts in the development of National project InCare and Regional project CUBICO. We setup a Smart Environment lab, where we could learn user preferences in terms of comfort and security. We collaborated with University Carlos III de Madrid, where the PhD candidate made an stage for one month, and we published a research paper in common [49] and a book chapter [73].

[**2009**]**:** This year we decided to focus on Saving Energy and Environmental sustainability within the context of Smart Environments. Papers [50, 24] and others presented the results of researching on Smart Environments.

[**2010-2012**]**:** We decided to focus on Saving Energy and Environmental sustainability within the context of Grid-Computing infrastructures for this period. This new approach comes as a result of my stage at Ecole Normale Supérieure de Lyon ENS with Dr. Laurent Lefèvre during 2008 and 2009. This research was developed during these years, but published in 2011 and 2012. These years was also the beginning of a new approach in Smart Environments, energy-saving in WSN, which is shown in Chapter 11.

A.1.1 JCR Indexed Journals

1. Title: **Smart scheduling for saving energy in Grid computing.**

   Authors: **A. Fernández-Montes, L. González-Abril, J. A. Ortega and L. Lefèvre.**

   Published in: **Journal of Expert Systems with Applications**, Elsevier, ISSN: 0957-4174, Date of Publication: August 2012, Volume: 39, Issue: 10, On Pages: 9443-9450, DOI: 10.1016/j.eswa.2012.02.115, **Q1 in three categories. JCR-2011 IF:2.203.**

2. Title: **Evaluating decision-making performance in a Grid-computing environment using DEA.**

   Authors: **A. Fernández-Montes, F. Velasco and J. A. Ortega.**

   Published in: **Journal of Expert Systems with Applications**, Elsevier, ISSN: 0957-4174, Date of Publication: November 2012, Volume: 39, Issue: 15, On Pages: 12061-12070, DOI: 10.1016/j.eswa.2012.04.028, **Q1 in three categories. JCR-2011 IF:2.203.**

3. Title: **A study on saving energy in artificial lighting by making smart use of wireless sensor networks and actuators.**

Authors: **A. Fernández-Montes, L. González-Abril, J. A. Ortega and F. Velasco.**

Published in: **IEEE Network**, ISSN: 0890-8044, Date of Publication: November-December 2009, Volume: 23, Issue: 6, On Pages: 16 - 20, DOI: 10.1109/M-NET.2009.5350348, **Q1 in four categories. JCR-2009 IF:2.148.**

4. Title: **Pervasive Computing Approaches to Environmental Sustainability.**

   Authors: **A. Fernández-Montes.**

   Published in: **IEEE Pervasive Computing**. ISSN:1536-1268, Date of Publication: January-March 2009, Volume: 8, Issue: 1, On Pages: 54-57, DOI: 10.1109/MPRV.2009.14, **Q1 in three categories. JCR-2009 IF: 3.079.**

A.1.2 International Conferences

5. Title: **THE CICA GRID: A Cloud Computing Infrastructure on demand with Open Source Technologies**

   Authors: **M.A. Álvarez, A. Fernández-Montes, J. A. Ortega and L. González-Abril.**

   Published in: **14th International Conference on Enterprise Information Systems (ICEIS 2012)**. Wroclaw, Poland. Springer-Verlag Berlin Heidelberg. Date of Publication: 2012. Pags. Pending.

6. Title: **Lecomp: Low Energy Consumption Mesh Protocol in Wsn. Ambient Intelligence.**

   Authors: **J. A. Ortega, A. Fernández-Montes, D. Fuentes and L. González-Abril.**

   Published in: **Ambient Intelligence - Software and Applications**. Ambient Intelligence and Future Trends-International Symposium on Ambient Intelligence. ISBN 978-3-642-19936-3. Date of Publication: 2011. Volume 92/2011, On Pages: 205-212, DOI: 10.1007/978-3-642-19937-0_26.

7. Title: **Smart Environment Software Reference Architecture.**

   Authors: **A. Fernández-Montes, J. A. Ortega, J.A. Álvarez and L. González-Abril.**

   Published in: **Fifth International Joint Conference on Inc, Ims, and Idc. IEEE Computer Society.** Date of Publication: 2009. On Pages: 397-403, DOI: 10.1109/NCM.2009.115.

