Rule-based Approaches for Energy Savings in an Ambient Intelligence Environment

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Abstract. This paper presents a real-world application targeting energy savings and user comfort in a Smart Building environment. The proposed system uses various heterogeneous networks of wireless sensors and actuators, while all functions and data are unified under a Semantic Web Service middleware. An initial approach to author and enforce energy-saving policies was to develop a reactive agent that maintains an internal representation of the world's state in the form of predicates and facts, gathered over the Web Service interface. System administrators are able to encode the policies, the effects of which are applied by invoking actuator Web Services. In order to improve the system even further, the proposed architecture also incorporates a deliberative agent based on defeasible logic that allows for more human-intuitive and effective management of policies. The application of defeasible reasoning is ideal in such environments with incomplete and contradictory information, offering more flexible expressiveness as well as a sophisticated conflict resolution mechanism. In our approach, the latter is used for defining three clusters of rules for preferences, maintenance and emergencies, respectively. After observing the building's yearly energy consumption and usage patterns, a policy was authored and applied, showing promising results (at least 10kWh or 2% to 4% daily savings in this specific setting). Although the percentage of energy savings may seem low, the greatest merit of this method is ensuring no energy is wasted by constantly enforcing the policies.

Keywords: defeasible logic, smart building, energy savings, ambient intelligence, semantic web services

1. Introduction

Contemporary information systems are rapidly undergoing various transformations, influenced by a multitude of emerging trends. One of these trends is *Green Computing* and the rise of the *Smart Grid*. Global warming, CO_2 emissions and energy waste have directed computing towards greener solutions at the hardware and software levels alike. At the same time, renewable energy sources and consumer-produced energy schemes have brought about the idea of the Smart Grid, an infrastructure for encouraging policies and means towards marketing and distribution of energy between producers, consumers, "prosumers" (i.e. producers and consumers) and brokers [Farhangi, 2010]. Overall, the concepts of sustainability and energy saving have penetrated all aspects of everyday life, including computing.

In the meantime, evolvements in microcontrollers, board computers and smartphones in particular, bring forward a novel computing paradigm, called *ubiquitous computing* (*ubiComp*), where users are being surrounded by powerful, portable computing devices [Weiser, 1993]. To take things a bit further, in *pervasive computing* (*perComp*), multiple non-intrusive computing devices are scattered across the environment, attracting far less or none of the user's attention. The vision of *Ambient Intelligence* (*AmI*) enriches perComp with *Artificial Intelligence* (*AI*) methodologies, aiming at increasing comfort and reducing intrusiveness for the user [Weiser, 1993]. Towards this affair, intelligent behaviors, deriving from various areas of AI such as Planning, Semantics, Reasoning and Learning, are typically employed for providing smart automations and intuitive human-computer interactions in such suitable environments.

Unsurprisingly, AmI is heavily based on the widespread usage, performance and affordability of microcontrollers and wireless sensors that form networks, providing the essential environmental input data required by AI algorithms. Likewise, actions to be performed after the decision making process have to go through actuators in the environment in the form of motors, switches or other endpoints. Since both Green Computing and AmI are facilitated by the increased popularity and low cost of smart meters, environmental sensors, actuators and other devices, these features constitute the common grounds among the two disciplines. Also, both fields share similar goals, i.e. the vision of a comfortable smart home.

However, the interaction of Smart Homes and AmI applications with hardware devices poses a substantial challenge, since the hardware market itself is highly diverse with different companies using different communication protocols and data formats. Towards this affair, the solution of *Service Oriented Architecture* (*SOA*) has been proposed [Papazoglou, 2003]. Since broadband connections have become a modern day standard, users have already moved on from looking up data on web sites to actually carrying out tasks from purchases and transactions to virtually any remote function. These remote procedure calls are supported by W3C-recommended APIs, called *Web Services*, while the *Web Service Description Language*[1] (*WSDL*) provides remote clients with syntactic interoperability, by type-defining service inputs and outputs. Understandably, Web Services in AmI environments have since grown to become a requirement, as they provide the necessary abstractions that allow for high-level programming and deliver a universal, unified middleware for using heterogeneous hardware. In addition, *dynamic service discovery* perfectly suits the dynamicity of ambient environments, where service consumers and portable providers spontaneously interleave the space.

Although AmI domains of application may vary widely, targeting energy savings has yet been only marginally explored. Most approaches focus on multimedia technologies, providing context awareness in smart homes or offices, e.g. being able to stream source audio or video to target outputs over UPnP/DLNA based on context, such as [Davidyuk et al. 2010]. Existing service-oriented approaches in conjunction with smart home equipment have not practically considered intelligence or savings, but rather the issue of communication protocol unification [Bottaro et al. 2008]. Multi-agent systems have been employed to provide enhanced functionality or service composition, but certain issues on truly interoperable semantic descriptions still persist [Vallée et al. 2008]. A categorization of AmI application domains in Smart Homes, Health, Transportation, Emergency, Education and Workplace, can be found in [Cook 2009].

This work presents a holistic approach to energy savings in a smart building belonging to a State University complex. The proposed approach lies in the intersection of many disciplines (AmI, Automated Reasoning, Semantic Web Services and Green Computing), facing challenges in each of the corresponding fields. According to principles of Smart Homes and Green Computing, a set of state-of-the-art wireless sensors, actuators and smart meters has been deployed at the University premises. The distributed heterogeneous data and functions they provide have been unified under a middleware based on Web Services. The middleware also complies with some of the latest Semantic Web [Berners-Lee et al., 2001] technologies to provide semantic interoperability on the application layer. Towards achieving energy savings, two approaches based on rule-based expert systems are proposed. Firstly, using production rules, domain experts are able to commit energy-saving policies maintained and applied by an autonomous reactive software agent. The second approach is based on a deliberative agent that incorporates a defeasible logic reasoner instead, greatly enhancing the expressiveness of the rule set committed by the expert. The application of defeasible reasoning [Nute, 1994] is ideal in such environments with incomplete and contradictory information, offering a sophisticated conflict resolution mechanism. In our approach, the latter is used for defining three clusters of rules for preferences, maintenance and emergencies, respectively. Using the underlying infrastructure, the University's yearly consumption has been observed to identify energy behavioral patterns. Consequently, energy-saving and comfort-providing policies have been authored accordingly and applied, showing promising results. All in all, savings are not directly visible in such a large infrastructure, but the policies do ensure that no energy is wasted in any undesired manner.

In the rest of this paper, the next section performs a thorough survey of state-of-the-art in the fields of AmI context-aware applications and also studies the (so far) limited application of defeasible reasoning in AmI environments. Section 3 presents the basic principles of defeasible logics, its main characteristics, its syntax and operational semantics as well as the motivation for applying defeasible reasoning in AmI and Smart Building management. The next section presents the architecture of the proposed system in three parts: the hardware, middleware and application layer. The two proposed software agents that reside on the application layer are presented subsequently, followed by a use case real-world application scenario, a proposed policy and its results in energy savings. Future work and conclusions are listed in the final sections.

2. Related Work

The proposed system is built on a synergy of fields such as Ambient Intelligence, Smart Homes, Context-aware Systems, Green Computing, Semantics and Logic. Thus, this section attempts to present the most relevant of existing state-of-the-art, originating from any of the above viewpoints. It also tries to appoint the novelty of the proposed system to each respective work coming from one or more fields.

[1] The Web Service Description Language - http://www.w3.org/TR/wsdl

2.1. Rule-based Context-aware Systems in AmI

A common task amongst many AmI systems is to address context awareness, by providing automatic service composition on demand. A thorough survey of such work can be found in [Stavropoulos et al., 2011]. However, we believe the policy definition process to be more fundamental. Automatic service composition offers the means to achieve a certain goal, but it does not define the goal itself or when to execute this series of actions. Hence, rules and triggers must come prior to composition, leaving the latter outside the scope of this work. Agents in state-of-the-art approaches many times constitute tools for the Web Service composition process itself, while in this work agents are self-contained entities that perceive and manage the environment.

On the other hand, certain paradigms of related work indeed address context-awareness by following rule-based methodologies, with the work by [Daniele et al., 2007] being a representative example. The authors have developed the *Event-Control-Action* (*ECA*) model, an architectural pattern for expressing context-awareness. According to this model, an "Event Module" is responsible for gathering context information, i.e. facts, a "Control Module" formulates rules about these facts and an "Action Module" executes the activated rules. To properly author ECA-rules, the proposed ECA domain language, *ECA-DL* [Etter et al., 2006] offers expressiveness (via the use of logical and arithmetical operands) and extensibility. To realize this higher level of expressing context information, ECA-DL integrates a UML-based representation model that defines a hierarchy of entities and relationships among them. ECA-DL rules assimilate to SQL, as they contain predicates for querying the taxonomy. The Java-based *JESS*[2] reasoner was chosen as the proper execution engine for the framework and the authors proposed a mapping from ECA to the JESS syntax. There is a direct analogy between the two architectures: instances of context-information in ECA correspond to facts in the working memory of JESS, while ECA-DL rules directly correspond to JESS defrules. Additionally, the hierarchy and relationships between instances defined in the ECA model can be expressed in deftemplates, JESS structures for describing complex facts.

In comparison to our Smart IHU system, the ECA model can be seen as an optional rule authoring meta-level. Both works address the concepts of context-awareness and, more generally, ubiquitous and pervasive computing. However, our proposed system focuses on energy savings and builds upon an AmI infrastructure of sensors, actuators and Semantic Web Services, while ECA-DL has not been deployed in such a practical manner. Additionally, the meta-level of ECA rule representation is considered rather redundant, since the JESS language itself provides sufficient expressiveness and extensibility. Moreover, ECA's representation model is fairly inferior to an ontology, which already provides querying mechanisms and significantly higher expressiveness. Instead of applying a UML-based model, our approach refers to our representation model, which is an OWL ontology, via semantic annotations on Web Service descriptions. Hence, instead of building a heterogeneous system that maps rules to ontological constructs, ontological entities are inserted into rules on-the-fly using *SAWSDL* [Kopecky et al., 2007]. Finally, both works use JESS as an execution engine, but, our approach offers higher expressiveness, integrating defeasible logic as well as the corresponding defeasible reasoner SPINdle (see Section 4.4.2).

Work by [Yang, 2013] employs a case-based reasoning (CBR) agent, Web Services and ontologies towards achieving energy savings. The CBR agent is placed within a multi-agent platform, along with a second agent responsible for data mining and a third for invoking Web Services. The complete system is installed over cloud services to enable remote reasoning. Data regarding temperature, humidity, luminance, CO_2 levels and consumption are collected over Web Services, parsed and placed within a domain ontology for energy. The sensor deployment for data collection contains three ZigBee networks of forty devices in total. Then, each data instance is reasoned upon, to investigate similarities with previously known cases. Evaluations show that the architecture can effectively assimilate around 40% of cases, which then do not need to be handled by the backend server. The authors also argue that an energy saving percentage of approximately 22% is achieved.

Our proposed system demonstrates many similarities with the work by [Yang, 2013], but also numerous key differences. Both approaches deploy large wireless sensor networks that measure environmental values and energy consumption. Also both lines of work employ one or more agents capable of reasoning based on different logics, in order to achieve energy savings. Finally, both approaches employ the use of Web Services and SOA standards (WSDL/SOAP). On the other hand, our proposed deployment is technically far more heterogeneous, containing ZigBee as well as Z-Wave and RF (and potentially any other) communication protocols. These protocols are unified under the Web Service middleware, which is the main role of services in this work, placing it in an AmI ecosystem, where other applications also coexist. For the same interoperability purposes, semantics are defining service operations instead of data. On the other hand, Yang employs Web Services to basically perform remote procedures, such as transforming syntactical data to semantic constructs and storing them. In other words, the main

[2] JESS rule engine: http://www.jessrules.com/jess/index.shtml

purpose of Web Services in Yang's system is operating it over the cloud. As far as this work is concerned, the use of cloud services is merely a technical matter that resolves computing and storage resource issues, which in our case are irrelevant; outsourcing computation over the cloud makes no alteration to the actual methodologies used, but rather to where resources are located.

Moreover, in Yang's approach it is unclear how decisions are applied to achieve energy savings and it is equally unclear how these energy savings are measured. We argue that savings should be measured relatively to carefully selected periods of time, since consumption is very context-sensitive especially in large-scale. Major fluctuations occur between different seasons, times of day and daily events. We state the energy saving percentage compared to a daily average of yearly consumption and have determined exactly where these savings come from to make sure it's not incidental. Secondly, the proposed system guarantees that, given the policies, a variable degree of savings can be achieved by prohibiting unnecessary devices from turning on. The lower bound of the saving is achieved when the building already presents an energy-efficient behavior (minimum saving margin) and its upper bound is achieved when the building presents its maximum energy-wasting behavior (maximum saving margin).

Another analogous project, called *SESAME-S* [Fensel et al., 2013], also presents many similarities to the presented work. SESAME-S is a partially commercial and partially research project with deliverables aiming at an all-in-a-box smart home platform for individuals. The system architecture revolves around a microcontroller that interfaces between wired smart devices, sensors and actuators and user endpoints. Deployed sensors measure temperature, humidity, luminance and energy consumption, while actuators control heating, cooling, water supply and power. Live data is collected over the LAN's router and propagated over Ethernet or Wi-Fi to local and remote terminals, where it is stored in an *OWLIM* repository [Kiryakov et al., 2005] in the form of RDF triples. Additionally, the system stores policies in the form of SWRL and SQWRL rules, performs reasoning and executes them using JESS. Rules are committed through a Web application, by both home and power users. Home users are able to enter any rule or choose from recommended rules (pre-built by domain-experts, based on past test-bed experiments). Power users, i.e. administrators and domain-experts, are able to view the raw, semantic rule format and the rules they insert have a higher significance. Hence, they are executed after any home automation rules, in order to enforce the desired final state of appliances. To support the above mentioned functionality, SESAME-S entails the use of three custom ontologies: (a) the *Automation Ontology* models policies, activities, appliances, sensors, locations and thresholds, (b) the *Meter Data Ontology* publishes meter data in compliance to the DLMS/COSEM specification, and, (c) the *Pricing Ontology* models usage tariffs and selection criteria for the system to allocate appliances to proper time slots, in the spirit of Smart Grids. The final test-bed embeds all hardware in a metal suitcase and has experimentally been used in a few buildings. Finally, it has been estimated that the adoption of such a system may lead to approx. 20% reduction in energy consumption.

In contrast to SESAME-S, our work presents many developments on all levels. At the infrastructure level, the Smart IHU architecture supports many wireless device platforms, unified under the aWESoME web service middleware [Stavropoulos et al., 2013], like Plugwise, Prisma sensor boards, CurrentCost and various other manufacturers under the Z-Wave alliance (see Section 4.2 for more information on these). Additionally, due to the nature of the semantic service infrastructure, devices can be scattered across buildings, allowing a wide and fully distributed deployment, instead of embedding everything in a box. Another major difference is the lack of storing all data in an ontology for reasoning. Instead, Smart IHU attaches semantics to Web Services using the SAWSDL standard. Hence, any Web client, human or machine is allowed access to the semantics of sensor data and actuator functions. Furthermore, the use of defeasible reasoning in the Smart IHU approach allows for more user-intuitive design of rules and an inherent prioritization and conflict resolution between them. This method avoids the "brute-force" application of all rules in order of priority that occurs in SESAME-S, improving the user experience and saving computing resources. Finally, due to the experimental and constrained current format of SESAME-S, results of energy savings constitute merely user predictions, while the Smart IHU platform already presents actual savings on its large-scale building-wide deployment.

A final observation in context-aware AmI systems is the different methodologies on defining and exploiting semantics. The majority of work had previously been focused on complex top-down approaches such as OWL-S and WSMO, extending an ontology for describing a service. The most recent tendency is to switch to lightweight bottom-up approaches such as SAWSDL and WSMO-Lite. Similarly to top-down approaches, convergence of various standards has not yet been realized. However, SAWSDL is recommended by W3C, and offers many advantages. It lies very closely to WSDL, which is a functional API, very popular among research and industry. Additionally, it has been found adequate to serve as a basis for selection, matching, discovery and composition of services, despite its low complexity [Hobold & Siqueira, 2012]. Consequently, the proposed system makes use of the SAWSDL standard to define and exploit semantic interoperability on services.

2.2. Defeasible Logic in AmI

To the best of our knowledge, only the work by [Bikakis et al., 2011] investigates the deployment of defeasible logics in an AmI setting. In their work, the authors propose a distributed reasoning approach based on the representation of context knowledge shared by the ambient agents in the environment. Taking into consideration the highly dynamic nature of the setting, defeasible logic is proposed as the basis for representing the context knowledge possessed by each agent (i.e. the agent's local rule base). Additionally, defeasible logic is also applied for resolving the potential conflicts that arise from the information exchange between the agents. More specifically, the authors introduce an extension to defeasible logics, called *Contextual Defeasible Logic* (*CDL*) [Bikakis & Antoniou, 2010]. The latter serves as a contextual reasoning model that leverages the challenges posed by the dynamic nature of the AmI environment using the concepts of context, mappings and contextual preferences. Compared to the work presented above, our proposed Smart IHU approach demonstrates apparent similarities: both approaches are designed for AmI environments and both of them apply defeasible reasoning in real-life, practical applications.

On the other hand, the different application domains (ambient-assisted living vs. energy consumption monitoring) constitute a secondary difference, whilst the most important distinction lies in the diverse areas – within each system – where defeasible reasoning is applied. More specifically, the work by [Bikakis et al., 2011] applies defeasible logics as a means for assisting the (often problematic) communication between heterogeneous devices within the environment. Contrasted, our approach investigates the application of this type of non-monotonic logics as a tool for supporting the end-user in representing his/her energy management scheme more effectively and improving the expressiveness of the authored policies. Finally, the Smart IHU approach follows a centralized architecture, where a central server is responsible for collecting the data from the sensor network and for performing the reasoning. The other piece of work represents a fully distributed architecture, arguing that such a model better suits environments, where context changes may be frequent, device connection can prove troublesome and wireless communications are unreliable and restricted by the range of the transmitters.

3. Defeasible Logics

This section describes the basic characteristics of defeasible logic, its syntax and operational semantics as well as the underlying motivation for applying defeasible reasoning in the context of Ambient Intelligence and Smart Building management.

3.1. Main Characteristics

Defeasible logics [Nute, 1994] stem from research in knowledge representation and inheritance networks in particular. In this context, defeasible logics can be seen as inheritance networks, expressed in a logical rule language.

Belonging to the family of non-monotonic logics, defeasible logics deal with conflicts and inconsistencies among knowledge items. Conflicts between rules are triggered by a conflict among their conclusions. The simplest case is that one conclusion is the negation of the other. However, more complex cases may arise, when conclusions are declared as *mutually exclusive*, a very convenient representation feature in practical applications that will be further examined later on.

Defeasible logics are sceptical in the sense that conflicting rules do not fire, preserving the consistency of the drawn conclusions [Antoniou et al., 1999]. Conflicts among rules are typically resolved via rule priorities, which constitute an additional representational feature of defeasible logics.

The main advantage of defeasible logics is their low computational complexity [Maher, 2001], which is achieved through:

- the local nature of conflicts;
- the fact that the logics are sceptical, as mentioned above;
- the absence of disjunction;
- the use of unidirectional rules;
- the local nature of priorities – only priorities between conflicting rules are used.

Undoubtedly, these restrictions come at the price of reduced expressive power, compared to other non-monotonic reasoning approaches. However, despite its conceptual simplicity, defeasible logic appears effective in the representation and execution of a variety of practical problems, like, e.g. recommender systems [Chesñevar & Maguitman, 2004], UAV navigation [Lam & Governatori, 2011] and elevator control [Covington, 2000b].

3.2. The Language

A knowledge base in defeasible logic is called a *defeasible theory* (let's represent it by $\mathcal{D}$) and consists of three basic elements: a set of *facts* ($\mathcal{F}$), a set of *rules* ($\mathcal{R}$) and a *superiority relationship* (>). Therefore, $\mathcal{D}$ can be represented by the triple ($\mathcal{F}$, $\mathcal{R}$, >).

In defeasible logic, there are three distinct types of rules: *strict rules*, *defeasible rules* and *defeaters*.