8. Title: **Service-oriented device integration for ubiquitous ambient assisted living environments.**

   Authors: **J. Andreu, J. A. Álvarez , A. Fernández-Montes and J. A. Ortega.**

   Published in: **Distributed Computing, Artificial Intelligence, Bioinformatics, Soft Computing, and Ambient Assited Living.** ISBN: 978-3-642-02480-1. Date of publication: 2009. Volume 5518/2009, On Pages: 843-850, DOI: 10.1007/978-3-642-02481-8_128

9. Title: **Smart environment vectorization. An approach to learning of user lighting preferences.**

   Authors: **Alejandro Fernández-Montes, J. A. Ortega Ramirez, L. González-Abril and J. A. Álvarez.**

   Published in: **Knowledge-based Intelligent Information and Engineering Systems.** Lecture Notes In Computer Science. Date of publication: 2008. Volume 5177/2008, On Pages: 765-772, DOI: 10.1007/978-3-540-85563-7_96.

10. Title: **Delivery improvement for transport companies.**

    Authors: **J. A. Álvarez, A. Fernández-Montes, J. Moreno, J. A. Ortega, L. González-Abril and F. Velasco.**

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11. Title: **Development Environment Using FPGA for Domotics Applications Based on X10 Technology.**

    Authors: **M.D. Cruz, J. A. Ortega, A. Barriga and A. Fernández-Montes.**

    Published in: **Novel Algorithms and Techniques in Telecommunications, Automation and Industrial Electronics**, Springer. Date of publication: 2008. On pages: 150-153, DOI: 10.1007/978-1-4020-8737-0_27.

12. Title: **Modeling smart homes for prediction algorithms.**

    Authors: **A. Fernández-Montes, J.A. Álvarez, J. A. Ortega, M.D. Cruz, L. González-Abril and F. Velasco.**

    Published in: **Knowledge-based Intelligent Information and Engineering Systems.** Lecture Notes In Computer Science. Date of publication: 2007, Volume 4693/2007, On Pages: 26-33, DOI: 10.1007/978-3-540-74827-4_4.

13. Title: **An orientation service for dependent people based on an open service architecture.**

    Authors: **A. Fernández-Montes, J. A. Álvarez, J. A. Ortega, N. Martínez Madrid and R. Seepold.**

    Published in: **HCI and Usability for Medicine and Health Care**, Springer. ISSN 0302-9743. Date of publication: 2007. Volume 4799/2007, On pages: 155-164, DOI: 10.1007/978-3-540-76805-0_13.

14. Title: **Extended sensations on interactive telecommunication.**

    Authors: **J. A. Álvarez, J. A. Ortega, A. Fernández-Montes, M. D. Cruz and P. Castilla.**

    Published in: **I International Conference on Ubiquitous Computing.** ISBN: 84-8138-704-5. Date of publication: 2006. Volume 208. DOI: 10.1.1.142.7890.

A.1.3 Book chapters

15. Title: **A home e-health system for dependent people based on OSGi.**

    Authors: **J. Martín, R. Seepold, N. Martínez, J. A. Álvarez , A. Fernández-Montes and J. A. Ortega.**

    Published in: **Lecture Notes in Electrical Engineering Intelligent Technical Systems.** ISBN: 978-1-4020-9823-9. Date of publication: 2009. Volume 38, Part III, On Pages: 117-130, DOI: 10.1007/978-1-4020-9823-9_9.

A.1.4 Other Journals

16. Title: **CUCA Project: Cooperative system of ubiquitous computing in welfare contexts.**

    Authors: **J. A. Álvarez, C. Angulo, J. A. Ortega, M. D. Cruz and A. Fernández-Montes.**

    Published in: **Monet Newsletter.** ISSN: 1464-9276. Date of publications: April 2005. On Page: 22.

A.1.5 National Conferences

17. Title: **Looking for Best Energy Policies to Save Energy in Grid Computing.**

    Authors: **A. Fernández-Montes, L. González-Abril, J. A. Ortega and J.I. Venzalá.**

    Published in: **XIII Jornadas de Arca. Sistemas Cualitativos y sus Aplicaciones en Diagnosis, Robótica e Inteligencia Ambiental.** ISBN: 978-84-615-5513-0. Date of publication: 2011 Num. 13. On Pages: 87-91.

18. Title: **Designing a Software Framework for Smart Environments.**

Authors: **J.I. Venzalá, A. Fernández-Montes, J. A. Ortega and F. Cuberos.**

Published in: **XIII Jornadas de Arca. Sistemas Cualitativos y sus Aplicaciones en Diagnosis, Robótica e Inteligencia Ambiental.** ISBN: 978-84-615-5513-0. Date of publication: 2011 Num. 13. On Pages: 77-80.