- *Strict rules* are denoted by $A \rightarrow p$ and are interpreted in the typical sense: whenever the premises are indisputable, then so is the conclusion. An example of a strict rule is: r_1: `summerTime` → `tempHigh` ("*the temperature is high during the summer time*").
- *Defeasible rules* are denoted by $A \Rightarrow p$ and, contrary to strict rules, they can be defeated by contrary evidence. Two defeater examples are: r_2: `tempHigh` ⇒ `switchOnCooler` ("*the cooler is typically turned on when the temperature is high*") and r_3: `highConsumption` ⇒ ¬`switchOnCooler` ("*the cooler should not be turned on whenever there is high energy consumption*").
- *Defeaters* are denoted by $A \rightsquigarrow p$ and their peculiarity is that they do not actively support conclusions, but can only prevent deriving some of them. In other words, they are used to defeat respective defeasible conclusions, by producing evidence to the contrary. A defeater example is: r_2': `isOnCooler` ⇝ ¬`switchOnCooler` ("*when the cooler is on, there is no need to turn it on again*"), which can defeat e.g. rule r_2 mentioned previously.

The *superiority relationship* is used for resolving conflicts among rules belonging to the rule set $\mathcal{R}$. For example, given the defeasible rules r_2 and r_3 above, no conclusive decision can be made about whether the cooler should be turned on or not. But, if the superiority relationship $r_3 > r_2$ is introduced, then r_3 overrides r_2 and we can eventually conclude that the cooler will not be turned on. In this case rule r_3 is called *superior* to r_2 and r_2 *inferior* to r_3. Note that the relation > on $\mathcal{R}$ is acyclic, meaning that the transitive closure of > is irreflexive.

Finally, another important element of defeasible reasoning is the notion of *conflicting literals* [Billington, 1997], a feature that plays a significant role in our framework as well. $\mathcal{C}$ is defined as a set of conflicting literals if-f at most one literal of the set should be derived each time. Obviously, if *p* is a proposition then {*p*, ¬*p*} is such a set of conflicting literals. However, in real-life applications there are various other kinds of sets of conflicting literals, which cannot be represented merely by a proposition and its negation. Such an example might be the distinct values a variable could take, like, e.g. {*on*, *off*}, {*hot*, *warm*, *cold*} or {*high*, *medium*, *low*}. Whenever there are three or more values, representation by just propositions and their negations becomes impractical and counterintuitive. Thus, a sample conflicting literal set might be:

$$\mathcal{C} = \{\texttt{switchOnCooler}, \texttt{switchOffCooler}\}$$

According to set $\mathcal{C}$ above, the following two rules will produce a conflict, which is resolved via the superiority relationship $r_4 > r_2$ and, thus, the conclusion of the latter rule will override the conclusion of the former one.

r_2: `tempHigh` ⇒ `switchOnCooler` ("*the cooler is typically turned on when the temperature is high*")

r_4: ¬`motion` ⇒ `switchOffCooler` ("*the cooler should be turned off if there is no motion inside the room*")

3.3. Motivation for using Defeasible Logics

Besides its evident advantage of low computational complexity (see Section 3.1), the motivation behind applying defeasible logic instead of classical logic involves certain additional incentives. Firstly, classical reasoning approaches, like e.g. First Order Logic, are based on the assumption of perfect knowledge of the environment, which is very difficult, if not impossible, to achieve in AmI settings. Reasoning with incomplete information regarding the context is significantly more convenient with non-monotonic approaches [Moawad et al., 2013].

Additionally, defeasible logic is much closer to human reasoning and is, therefore, more intuitive. The use of classical logic would require that the truth status of all pieces of information is known, before commencing the reasoning process. But, as human knowledge is quite often incomplete or even contradicting, this requirement cannot be always satisfied. Defeasible logic introduces non-monotonicity, which leads to a more intuitive type of reasoning, where the emergence of new information can lead to abandoning (i.e. defeating) previously established conclusions and adopting new ones.

A further motivating factor for using defeasible logic is the conciseness of its representation. Defeasible logic does not promise to do more than other logics, but, instead, as Covington puts it "[...] *the difference is in how it does it*" [Covington, 2000]. Consequently, while classical logic would probably need extensive representations for expressing all possible exceptions to a rule, defeasible logic can simply add a more specific rule that overrides the former rule and expresses exactly the same information.

4. Implementation

The framework proposed in this work is applied at a Greek State University, namely Building A of the International Hellenic University (IHU). The rule-based system is a component of a wider AmI system, aimed to provide automations, comfort and savings, named the Smart IHU project[3]. This section presents the overall architecture of the proposed system within Smart IHU and describes each of its components in detail.

4.1. Architecture

The generic architecture of the Smart IHU environment follows a three-layer approach (see Figure 1). The bottom layer hosts the hardware, namely, the wireless sensor and actuator networks deployed within the University building. A service-oriented middleware in the middle layer is responsible for handling the platform and data heterogeneity present at the hardware layer. The devices are also distributed in the environment, so that each cluster of co-located devices is allocated to a server running an instance of the Web Service middleware. Finally, client applications can receive data and operate on the infrastructure via one or more instances of the middleware on various servers. Applications provide a graphical interface to communicate with human users when necessary. Services additionally provide semantically annotated interfaces and a broker for effective and automatic discovery.

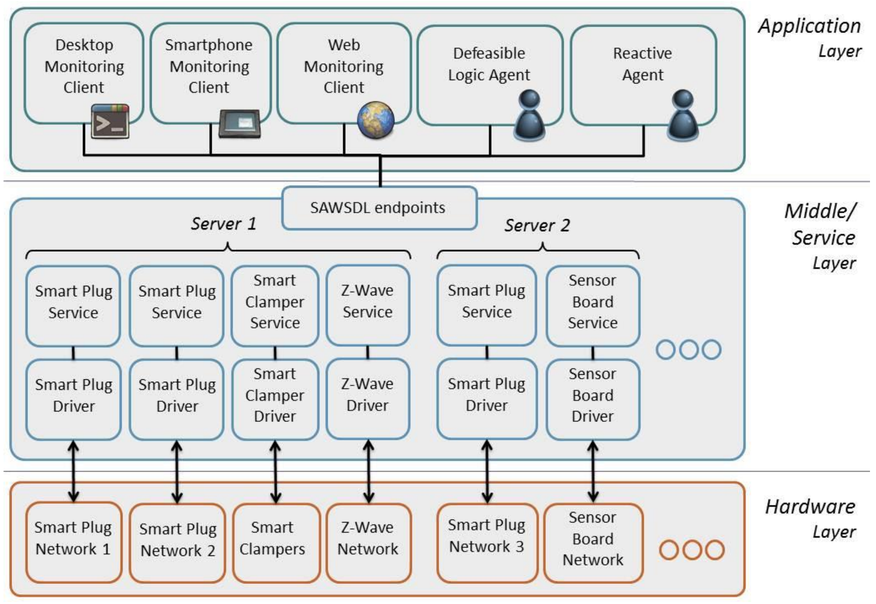


Figure 1. The Smart IHU overall architecture, showing two server instances and all applications.

In the specific case of rule-based systems introduced in this work, the application layer hosts intelligent agents that automatically monitor and manage the infrastructure (see Section 4.4). Each agent integrates a knowledge base and a reasoning engine. The knowledge base is filled with facts about the world, i.e. measured values of the environment, but also contains policies in the form of rules, entered by expert human users. After collecting the facts at each cycle, the agent performs reasoning on the policies, in order to decide on a proper set of actions. The agents are also accompanied by a graphical user interface (GUI).

4.2. Hardware Layer – Deployment of Wireless Sensors and Actuators

The hardware layer of the proposed system hosts mainly a wide range of sensors for perceiving and actuators for manipulating the environment. A first requirement for selecting a set of sensors was to examine which parameters would be suitable for composing and enforcing decision-making policies. Such parameters should include

[3] The Smart IHU Project : http://rad.ihu.edu.gr/smartihu/

environmental qualities, power measurements and user-activity metrics. Additionally, the target large-scale deployment calls for devices that can form wireless networks of sufficient range and are affordable in large quantities. Consequently, a further substantial requirement was to build the platform over devices that are inexpensive and widely-available in the market.

The set of chosen devices is believed to satisfy the trade-off between cost and efficiency. The first set of deployed devices is a sensor/actuator network, referred to as *Smart Plugs*[4]. Each Smart Plug is plugged between a wall socket and any electronic appliance and can measure its power consumption, return its power state (on or off) and switch it on or off. A special kind of Smart Plugs, intended for non-pluggable appliances e.g. air conditioning, can intersect power supply cables to carry out the same operations. From now on, both kinds will be referred to as Smart Plugs to preserve generality. Each network of maximum thirty Smart Plugs, interconnected over encrypted ZigBee, has a coordinator that gives access to data and functions. The current deployment consists of forty-five plugs, divided into three plug networks.

While Smart Plugs cover small-scale, per appliance power measurements, *Smart Clampers*[5] are designated to measure large-scale consumption, i.e. whole departments or buildings. The Clampers are attached to the main power supply cables and measure consumption via induction. In this deployment, two three-phase clampers are placed at the building's main power supply and one at the data centre, the University's server room. Hence, the sum of the first two clampers measures the total building consumption (including the data centre), while the third clamper measures the data centre's consumption. Then, all clampers transmit their data to a single monitor/receiver with a PC-interface, over simple radio frequency (433MHz SRD band).

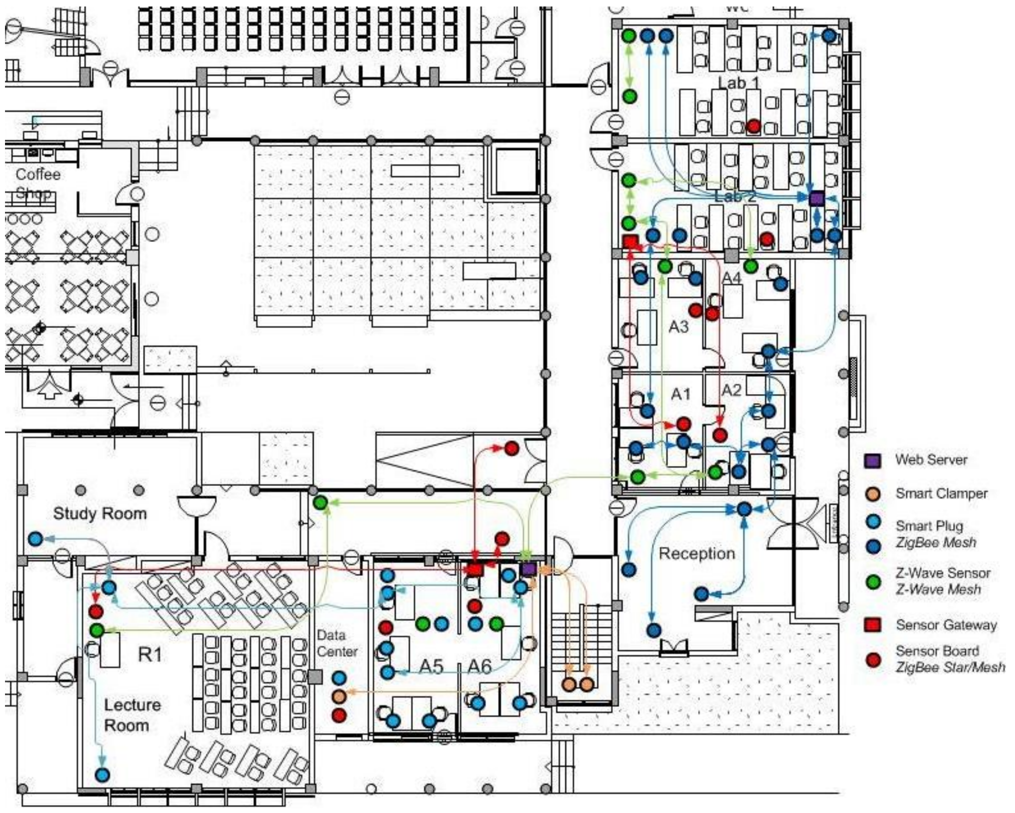


Figure 2. Topology of Wireless Sensor Networks on the ground floor of the building.

The third set of devices enables indoor and outdoor environmental monitoring. Twenty *Sensor Boards*[6] form another ZigBee mesh network and report temperature, luminance and humidity measurements to two designated ZigBee-to-TCP/IP Gateways. The Sensor Boards are fully customizable via coding their microcontroller. To maximize battery life, the period for measurement transmission has been set to ten minutes. Additionally, they

[4] Plugwise: http://www.plugwise.com
[5] Current Cost: http://www.currentcost.com/
[6] Prisma Electronics - http://www.prismaelectronics.eu

have been configured not to act as routers, transforming the network topology from mesh to star. Thus, they are able to enter sleep mode in-between transmissions, which is critical, again, for extending battery life.

The final set of devices complies with a different wireless communication protocol, especially designed for smart spaces, the Z-Wave protocol. The Z-Wave alliance supports extensive interoperability between all compliant devices. In fact, almost every device in a network comes from another manufacturer. A USB Stick is set as the network coordinator and PC interface. The mesh network of sensors comprises of fourteen motion detection sensors, four smoke alarms, a multi-sensor (for temperature, luminance, humidity and motion) and air quality sensors that measure CO_2 levels. More devices are instantly supported at communication protocol level and could possibly be added in the future, e.g. door or window sensors, to further enrich automation scenarios.

Figure 2 presents the exact placement of sensors, actuators and web servers in the building. To satisfy wireless range restrictions, two clusters of networks mainly exist in the building, each administrated by a server collector. The first cluster is found at the southern part and includes Rooms A5, A6, the Data Centre, Lecture room 1, the Hall and the Study Room. The second cluster is visible at the eastern part of the building and includes the Reception, Rooms A1, A2, A3, A4 and the two Computer Labs. Each cluster has its own Sensor Board star network and a corresponding gateway collector. The first cluster is appliance-rich, so it contains two overlapping Smart Plug networks, while the second cluster only contains one. The Z-Wave network features fewer nodes and longer range so it spans across both clusters. The building's power supply is close to the first cluster, so the Smart Clamper receiver is placed within the latter. Sensor Boards can also be received by both clusters so the second was chosen due to its lower load. Each cluster has a web server to collect and expose data and functions, as described in the next section.

4.3. Middle Layer – aWESoME Web Service Middleware

Possibly the principal challenge for AmI applications is to find the common grounds for high-level programming of tasks and activities. The low-level hardware programming of a diverse variety of sensors and actuators needs to be transparent on the upper (application) layer. Wireless sensor network management, topology and properties need to be transparent as well. Devices enforce various constraints such as data format heterogeneity and platform-specific APIs. Applications, on the other hand, require universal, platform-agnostic access to device functions and data. In a large, distributed environment, such as a smart building, universal and remote access also needs to be ensured. Additionally, in such environments, devices dynamically enter and leave the space and this is a non-trivial parameter that has to be seriously taken into consideration.

Table 1. List of service operations available in the environment.

Service	Operation	Output Semantics	Operation Semantics
SmartPlugService	SwitchOn	hasEffect:Status	ActuatorOperation
SmartPlugService	SwitchOff	hasEffect:Status	ActuatorOperation
SmartPlugService	GetPower	Power	SensorOperation
SmartPlugService	GetStatus	Status	SensorOperation
SmartClamperService	GetPower	Power	SensorOperation
SensorBoardService	GetTemperature	Temperature	SensorOperation
SensorBoardService	GetHumidity	Humidity	SensorOperation
SensorBoardService	GetLuminance	Luminance	SensorOperation
SensorBoardService	GetBatteryLevel	BatteryLevel	SensorOperation
ZWaveService	GetMotion	Motion	SensorOperation
ZWaveService	GetCO2	CO_2 level	SensorOperation
ZWaveService	GetTemperature	Temperature	SensorOperation
ZWaveService	GetHumidity	Humidity	SensorOperation
ZWaveService	GetLuminance	Luminance	SensorOperation
ZWaveService	GetSmoke	Smoke Alarm	SensorOperation
ZWaveService	GetBatteryLevel	BatteryLevel	SensorOperation

With the rise of Service-Oriented Architecture and Service-Oriented Computing, Ambient applications found a suitable paradigm that tackles all aforementioned requirements. Service-orientation follows the principle of "services instead of data", hiding data and functions behind a universal API. Thus, internal application logic is transparent to the service client. In this case, hardware or software related services in the environment provide the necessary abstractions from device topology and function. Additionally, services allow for universal service-clients on any platform and in any programming language. Platform-dependent device operation is performed, regardless, on the server-side.

To realize the Smart IHU platform, a service-oriented middleware has been developed following well-defined Web standards. The *aWESoME middleware* [Stavropoulos et al., 2013] provides access over WSDL services to every device operation on the hardware layer. Since WSDL provides syntactic interoperability, services are usable even outside the borders of this system. To enhance the middleware and provide higher-level intelligence, it was further enriched with SAWSDL semantic annotations [Farrel & Lauser, 2007]. The so-called Semantic Web Services are machine interpretable and can be utilized for automatic discovery, selection, matching and composition. Table 1 provides a comprehensive list of service operations available, along with their semantic annotations (SAWSDL model references). The BOnSAI ontology's smart building concepts, environmental parameters and devices were used for the annotation [Stavropoulos et al., 2012]. The semantic description of device capabilities constitutes an added-value addition that further enhances dynamicity and interoperability.

Apparently, different services host similar operations, as different sensors provide the same environmental measurements. Semantic annotations help applications handle these operations similarly, e.g. get a temperature reading either from SensorBoardService or ZWaveService. Also, sensor operations are distinguished from actuator operations, which bear an object property of 'hasEffect' on the status of devices. Finally, note that different instances of the same services are hosted by more than one server in the environment, as detailed previously in our sensor network deployment.

4.4. Application Layer

The syntactic and semantic interoperability provided by the middle layer (see previous section) support a variety of platform independent applications on the topmost layer of the infrastructure. Applications developed so far cover all major platforms and many different purposes. A desktop application enables comprehensive monitoring and management of the complete infrastructure. Users are able to monitor all real-time and historic data in graphs. Additionally, they can invoke actuator operations and manipulate the building's energy consumption, thus enabling savings through decision making [Stavropoulos 2011b]. An Android mobile application enables the same administrative functionality. Various other applications enable querying the service registry using semantic criteria, i.e. service selection, discovery and matching. History-monitoring clients mentioned above are not presented here, since they are outside the scope of this work. However, their monitoring capabilities have been used to observe and design the energy-saving policies applied by the rule-based systems.

This work focuses specifically on two rule-based agents for automatic and effective energy management, both of which are designed to act autonomously, based on an initial rule base and input from sensor readings. The first agent, called *Wintermute*, represents an initial attempt to using production rules, while the second agent, called *DeL*, evolves the approach one step further, using defeasible logics (see Section 3). Each is presented in the corresponding sections that follow.

4.4.1. Reactive Agent (Wintermute)

Wintermute represents the first agent implemented and integrated into the architecture. The initial requirements analysis is aiming at an intelligent agent system that incorporates user knowledge and, from then on, acts autonomously to achieve the energy-saving goal. The following functional requirements have been set:

a. The agent must be able to maintain a knowledge base, which will serve as its own internal representation of the world's state. This information will apparently have to be acquired through the Semantic Web Service interface of the middleware.
b. The agent must be able to perform reasoning on the status of the world and apply the derived decisions towards modifying the world state accordingly. This is again performed, by invoking the Semantic Web Service functions.
c. The agent must be able to communicate with human users and/or other software agents to exchange information or negotiate actions.

Additional non-functional requirements to be considered include reliability, fast performance, low response time, extensibility, usability and interoperation with other already active clients.

Different methodologies of AI, like e.g. learning, can be employed to automate the decision making process of such a system. In this approach, we chose to embed a rule-based expert system into an intelligent agent residing on a multi-agent platform. Expert systems traditionally comprise of two parts: (a) the knowledge base, which is a dynamically changing repository of known facts and rules, and, (b) the inference mechanism that performs reasoning on the knowledge base using principles of a formal logic.

Facing the above challenges, a multi-component architecture comprised of closely connected modules has been adopted to manipulate the Smart IHU environment (see Figure 3). Like every other application on the Smart IHU platform, Wintermute is built on top of the already established middleware and hardware layers. The aWESoME middleware exposes all data and functions through Web Services, providing the necessary abstractions for Wintermute to manipulate the environment. As stated before, aWESoME has been enriched with semantic descriptions, following the SAWSDL standard, to enhance semantic interpretation by the applications themselves.