19. Title: **Energy-Efficient Routing Approach for Wireless Sensor Networks.**

    Authors: **D. Fuentes, A. Fernández-Montes, J. A. Ortega and L. González-Abril.**

    Published in: **Ubiquitous Compunting & Ambient Intelligence. Congreso Español de Informática CEDI.** ISBN: 978-84-92812-61-5 Date of publication: 2010. Num. 4. Valencia, España. On Pages: 9-12.

20. Title: **Saving Energy in Grid-Computing.**

    Authors: **A. Fernández-Montes, J.I. Venzalá, J. A. Ortega and L. González-Abril.**

    Published in: **XII Jornadas de Arca. Eficiencia Energética y Sostenibilidad en Inteligencia Ambiental.** ISBN: 978-84-614-6457-9. Date of publication: 2010 Num. 12. On Pages: 89-90

21. Title: **A Survey About Ami: Areas, Tasks and Technologies.**

    Authors: **J.I. Venzalá, A. Fernández-Montes, J. A. Ortega and F. Cuberos.**

    Published in: **XII Jornadas de Arca. Eficiencia Energética y Sostenibilidad en Inteligencia Ambiental.** ISBN: 978-84-614-6457-9. Date of publication: 2010 Num. 12. On Pages: 111-117.

22. Title: **Energy-Efficiency in Wireless Sensor Networks using Routing Algorithm.**

Authors: **D. Fuentes, A. Fernández-Montes, J. A. Ortega and L. González-Abril.**

Published in: **XII Jornadas de Arca. Eficiencia Energética y Sostenibilidad en Inteligencia Ambiental.** ISBN: 978-84-614-6457-9. Date of publication: 2010 Num. 12. On Pages: 21-24.

23. Title: **An Approach for Saving Energy in Smart Environments.**

    Authors: **A. Fernández-Montes, L. González-Abril , J. A. Ortega and M.L. Vilchez.**

    Published in: **XI Jornadas de Arca. Sistemas Cualitativos, Diagnosis, Robótica, Sistemas Domóticos y Computación Ubicua.** ISBN: 978-84-613-71-587. Date of publication: 2009. Volume 50. On Pages: 35-38.

24. Title: **Experimental environment to learn user preferences.**

    Authors: **A. Fernández-Montes, J. A. Ortega, J. A. Álvarez and L. González-Abril.**

    Published in: **X Jornadas de Trabajo de Arca. Sistemas Cualitativos y Diagnosis.** ISBN: 978-84-89315-54-9. Date of publication: 2008. On Pages: 49-53.

25. Title: **A Location of Robots Proposal in Collaborative Environments.**
    Authors: **M.A. Álvarez, A. Fernández-Montes, J. A. Ortega and Jesús Torres.**

    Published in: **X Jornadas de Trabajo de Arca. Sistemas Cualitativos y Diagnosis.** ISBN: 978-84-89315-54-9. Date of publication: 2008. On Pages: 40-43.

26. Title: **An approximation to the features of smart prediction algorithms.**

    Authors: **A. Fernández-Montes, J.A. Álvarez, J. A. Ortega, L. González-Abril, F. Velasco and J. Torres.**

Published in: **IX Jornadas de Arca. Sistemas Cualitativos y Diagnosis.** ISBN: 978-84-8458-231. Date of publication: 2007. On Pages: 65-70.

27. Title: **Domoweb: pasarelas residenciales, estudio práctico. Sesión de demostración:**

    Authors: **A. Fernández-Montes, M.D. Cruz, J. A. Ortega and J.A. Álvarez.**

    Published in: **VIII Jornadas de Arca. Sistemas Cualitativos y Diagnosis.** ISBN: 84-611-1401-9. Date of publication: 2006. On Page: 87.

28. Title: **Experiencias en entornos de computación ubicua mediante arquitecturas orientadas a servicios.**

    Authors: **J. A. Álvarez, M.D. Cruz, A. Fernández-Montes, J. A. Ortega and J. Torres.**

    Published in: **Jornadas Científico-Técnicas de Servicios Web, JSWEB (W3C). Congreso Español de Informática (CEDI).** ISBN: 84-9732-455-2. Date of publication: 2005. On Pages: 167-174.

29. Title: **Soluciones a problemas de comunicación e interacción en entornos de computación ubicua con OSGi.**

    Authors: **J. A. Álvarez, J. A. Ortega, A. Fernández-Montes and M.D. Cruz.**

    Published in: **I Simposio de Computación Ubicua e Inteligencia Ambiental, UCAmI. Congreso Español de Informática (CEDI).** ISBN: 84-9732-442-0. Date of publication: 2005. On Pages: 279-284.