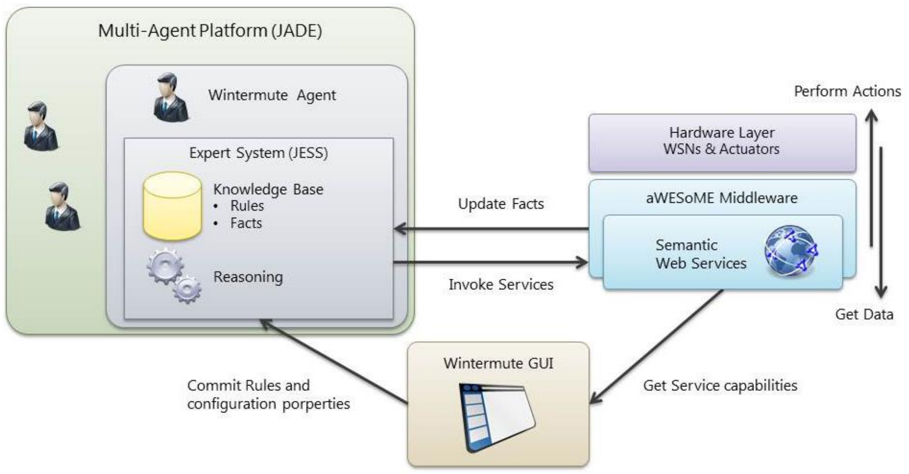


Figure 3. Wintermute agent architecture.

The multi-agent platform hosting Wintermute is *JADE*[7] (*Java Agent Development* framework). Within the platform it is possible to have many Wintermute agent instances running simultaneously and each instance can bear a different portion of the knowledge base and be appointed to different subsets of tasks. Collaboration and negotiation between Wintermute and potentially any other type of agent within the platform is possible; however, as agent negotiation techniques are outside the scope of this work, from now on we consider a single instance of Wintermute responsible for all aspects of energy saving within the building.

Wintermute's GUI component provides a connection between the system and human user administrators. The GUI is semantically-enabled, using information from semantic service descriptions to help users author policies, which are later committed to the Wintermute agent's knowledge base. The application is developed in Java and the JavaFX UI platform. A primary purpose is to allow and facilitate users to author rules that represent user-defined energy saving policies. Towards this end, the tool parses Semantic Web Service descriptions (SAWSDL files) of Web Services available in the SmartIHU environment. These machine interpretable semantic descriptions enhance the effectiveness, scalability and easy-of-use of the application. Specifically, the ontology contains an Operation concept having an ActuatorOperation and a SensoryOperation subclass. Service operations annotated as 'SensoryOperation' belong to sensors and retrieve sensory output. Hence, a direct convention can be made, that all sensory operations are suitable to be used as rule condition predicates (LHS) but are completely unfit for rule actions (RHS). Similarly, service operations annotated with the 'ActuatorOperation' concept are fit for rule action predicates. As a result, the application is each time dynamically aware about which operations should be presented during the condition (rule body) or action (rule head) authoring process of a rule. This also enhances the extensibility of the application, when adding completely new services, and its adaptability, as service providers interleave the ambient environments.

The majority of services utilized so far is summarized on Table 1. To implement the service description parser, the *easyWSDL* toolbox[8] was used. Figure 4 shows the main window of Wintermute's GUI. The right panel shows a collection of rules loaded in the workspace. The left pane allows authoring or editing an existing rule. Semantic information of services is loaded in a dropdown box for the user to select available conditions or actions dynamically. Additionally to rules, the GUI also provides the agent with configuration properties such as the time interval between the invocations of the services.

The rule inference engine in the core of Wintermute is JESS, found to be the fastest and most powerful amongst CLIPS, jDREW and Mandarax [Daniele et al., 2007]. The agent's knowledge base is filled with facts and rules

[7] Java Agent Development framework – JADE: http://jade.tilab.com/
[8] The easyWSDL toolbox: http://easywsdl.ow2.org/

about the state of the building, environmental-, power- and energy-wise. Rules are authored by the user over the GUI and represent energy saving or user comfort policies. The agent semantically parses these rules and monitors aspects of interest that they may contain. Values are returned by invoking the corresponding Semantic Web Service operations. A rule's conditions correspond to specific measurements that translate to particular sensors, e.g. a room's temperature sensor. This way, the agent does not have to constantly monitor the entire infrastructure, thus, saving traffic load on the Web Server. The monitored values take the form of deffacts in the knowledge base that represent a model of the current knowledge about the world's state, while rules are represented as JESS defrules. For instance, a rule for switching off the cooler, when the temperature is below a given threshold, would be expressed as follows:

```
(defrule ruleTemp
         (call GetTemperature 8C3C0A ?x0)
         (test (< ?x0 25) )
=>
         (call SwitchOff 99678C)
)
```

where `8C3C0A` and `99678C` are the IDs for the temperature sensor and cooler actuator, respectively.

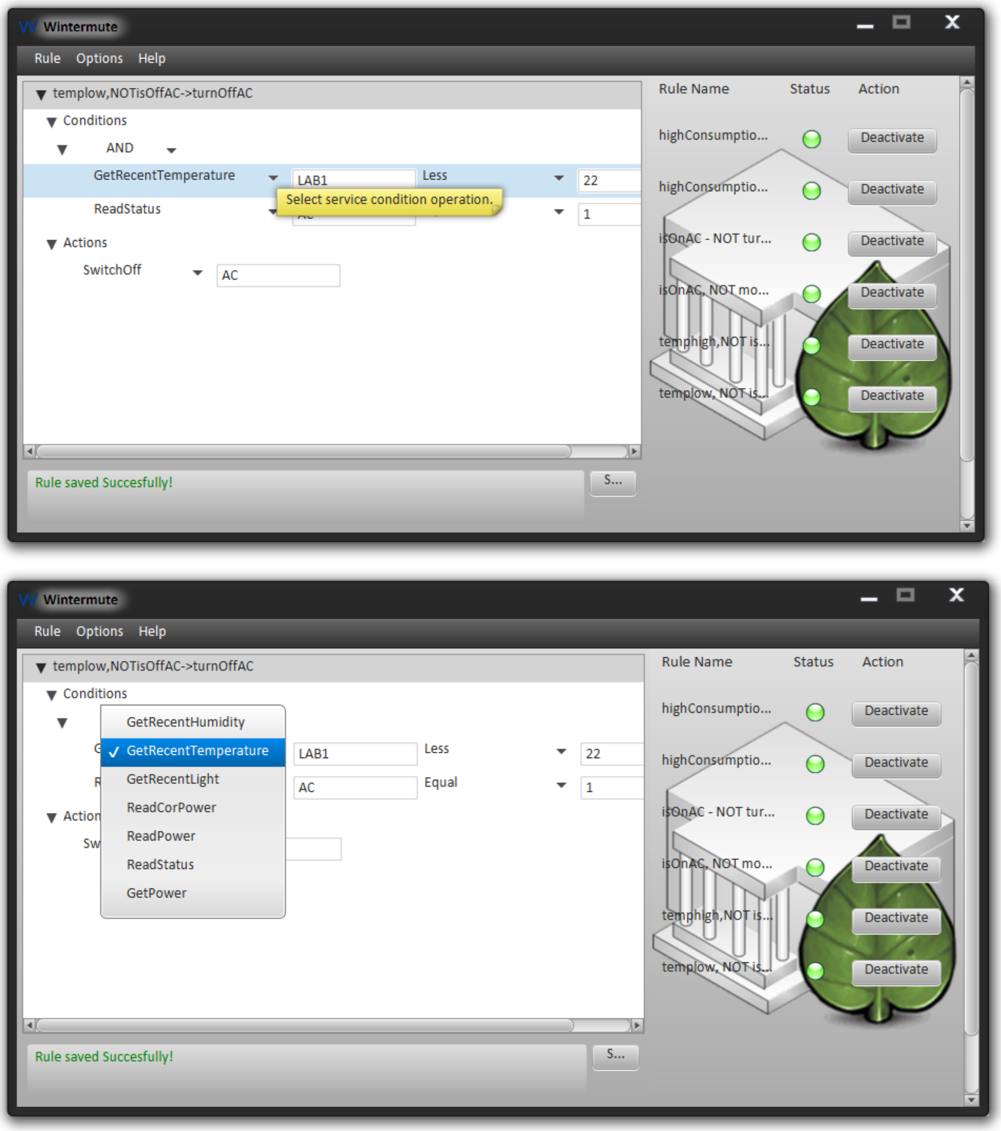


Figure 4. Both images illustrate the Wintermute GUI and its rule editing capabilities: rule conditions and actions can be manipulated accordingly in a user-friendly manner (top), and, the user is able to select conditions and actions from a dropdown list, dynamically retrieved from semantic web service descriptions (bottom).

To improve the agent's capacity for better performance and accessibility, the invoking frequency can be appropriately adjusted, also through the GUI component in real time. When a high sampling frequency is selected, the agent is fast and responsive, while a low frequency gives room to other service client applications running concurrently.

At the same time, the JESS inference engine checks for activated rules by matching patterns (sampling frequency, rules triggered and activated). Upon activation, web services are invoked to apply the appropriate actions. Since, even with numerous actuators on various appliances, the platform is still much less flexible than a human being, email alerts are in some cases issued to the system administrator. The latter can then physically act himself or simply take notice on needed changes. In the future, a wider variety of more sophisticated actuators, perhaps even robotic agents, could take over the workload from humans.

Notice that in case multiple rules fire, the system is not able to automatically handle conflicts, e.g. two rules invoke contradictory actions. When such behavior is observed, manual re-authoring of the rule base is needed. This drawback of reactive rules has been alleviated by using defeasible logic, as shown in the next section. Section 5.3 elaborates on the comparison between the two rule paradigms.

4.4.2. Deliberative Defeasible Logic Agent (DeL)

Building on top of Smart IHU's middleware layer, the defeasible logic (DeL) agent is an autonomous software tool responsible for maintaining user comfort and improving energy consumption. Its purpose is more or less identical to that of Wintermute; both agents aim to provide an overall user-friendly interface for system administrators and energy experts to formulate energy-saving and preservation policies. The agents are then responsible for autonomously acting and carrying out these policies, manipulating the environment via the actuators. However, DeL features a comparatively more "deliberative" behavior, entailing at the same time a different software architecture. More specifically, DeL offers more flexibility and user-friendliness in the representation of the policies, providing the advantages outlined previously in this paper (see Sections 3.1 and 3.3).

4.4.2.1. Defeasible Logic Rule Base

Based on the superiority relationship feature of defeasible logics (see Section 3.2), DeL presents the user with the definition of three distinct rule sets $\mathcal{P}$, $\mathcal{M}$ and $\mathcal{E}$:

- *Preferences rules* ($\mathcal{P}$): These are rules that deal with the comfort of the user and his/her personal preferences, like e.g. the desired room temperature during the winter months. A sample preference rule is r_2 from Section 3.2: `tempHigh` ⇒ `switchOnCooler`.
- *Maintenance rules* ($\mathcal{M}$): Namely, the rules that formulate the power management scheme of the building, like e.g. the deactivation of certain devices or appliances during late night hours. A maintenance rule paradigm is: `highConsumption` ⇒ `switchOffCooler`.
- *Emergency rules* ($\mathcal{E}$): These are rules that are triggered in case of an emergency, like e.g. the activation of emergency lights in the case of fire, which could be represented by the following rule: `fire` ⇒ `switchOnLights`.

If $\mathcal{R}$ is the set of all rules in the framework, then for the three rule sets: $\mathcal{P} \cup \mathcal{M} \cup \mathcal{E} \equiv \mathcal{R}$. Hence, in our approach rules can belong to preference, maintenance or emergency rule sets, adding an intuitive and effective classification practice for energy experts. Additionally, this approach is a refined version of the rules deployed in the Wintermute agent (see Section 4.4.1).

Regarding the scope of each rule set, $\mathcal{P}$ is restricted to isolated rooms, since it contains rules that deal with the user-defined "micro-management" of the conditions inside a room. The scopes of the other two rule sets are broader, covering the whole building, where the framework is deployed, including the rooms as well as the rest of the other shared areas and facilities, like corridors and storage rooms. The three rule sets demonstrate escalating priority and, more specifically: $\forall\, p \in \mathcal{P}, \forall\, m \in \mathcal{M}, \forall\, e \in \mathcal{E} \rightarrow p < m < e$. Notice that rules belonging to any of the three sets must – in essence – be defeasible, in order for the priority relationship to be effective.

4.4.2.2. Defeasible Reasoning

For the reasoning process, DeL incorporates an instance of *SPINdle* [Lam & Governatori, 2009], a Java-based state-of-the-art defeasible reasoning engine. Although SPINdle lacks a theory grounding mechanism (i.e. no variables can be used in the predicates), which would be greatly beneficial for the purposes of this work, the engine's advantages (fast, reliable, highly integrated and easily-deployable) constitute the incentive for preferring the specific reasoner. The lack of this grounding mechanism is solved in our approach via replacing atoms containing arguments and variables with appropriately composed (sets of) "synthetic" predicates and appending them to the knowledge base. For example, atom `switchOn(cooler)` becomes `switchOn_cooler`, while atom `switchOn(X)` is replaced by a set of synthetic predicates {`switchOn_device_1` , `switchOn_device_2` , …, `switchOn_device_n`} for all the devices registered in the framework. In case SPINDLE supports first-order theories in the future, this grounding pre-processing phase will not be necessary any more.

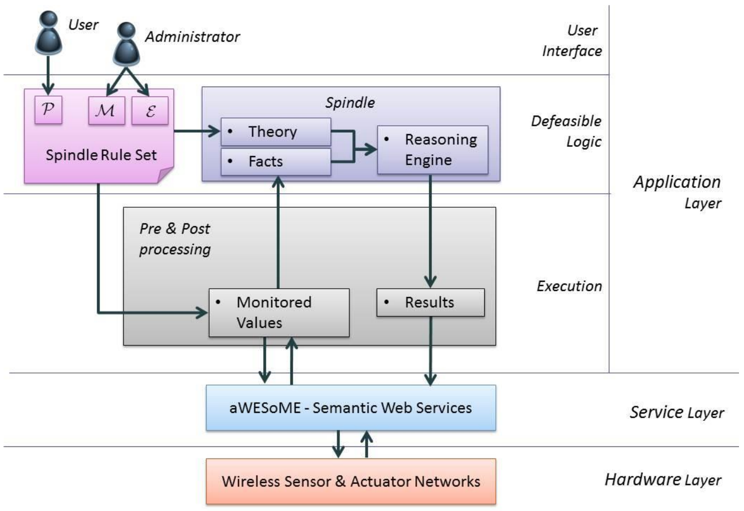


Figure 5. Architecture of the DeL agent in the application layer.

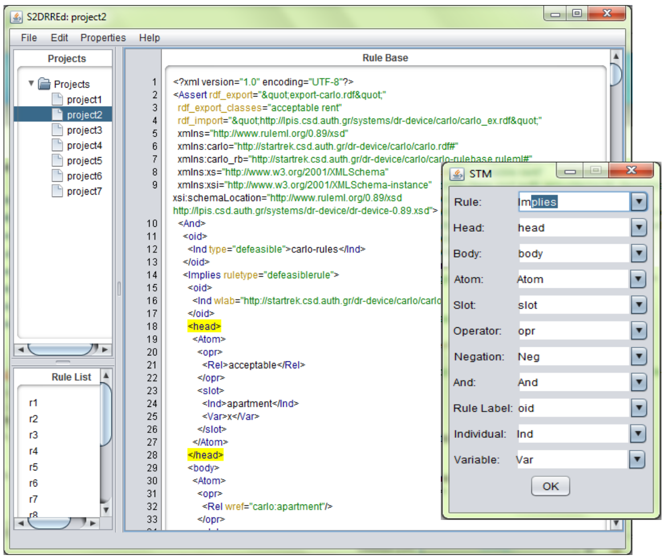
Figure 5 depicts the software architecture of the DeL agent and the information flow between its components. At the topmost level, human administrators and domain experts use an interface to author policies for the agent to enforce. Contrary to Wintermute, DeL does not feature an integrated GUI for rule authoring, but one could separately download one of the available defeasible logic rule editors, like, e.g. *SPINdle's Defeasible Logic Theory Editor*[9], or the much more flexible *S²DRREd* (*Syntactic-Semantic Defeasible Reasoning Rule Editor*) [Kontopoulos et al., 2012]. The latter editor adds a supplementary level of semantic assistance during rule base development, creating meta-models of the main defeasible logic theory notions and, thus, offering the flexibility of authoring rule bases of various syntaxes. Figure 6 displays the main window of the tool as well as its *STM* (*Semantic Tag Mapping*) window that provides a meta-modeling facility for generating schemas over various language versions. A meta-model provides a schema for semantic data, specifying what elements may be contained in the model and how they relate to one another. In essence, each meta-model is a specification of a domain-specific modeling language.

Notice that each type of system user is granted authoring rights for different rule subsets (see previous subsection). Either manually or via the help of a specialized GUI, a part of the authored policies is directly translated into SPINdle-compliant syntax and formulates the initial rule base of the system, while the remainder needs to undergo a pre- and post-processing phase at the execution layer. The purpose of this layer is to handle rules with conditions containing predicates that require the invocation of sensors via the middleware layer of the architecture. Thus, the literals of the rule conditions have to be transformed into a suitable syntax for invoking the respective Web Services. For example, the `motion` predicate is replaced by a '*ZWaveService.GetMotion*()' service operation call. This preprocessing transformation is currently performed via a lookup table, but future plans involve integrating this association in the back-end ontology of the system. Finally, instead of serially examining all conditions, each service operation is only invoked once, as duplicate conditions may exist within the rule set.

Transcending from the Middleware (or Service) layer to the hardware layer, values are retrieved from the distributed wireless sensor networks across the building. Upon completion, all predicates are replaced with numeric values forming the actual facts to be appended to the knowledge base of the SPINdle reasoner, again with the help of the lookup service. This is the reverse process (i.e. post-processing) that has to take place when the readings of the sensors are retrieved. Notice that, rule conditions typically involve sensor readings and rule conclusions usually point to actuator activities. However, contrary to production rules, defeasible logic allows for

[9] SPINdle Defeasible Logic Theory Editor: http://spin.nicta.org.au/spindle/tools.html

more complex reasoning, where the conclusions of a rule may serve as conditions for further rules. Although our rule bases do not currently include such cases, this feature is already handled by the aforementioned lookup service that clearly distinguishes sensor readings and actuator activities.



```xml
<?xml version="1.0" encoding="UTF-8"?>
<Assert rdf_export="&quot;export-carlo.rdf&quot;"
 rdf_export_classes="acceptable rent"
 rdf_import="&quot;http://lpis.csd.auth.gr/systems/dr-device/carlo/carlo_ex.rdf&quot;"
 xmlns="http://www.ruleml.org/0.89/xsd"
 xmlns:carlo="http://startrek.csd.auth.gr/dr-device/carlo/carlo.rdf#"
 xmlns:carlo_rb="http://startrek.csd.auth.gr/dr-device/carlo/carlo-rulebase.ruleml#"
 xmlns:xs="http://www.w3.org/2001/XMLSchema"
 xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.ruleml.org/0.89/xsd
http://lpis.csd.auth.gr/systems/dr-device/dr-device-0.89.xsd">
 <And>
  <oid>
   <Ind type="defeasible">carlo-rules</Ind>
  </oid>
  <Implies ruletype="defeasiblerule">
   <oid>
    <Ind wlab="http://startrek.csd.auth.gr/dr-device/carlo/carlo
   </oid>
   <head>
    <Atom>
     <opr>
      <Rel>acceptable</Rel>
     </opr>
     <slot>
      <Ind>apartment</Ind>
      <Var>x</Var>
     </slot>
    </Atom>
   </head>
   <body>
    <Atom>
     <opr>
      <Rel wref="carlo:apartment"/>
     </opr>
```

Rule:	Implies
Head:	head
Body:	body
Atom:	Atom
Slot:	slot
Operator:	opr
Negation:	Neg
And:	And
Rule Label:	oid
Individual:	Ind
Variable:	Var

Figure 6. S^{2}DRREd Main and STM windows.

The reasoning process is performed once in the beginning, when the knowledge base is complete after the pre- and post-processing phases, and afterwards it is repeated every time the knowledge base is updated with new facts. The reasoning results from each cycle have to go through the same processing steps and then to the invocation of the respective services (if any). Following this pattern, e.g. the `switchOnLight` derived predicate would point to the '*SmartPlugService.SwitchOn*(*Light*)' service operation call. Regarding the rest of the predicates, they are all expressed in direct correspondence to service operation names on Table 1 via the lookup table. Through service invocation, wireless actuator networks in the building are used to apply the desired effects. In other cases, services simply perform software operations such as sending an email alert.

5. Use Case: International Hellenic University Building A

As already stated, the framework is applied at the International Hellenic University (IHU) Building A; this section demonstrates the deployment of the policies and their impact on the overall energy consumption. The specific building is a large, appliance-rich building that bears a restrictive and wasteful infrastructure. Thus, it can serve as a stimulating test-bed of our methodology, which can then be applied to other buildings as well.