30. Title: **Innovando Hacia un Entorno Educativo Global: del Elearning al Mlearning.**

    Authors: **J. A. Ortega, J. Torres, J. A. Álvarez, A. Fernández-Montes and M.D. Cruz.**

Published in: **Actas de las III Jornadas de Calidad de los Servicios Educativos y de Formacion.** ISBN: 84-86849-33-0. Date of publication: 2005. On Pages: 159-169.

31. Title: **Aplicando el razonamiento cualitativo al hogar digital.**

    Authors: **J. A. Álvarez, J. A. Ortega, J. Torres, A. Fernández-Montes, M. D. Cruz, C. Angulo and F. Velasco**

    Published in: **VII Jornadas de trabajo ARCA.** ISBN: 84-689-3357-0. Date of Publication: 2005. On Pages: 47-52.

A.2 Patents

32. Title: **Sci (Simple Cluster Interface).**

    Authors: **J. A. Ortega, L. González-Abril, J. A. Álvarez, M.A. Álvarez, D. Fuentes, A. Fernández-Montes, J. Cantón, A. Silva, D. Bosque, F. Velasco, J. Torres, M.J. Escalona and L. Soria.**

    Reference: **Request:2010-10-22, Nr.:P1001371**.

33. Title: **Dilos: Dispositivo de Localización y Seguimiento Energéticamente Eficiente.**

    Authors: **L. Soria, M.A. Álvarez, J. A. Álvarez, A. Bellido, D. Fuentes, A. Fernández-Montes, L. González-Abril, J. A. Ortega, F. Velasco, J. Torres and J.I. Venzalá.**

    Reference: **Request:2010-03-22, Nr.:P201000969**, International Application Number: PCT/ES2011/000237. Publication Number: WO/2012/010727.

A.3 Awards

During years 2005 and 2006 the project called Domoweb was developed. Domoweb was my final project to obtain the degree of *Ingeniero en Informática*. Awarded with the **first prize of final projects**, given by Fidetia, selected from best projects developed in the *Escuela Técnica Superior de Ingeniería Informática* for last two years (2005-2006).

A.4 R&D projects

This thesis dissertation has been developed within the framework of the following research projects:

- Title: **Simon. Saving Energy by Intelligent Monitoring (TIC-8052)**.

  Main researcher: **Juan Antonio Ortega Ramírez.**

  Granting Entity: **Consejería de Economía, Innovación y Ciencia.**

  Period: 2012 – 2014**.**

  Reference: **TIC-8052.**

- Title: **Arquitectura para la eficiencia energética y sostenibilidad en entornos residenciales** .

  Main researcher: **Juan Antonio Ortega Ramírez.**

  Granting Entity: **Ministerio de Ciencia e Innovación.**

  Period: **2009-2012.**

  Reference: **TIN2009-14378-C02-01.**

- Title: **Sistema de cuidados ubicuos y asistencia controlado por familiares y centros médicos para personas con dependencias - CUBICO**.

  Main researcher: **Juan Antonio Ortega Ramírez.**

  Granting Entity: **Junta de Andalucía.**

  Period: **2007-2010.**

  Reference: **P06-TIC-02141.**

- Title: **InCare: Plataforma abierta para la integración en el hogar de servicios cooperativos de teleasistencia y telemedicina** .

  Main researcher: **Ralf Seepold.**

  Granting Entity: **Ministerio de Educación y Ciencia.**

  Period: **2007-2009.**

  Reference: **TSI2006-13390-C02-02.**

- Title: **E-TAO: Sistema de telemedicina asíncrona basado en estándares médicos para control de pacientes que siguen la terapia de anticoagulante oral.**

  Main researcher: **Francisco José Moriana Garia.**

  Granting Entity: **Junta de Andalucía.**

  Period: **2006.**

  Reference: **PRO-081.**

- Title: **Navegación e Interacción con el Usuario en el Desarrollo de Sistemas de Información Web: Métodos, Técnicas y Herramientas.**

  Main researcher: **Jesús Torres Valderrama.**

  Granting Entity: **Ministerio de Ciencia y Tecnología y fondos FEDER.**

  Period: **2003-2006.**

  Reference: **TIC 2003-369.**

- Title: **DOMOWEB: metodologías para el diseño y desarrollo de sistemas domóticos controlados vía Web.**

  Main researcher: **Juan Antonio Ortega Ramírez.**

  Granting Entity: **Junta de Andalucía.**

  Period: **2003-2005.**

  Reference: **SC/AT/0108/2003.**

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