The percentage of energy savings accomplished by any method is only subject to a building's prior state of efficient usage, i.e. the greater the waste the greater the savings are. Thus, prior to formulating the energy management scheme policies, the building's current behavioral patterns had to be observed and identified, at least as far as energy consumption is concerned.

5.1. Current Scheme

As presented in previous attempts [Stavropoulos et al., 2013], the hardware, Web Service middleware and appropriate client applications have already provided a basis for comprehensive monitoring and management of energy consumption along with environmental sensor readings. Apart from desktop and mobile administration software, a Web application[10] makes energy monitoring publicly accessible to any external viewer as well.

Observing the vast energy consumption of the building in total, one has to initially disaggregate it to smaller clusters of appliances and/or activities. Attaching a sensor on the data center's power supply allows us to directly isolate its power consumption from the rest of the building. Unfortunately, the data center consisting of servers and cooling units is already configured to its energy-consumption minimum for adequate cooling, meaning that its consumption (~ 50% of total daily consumption) has to be taken as granted. The remaining consumption refers to appliances in the building and comprises mainly of computers, lighting, heating and cooling units and a few

[10] Smart IHU Portal: http://smart.ihu.edu.gr

projectors, peripherals, coffee makers and kitchen appliances. Most of this equipment is monitored separately using individual meters/actuators. Interesting observations include many appliances left constantly on, especially the high consuming photocopiers. Lighting during the night is already working on schedule and is responsible for the nightly consumption along with the stand-by consumption of all appliances.

However, taking action on heating and cooling is moderately restricted due to the nature of the building's existing infrastructure. Heating and cooling both take place in a central boiler/cooler and are distributed to the building through fan coil endpoints, typically one per room. During the winter, the central heating system consumes oil, which translates to less power usage. The cooling system, on the other hand, uses a considerably large amount of energy per day to centrally freeze water. During the winter, fan coils just let heat pass through, even while powered off. When powered on, the fans accelerate heat dissemination. Conversely, during the summer, fan coils provide utility only while they are on, while having the fans off actually saves up on the central cooling system consumption, as it has to freeze less water over time. However, most of the fan coils in the building would have to coordinate for this savings to take effect. Overall, the fans themselves hold an insignificant amount of consumption even as a whole. Observing the yearly course of the seasons, consumption of appliances was thus found to be much lower, since oil is used and fan coils are mostly powered off. Additionally, the university employees do keep the fan coil usage to a minimum. Combined with their very small consumption, their daily energy needs go unnoticed in total. All the above, result in much less energy spent for heating compared to cooling and, thus, much less saving potential.

A final observation was made during the early morning hours. Every morning, from 6am to 8am, the total power consumption increases by 5kW, resulting in 10kWh of energy per day, in average over the last year (higher during working days and lower during weekends). Inspecting the appliances, this amount comes from the building lighting being switched on by the early morning cleaning services. Since the cleaning crew does not need constant lighting to the whole university for this course of two hours, there is definitely some space for savings here.

5.2. Applying Defeasible Logics – Sample Policies

This subsection features a simplified example demonstrating the deployment of the policies rule base and the improved flexibility offered by the different rule sets (see Section 4.4.2.1). Suppose that the following example explicitly involves room 'A6' of IHU's Building A and revolves around the operation of the room's cooler during the summer months. Towards this affair, we can formulate the three distinct rule sets $\mathcal{P}$, $\mathcal{M}$ and $\mathcal{E}$ that, as already stated, represent the policies for preference, maintenance and emergency, respectively.

To begin with, let's suppose that the employees working at room 'A6' define the following preferences policy (rule set $\mathcal{P}$) regarding the operation of the room's cooler:

p_{01}: `temp(a6,X), X < 18` → `tempLow(a6)`

p_{02}: `temp(a6,X), X > 28` → `tempHigh(a6)`

p_{1}: `tempHigh(a6)` ⇒ `switchOn(a6,cooler)`

p_{2}: ¬`tempHigh(a6)` ⇒ `switchOff(a6,cooler)`

As mentioned before, the preferences rules primarily handle user comfort. Thus, according to the above preferences, the employees-users determine the thresholds that define – by their personal standards – the 'low' and 'high' temperatures in the room and designate when the cooler should be turned on or off in accordance to these thresholds. Preference policies like these allow for a periodic use of fan coils, instead of the non-stop, manually scheduled usage in the past. Usage history has shown that employees usually do not mind crossing the temperature thresholds and leave the appliances on, even after leaving the room they are working in. The periodic usage of coolers has a positive impact on the building daily usage, removing the fan coil footprint itself, but most importantly by saving up on the central cooling system consumption, less water has to freeze over time.

Moving on to the system's administrator, a maintenance policy (rule set $\mathcal{M}$) has to be defined, in order to optimize the overall operation of the building and its respective power consumption. Maintenance rules tend to enforce further savings, often compromising the comfort requested by the user-defined preference rules. The scope of the following rules lies in the specific room and the operation of its cooler:

m_{01}: `consumption(a6,X), X > 2000` → `savingMode(a6)`

m_{02}: `time(X), X > 2200` → `savingMode(a6)`

m_1: ¬motion(a6) ⇒ switchOff(a6,cooler)

m_2: savingMode(a6) ⇒ switchOff(a6,cooler)

m_{03}: isOn(a6,cooler) ⇝ ¬switchOn(a6,cooler)

m_{04}: isOff(a6,cooler) ⇝ ¬switchOff(a6,cooler)

As can be observed, the administrator starts by determining the conditions for having the room switch to 'saving mode', during which the system will attempt to minimize consumption. More specifically, rule m_{01} deals with the total energy consumption of the room, handling flexible loads to ensure a total consumption is not exceeded in any given moment. Rule m_{02} handles the operation of the room's appliances during late night hours[11]. The following two rules, m_1, and m_2, determine when the cooler will switch off, depending on the presence of people in the room and the activation of the 'saving mode'. Finally, the last two defeaters make sure that the cooler's actuator will not attempt to turn on an already operating cooler and, conversely, will not attempt to turn off a cooler that has already been switched off.

Eventually, the administrator has to formulate the policy for emergency situations (rule set $\mathcal{E}$):

e_{01}: smoke(a6) → alert(a6)

e_{02}: highCO2(a6) → alert(a6)

e_1: alert(a6) ⇒ switchOn(a6,alarm)

e_2: alert(a6) ⇒ switchOff(a6,cooler)

When a sensor reading is received that implies unsafe conditions inside the room, like e.g. smoke or too high CO_2 concentration or other measured values exceeding safety limits, the system activates the room's alert (rules e_{01} and e_{02}). The alert then handles the operation of the appliances in the room accordingly (rules e_1 and e_2).

Concluding the example, the following set of conflicting literals (see Section 3.2) has to be inserted into the rule base:

$\mathcal{C}$ = {switchOn(X,Y), switchOff(X,Y)}

This way, a conflict is automatically generated between pairs of rules, where one rule concludes that a device (e.g. cooler, alarm etc.) should be turned on and the other one concludes that it should be turned off and vice-versa. These conflicts will then have to be resolved via appropriate superiority relationships among each pair of conflicting rules. In the cases of conflicts between rules belonging to the same rule set (e.g. both rules are maintenance rules), the superiority relationship has to be explicitly added to the knowledge base by the user with the appropriate access permissions (in the case of maintenance rules this would be the administrator). On the other hand, the cases of conflicts between rules belonging to different rule sets is handled automatically by the system, via rewriting the theory and adding the respective superiority relationships, according to the scope of each rule set. Thus, for the specific rule set presented in this subsection, the following superiority relationships are appended to the rule base:

$m_1 > p_1$

$m_2 > p_1$

$e_2 > p_1$

Understandably, the overall sample rule base presented here is rather simplistic, but hopefully demonstrates the expressiveness and user-friendliness of the defeasible logic representation. Moreover, the flexibility of the conflict resolution mechanisms of defeasible reasoning combined with the three distinct rule sets of escalating priority proposed in this approach, produce a versatile Smart Building management system. To give a deeper insight, we present the following brief examples.

[11] Other appliances that could potentially benefit from this operation are the printing devices that typically remain on during the night and are responsible for some major energy waste due to periodic calibrations. Having the system automatically switch off the printers according to timely schedule would provide a solution. During the past year, though, many students have visited the computer lab after late hours, wanting to print out lecture notes. Thus, an appropriate rule should also turn on the photocopiers in case of detected motion. Of course, this functionality can easily be integrated into the system, but is omitted here due to simplicity.

Example 1

Suppose that the following facts, generated by respective sensor readings in room A6, are inserted into the above rule base:

f_1: `temp(a6,30).`

f_2: `time(2300).`

f_3: `motion(a6).`

Fact f_1 triggers rule p_{02}, whose derived conclusion matches the condition of rule p_1. At the same time, fact f_2 triggers rule m_{02} and the derived conclusion of the latter matches the condition of rule m_2. By observing rules p_1 and m_2 one can detect that the two conclusions (`switchOn(a6,cooler)` and `switchOff(a6,cooler)`) contradict each other, because of the set of conflicting literals $\mathcal{C}$. Thus, it is not clear whether the cooler should eventually be turned on or off. However, since all maintenance rules have a higher priority than preference rules (see previously), the system automatically infers that $p_1 < m_2$ and the maintenance rule eventually prevails.

Example 2

In addition to the three facts inserted during the previous example, suppose that a fourth fact is also inserted:

f_4: `highCO2(a6).`

Fact f_4 triggers rule e_{02}, whose derived conclusion matches the conditions of rules e_1 and e_2. Rule e_1 is not attacked by any other rule, thus, the alarm in room A6 is activated. However, the conclusion of rule e_2 contradicts the conclusion of rule p_1. But, as already stated, all emergency rules have top priority when attacked by preference or maintenance rules. Thus, it is automatically inferred that $p_1 < e_2$ and we can safely conclude that the cooler will eventually be turned off. Demonstrating the dynamicity of the system, if CO_2 levels fall back to normal later on, the fact base will be updated resulting to a new execution of the rule set and a new set of derived conclusions.

As already mentioned before, SPINdle does not support theory grounding and, additionally, features like conflicting literals are substituted by appropriate sets of conventional defeasible rules and superiority relationships before being submitted to the reasoner. Appendix A illustrates the above theory, together with the facts used in the two previous examples, in the SPINdle-specific syntax. The transformation from the initial syntax, or any other input rule syntax like e.g. *defeasible RuleML*[12]), to the target syntax constitutes a task appointed to the end-user/administrator, potentially via a specialized GUI used for authoring the rule base (see Section 4.4.2.2).

5.3. Comparison of the Two Rule Paradigms

As demonstrated in the previous subsection, the representation of policies via defeasible logic is highly intuitive and flexible. In order to demonstrate these advantages, we present the reader with rule p_1 from the above rule base, expressed however as a reactive rule instead of a defeasible one:

```
tempHigh(a6), motion(a6), ¬savingMode(a6), ¬isOn(a6,cooler), ¬alert(a6)

        → switchOn(a6,cooler)
```

One can easily realize that the latter version of the rule is required to include all possible exceptions (e.g. `¬savingMode`) in its body. It should be mentioned here that negation in the reactive rule setting is not strong negation, but negation-as-failure, i.e. a negated atom is true, when it is not present in the current content of the knowledge base. These extensive representations for expressing all possible exceptions to a rule is counterintuitive, since in cases of hundreds of rules the resulting representations would be greatly impractical.

Additionally, this peculiarity makes the whole system less flexible, as it would require the end-user to have access to (and knowledge of) parts of the internal policies, namely, more than his preferences, which does not comply with the end user's access levels. Likewise, maintenance rules would need to have access to predicates belonging to emergency policies, ultimately rendering useless the initial distinction in three separate classes (preferences, maintenance, and emergency).

Finally, as already mentioned in Section 4.4.1, the production system cannot easily handle rule conflicts that arise when two rules invoke contradictory actions. Such conflicts could be resolved by rewriting (parts of) the rule base,

[12] Schema Specification of Defeasible RuleML Version 1.0: http://ruleml.org/1.0/defeasible/defeasible.html

which is a counterintuitive approach. On the other hand, defeasible logic offers more intuitive conflict resolution mechanisms, via rule superiorities and sets of conflicting literals.

5.4. Results

Via persistently enforcing policies like those mentioned in the previous subsection, we noticed a daily energy consumption reduction throughout the building. Considerable changes commence from certain rules, such as those that schedule the operation of printers. However, these amounts are not significant, when taking into account the total building consumption. In addition, the various events (workshops and lectures) taking place daily at the university premises at a non-periodic fashion result in small changes that are harder to detect.

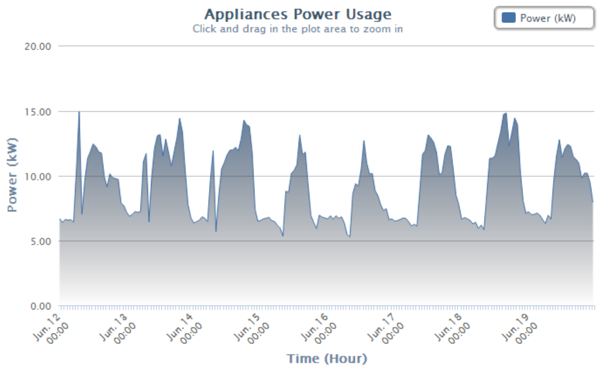


Figure 7. Savings on everyday morning maintenance.

An exception to the above is the building consumption during early morning cleaning. As can be seen in Figure 7, every morning between 6am and 8am, consumption peaks up by an average of 5kW up to 15th June. As reported before (see Section 5.1), the reason for this peak lies in the fact that, during early morning hours, the cleaning crew had been keeping all lights on even when interleaving the rooms. The presence of rules that involve motion detection in the rooms (lights are switched off, when no one is present in the room – e.g. see rule m_1 in Section 5.2) eliminated this peak.

However, a slight adjustment was required, in order to handle this peculiarity during early morning hours. More specifically, during those hours the system has been regulated to run on *responsive mode*, switching the lights instantly on or off according to motion detection. This mode is, of course, unsuitable for any other time of the day, as office employees typically stay put (no motion detected), so the lights respond to much longer periods of undetected motion.

On the other hand, during responsive mode, we noticed that the system could not instantly respond to sensor readings, due to serially processing all service calls within the loop. Although each service call's response time averages below 1 sec, the sum of all calls within the monitor loop takes up a considerable amount of time. Thus, a composite paradigm of the agent application was deployed, having an instance of the responsive agent (Wintermute) handle few, reactive policies only and an instance of the deliberative agent (DeL) handling the rest, long-term policies. As a result, the reactive agent has only a single or just a few monitor calls and responds within a time span of a second.

All in all, the integration of the agents in the Smart IHU architecture guaranteed at least 2% to 4% daily energy savings, which is a significant percentage considering the large scale of energy consumed by a university building. To put it in perspective, the university consumes around 438.2kWh per day (average of past year), around half of which belongs to the data center (221.5KWh). This amount could easily be matched to a monthly consumption of a small household, while the amount of 2% could equal the total daily consumption of that household.

As a final remark, the amount and percentage of the system's savings are only relevant to how much energy was being wasted in the first place. All in all, the system can only guarantee to enforce all energy-saving behavior and ensure that energy-wasting behavior is kept to a minimum.

5.5. Critical Discussion

The previous subsection demonstrated the advantages of combining the two agent types (reactive and deliberative) inside a common AmI architecture, since each type features certain pros and cons. More specifically, the reactive agent is based on production rules and naturally excels at instantly invoking actuators, thus, managing the reactive operation of devices in cases when response time is critical. On the other hand, the deliberative agent offers higher expressiveness and more intuitive conflict resolution mechanisms, permitting a clear distinction of the different rule sets and access levels. A further advantage of this agent type is the fact that it can reason on more complex rule bases, where the conclusions of a rule may serve as conditions for other rules etc. This capability provides an internal state to the agent as well as a more complete modeling of the environment.

Although both agent types bring different elements to the table, it is not necessary to choose one over the other. Instead, the *hybrid* agent type has been proposed in literature that is concurrently capable of reactive and proactive behavior [Wooldridge, 2001]. Hybrid agents typically integrate – amongst others – two distinct layers in their architecture that deal respectively with the two types of behaviors (reactive and proactive). The specific architecture of the agent, nevertheless, depends on the layering as well as the information and control flows within the layers. Though stimulating as an idea, the hybrid agent type is out of the scope of this paper and is included in plans for future development.

6. Future Work

Besides investigating the integration of a hybrid agent type into the proposed architecture (see previous subsection), our future plans involve extending the scale and invasiveness of the experiments. Rules can grow in numbers, raising the load of operations to perform throughout the building. More interfering rules, such as killing the stand-by mode of PCs, will carefully be introduced. Such rules have been avoided thus far, due to their high intrusiveness and difficulty to detect when that device will be needed again (the placement of the appropriate hardware can be experimented with). Towards improving the tools accompanying the framework, a Web UI is being developed, in order to enhance user experience and convenience, but will obviously have no impact on the observed results.

Furthermore, the platform can be extended and enhanced on every layer. Regarding the service layer, the agents can benefit from automatic service discovery, for dynamically discovering or substituting services that interleave the environment in real time. This way, new portable and redundant service providers could be introduced into the system. On the user and rule layers, a machine learning subsystem can be employed to discover regular consumption patterns and suggest respective energy-saving rules.

On the agent platform level, we will investigate integrating more instances of same or different agent types (reactive, deliberative or hybrid) to serve different roles. Each agent will be assigned a sub-task or a region within the building and negotiate with the others towards achieving a certain goal (e.g. comfort and/or energy savings). Agent negotiation will be needed especially for resolving potential conflicts among agents, e.g. when two or more agents are assigned the operation of the same device(s).

A final future goal is to investigate the application of *temporal defeasible logics* [Governatori & Terenziani, 2007], in order to efficiently deal with temporalized durative facts and with potential delays between rule antecedents and consequences and overall capture the temporal aspect in our framework.

7. Conclusions

This work presents a building-wide real-world rule-based Ambient Intelligence application that aims for user comfort and energy savings. Multiple wireless sensor and actuator networks that comply with different product families and communication protocols have been deployed to collect environmental and energy data across a State University building. The infrastructure integrates a middleware providing service-orientation by unifying all underlying distributed and heterogeneous wireless sensor and actuator platforms. Two rule-based approaches for managing energy saving schemes have been proposed: Wintermute and DeL.

The former involves a reactive rule-based agent, which enables administrators to author and enforce energy saving policies, as sets of production rules that run using a production rule engine. The latter, more advanced, approach involves a defeasible logic reasoner that delivers more intuitive policy authoring, offering sophisticated conflict representation and resolution mechanisms. A priority ordering for each rule type is defined and, via this capability, a priority scheme is proposed that categorizes rules in clusters of preference, maintenance and emergency policies.

For the experimental part, a careful analysis and monitoring of year-long consumption data has been performed and suitable policies were authored. A considerable amount of savings was achieved, but most importantly, the policies guarantee to keep any potential energy waste to a minimum. Another observation was that such real time systems require the use of more than one software agent to especially ensure instant response and reactiveness for the most important of policies.

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Appendix A – SPINdle Syntax

The following fragment illustrates the SPINdle-specific syntax for the sample rule base presented in Section 5.2. Notice that conflicting literals are represented by specific rules added to the rule base, accompanied by respective superiority relationships.

```
set @temp_a6 = 30
set @time = 2300
>> motion_a6
>> highCO2_a6

# preference rules
p01: $@temp_a6 < 18$ -> tempLow_a6
p02: $@temp_a6 > 28$ -> tempHigh_a6
p1: tempHigh_a6 => switchOn_a6_cooler
p2: -tempHigh_a6 => switchOff_a6_cooler

# maintenance rules
m01: $@consumption_a6 > 2000$ -> savingMode_a6
m02: $@time > 2200$ -> savingMode_a6
m1: -motion_a6 => switchOff_a6_cooler
m2: savingMode_a6 => switchOff_a6_cooler
m03: isOn_a6_cooler ~> -switchOn_a6_cooler
m04: isOff_a6_cooler ~> -switchOff_a6_cooler

# emergency rules
e01: smoke_a6 -> alert_a6
e02: highCO2_a6 -> alert_a6
e1: alert_a6 => switchOn_a6_alarm
e2: alert_a6 => switchOff_a6_cooler

# rules for handling conflicting literals
c01: switchOff_a6_cooler => -switchOn_a6_cooler
c02: switchOn_a6_cooler => -switchOff_a6_cooler
m1 > c02
m2 > c02
e2 > c02
c01 > p1
```